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Intelligent Distribution Network Design

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Frans Provoost

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Dit proefschrift is goedgekeurd door de promotor:

prof.ir. W.L. Kling

Copromotor:
dr.ir. J.M.A. Myrzik

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First promotor: prof.ir. W.L. Kling

Copromotor: dr.ir. J.M.A. Myrzik

Core committee:

prof.dr.ir. G. Andersson
prof.dr.ir. R. Belmans
prof.dr.ir. J.H. Blom

Other members:

prof.ir. M. Antal
prof.dr.ir. A.C.P.M. Backx (chairman)
ir. P.M. van Oirsouw

Intelligent Distribution Network Design

Summary

Distribution networks (medium voltage and low voltage) are subject to changes caused by re-regulation of the energy supply, economical and environmental constraints, more sensitive equipment, power quality requirements and the increasing penetration of distributed generation. The latter is seen as one of the main challenges for today's and future network operation and design. In this thesis it is investigated in what way these developments enforce intelligent distribution network design and new engineering tools. Furthermore it should be investigated how a new design and control strategy can contribute to meet the power quality and performance requirements in distribution networks in future.

This thesis focuses on network structures that, typical for the Netherlands, are based on relatively short underground cables.

Managing current and voltage in such networks both during normal and disturbed operation, requires a good network design and an adequate earthing concept. The limited size of Dutch distribution networks has a positive effect on power quality aspects and reliability. The use of impedance earthing for medium voltage (MV) cable networks reduces the risk of multi-phase faults that cause large fault currents and deep dips. It also reduces the risk on transient over-voltages due to re-striking of cable faults. A TN earthing system for the low voltage (LV) network reduces the risk of damaged apparatus and it maintains safety for people. However, care must be taken for the earthing of devices of other service providers, which requires a co-operative solution.

The fast developments of computation techniques and IT equipment in the network opened the possibility to perform many calculations in short time based on both actual and historical data. Examples are the on-line distribution load-flow and the short-circuit calculation for protection coordination and intelligent fault location. In LV and MV network calculations the accuracy of the models and the availability of data are the main obstacles. Because of the unsymmetrical nature of load and generation in LV networks a multiple conductor model is needed. For safety calculations also the earth impedances have to be modelled as well as the neutral and protective earth impedances and their mutual interactions.

The protection philosophy in MV networks must take into account the changing requirements regarding safety and power quality. An overall philosophy concerning both network and generator protection is necessary.

New developments in substation automation benefit future upgrade and refurbishment of substation control and protection. As a result, also cheap, accurate and fast fault location becomes feasible, reducing the outage time of the customers.

Next the influence of distributed generation on the above subjects is investigated. The increasing magnitude of short-circuit currents and the increasing voltage variations in the network are seen as a major challenge for the network planners. Conventional measures for reducing voltage problems may introduce problems with the short-circuit current level and vice versa. In networks which contain a large amount of both load and distributed generation, adverse voltage problems may occur, especially when the generation is located in the LV network. In order to reduce this, specific control strategies need to be developed.

The last part of the thesis is related to these control strategies as a solution for operating future distribution networks. By introducing storage and power electronics, networks can be transformed into autonomously controlled networks. These networks remain an inseparable part of the electricity network but may behave in a fairly autonomous manner, both internally and externally, with respect to the rest of the network. The focus in this thesis is on maintaining an optimal voltage for all customers during all combinations of load and generation. Because of the autonomous behaviour of the control systems, their operation must be based on local measurements. A suggested approach is to replace the normal open point between MV feeders by a so called “intelligent node”. This node is able to control the power flow in several feeders by means of power electronics and, if provided, by electricity storage. The voltage profile can be improved further, by introducing an intelligent voltage control on the HV/MV transformer feeding the distribution network.

The simulation studies in this research have been performed on a realistic model of a typical Dutch MV/LV distribution system. Based on the results the following conclusions are drawn:

- The HV/MV transformer control must be based on line drop compensation. This compensation must use the load situation instead of the measured exchange signal. The compensation factor must differ between cases of high load and of high generation.
- The optimal control of the intelligent node is a voltage control, based on a linear dependence of the voltage at the node and the power flow towards that node. This method can be improved when the voltage of the MV bus bar in the substation is taken into account.
- Methods to obtain a perfect voltage profile will lead to a storage device that is not available for this voltage level yet.

- A voltage control based on a fixed value at both terminals of the intelligent node and at the MV bus bar of the HV/MV substation does not result in the optimal voltage profile, although guarantees a good voltage quality and might therefore be a good alternative.

Intelligent Distribution Network Design

Samenvatting

Elektriciteitsdistributienetten voor middenspanning (MS) en laagspanning (LS) hebben in toenemende mate te maken met randvoorwaarden gesteld door regulering en economie, eisen ten aanzien van milieu, gevoelige apparatuur en power quality, alsmede met de groei van decentrale opwekking. Dit laatste wordt gezien als een van de grootste uitdagingen voor hedendaags en toekomstig ontwerp en bedrijfsvoering. In dit proefschrift is onderzocht op welke manier bovenstaande ontwikkelingen leiden tot een intelligent ontwerp van distributie netwerken en tot nieuwe engineering tools. Verder wordt onderzocht hoe een nieuw ontwerp en regel strategie kan bijdragen aan het voldoen aan eisen ten aanzien van bedrijfsvoering en performance in distributienetten van de toekomst.

Het proefschrift richt zich met name op netwerk infrastructuren die typerend zijn voor Nederland en bestaan uit ondergrondse kabelverbindingen.

Het beheersen van spanning en stroom in deze netwerken zowel tijdens normaal als gestoord bedrijf vraagt om een goed netontwerp en een goed aardingsconcept. De relatief korte afstanden in Nederlandse distributienetten hebben een positief effect op power quality aspecten en betrouwbaarheid. Een impedantie geaard MS net verkleint het risico op meerfase fouten en de daarbij horende diepe spanningsdips. Een TN aardingssysteem in het LS net vermindert het risico op beschadiging van gevoelige apparatuur terwijl de het de veiligheid van mensen niet in gevaar brengt. Er moet echter wel aandacht besteed worden aan de aarding van apparatuur die tevens aangesloten is op netwerken van andere providers. Een coöperatieve oplossing hiervoor is noodzakelijk.

De snelle ontwikkelingen in rekenprogrammatuur en IT apparatuur hebben het mogelijk gemaakt om veel berekeningen in korte tijd uit te voeren, gebaseerd op actuele en historische gegevens. Voorbeelden zijn on-line distributie loadflow en kortsluitberekeningen ten behoeve van coördinatie van beveiliging en intelligente foutplaatslocalisatie. Het grootste aandachtsgebied voor berekeningen in LS en MS netten is de nauwkeurigheid van de modellen en de beschikbaarheid van betrouwbare gegevens. Vanwege het asymmetrische gedrag van belasting en opwekking in LS netten is een meergeleider model noodzakelijk. Voor berekeningen aan veiligheid moeten ook de impedanties van de aarde, de nulgeleider en de aardgeleider met hun mutuele interacties meegenomen worden.

De beveiligingsfilosofie moet rekening gaan houden met eisen ten aanzien van veiligheid en power quality. Een algemene beveiligingsfilosofie met betrekking tot het distributienet en de daarop aangesloten decentrale opwekeenheden is noodzakelijk.

Nieuwe ontwikkelingen in stationsautomatisering hebben een positief effect op toekomstige uitbreiding, vervanging en modernisering van besturing en beveiliging. Hierdoor is ook een betaalbare, nauwkeurige en snelle foutplaatslokalisatie mogelijk geworden, waardoor het aantal storingsminuten kan verminderen.

De grootste uitdaging voor netwerkplanners is het beheersen van de groeiende kortsluitstromen en de groter wordende spanningsvariaties ten gevolge van toenemende hoeveelheid decentrale opwekking. Conventionele oplossingen voor het verminderen van de spanningsproblematiek kunnen de problematiek met kortsluitstromen vergroten en vice versa. In netwerken met zowel grote hoeveelheden belasting als grote hoeveelheden opwekking kunnen spanningsproblemen ontstaan, met name als de opwekking zich op LS niveau bevindt. Om die problemen te voorkomen of te verminderen moeten specifieke regelstrategieën ontwikkeld worden.

Een in dit proefschrift voorgestelde regelstrategie maakt gebruik van elektriciteitsopslag en vermogenselektronica, waarmee distributienetwerken getransformeerd worden tot zogenaamde autonoom regelende netten. Deze netwerken blijven aangesloten op de rest van het elektriciteitsnetwerk, maar vertonen een autonoom gedrag, zowel intern als extern naar de rest van het netwerk. De focus bij deze regeling richt zich op het handhaven van een optimale spanning bij de gebruikers onder alle denkbare regimes van opwekking en belasting. Vanwege het autonome gedrag moet de werking van de regelmechanismes gebaseerd zijn op lokale metingen. In de voorgestelde oplossing wordt de netopening vervangen door een zogenaamd intelligent knooppunt. Dit knooppunt regelt de vermogensstromen in de verschillende aangesloten richtingen door middel van vermogenselektronica en opslag. Het spanningsprofiel kan verder verbeterd worden door de introductie van een intelligente spanningsregeling op de voedende HS/MS transformator.

De netwerksimulaties in dit onderzoek zijn gebaseerd op een realistisch model van een typisch Nederlands MS/LS netwerk. Gebaseerd op deze studie kunnen de volgende conclusies getrokken worden:

- De spanningsregeling van de transformator is gebaseerd op stroomcompensatie (compoundering). Deze compoundering moet gebruik maken van de belastingen in het netwerk in plaats van de stroom door de transformator. De compensatie factor is anders voor situaties met veel belasting en situaties met veel opwekking.

- De optimale regeling van het intelligente knooppunt is een spanningsregeling die gebaseerd is op een lineaire afhankelijkheid tussen de spanning op dat knooppunt en de vermogensstroom naar dat knooppunt. Deze methode kan worden verbeterd als de spanning op het MS railsysteem in het onderstation wordt meegenomen in de regeling.
- De methodes om een optimaal spanningsprofiel te verkrijgen, maken gebruik van een opslag system dat nog niet beschikbaar is voor dit spanningsniveau.
- Een spanningsregeling die gebaseerd is op een vaste spanning bij het intelligente knooppunt en de MS rail van het voedende onderstation zal niet leiden tot een optimale spanning in het netwerk, maar garandeert wel een voldoende spanningskwaliteit en kan gezien worden als een goed alternatief.

Contents

1 Introduction

The main objective of an electric power system is to transfer the electrical energy from the generators to the consumers. A power transmission network connects large-scale power plants to multiple substations near a populated area. A power distribution network connects the customers to the substations. Electric power transmission allows distant power plants to be connected to consumers in population centres.

Since the electric power cannot be stored in large amounts, the electricity generation must always be balanced with the momentary consumption and losses. Multiple sources and loads can be connected to the transmission system and they must be controlled to provide orderly transfer of power. In the long term this process is dominated by the electricity market, that affects the purchase and sale of electricity, using supply and demand to set the price.

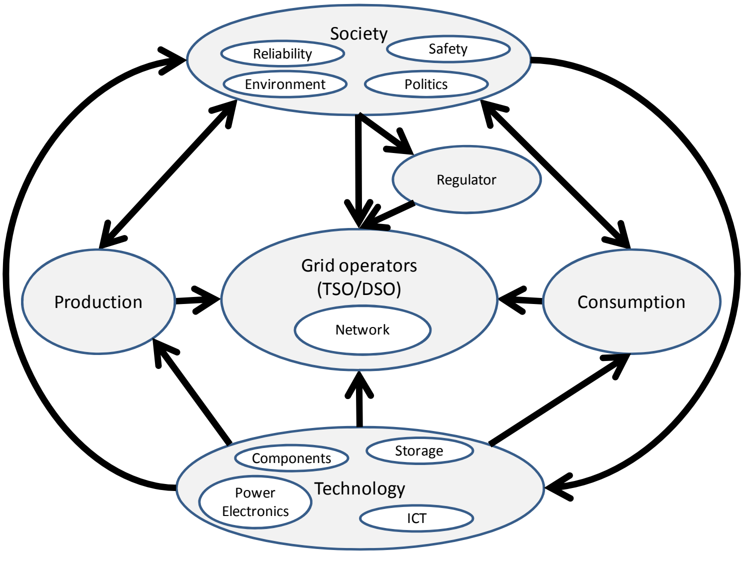


Figure 1.1 Players in the field of electricity supply

Operating an electric power system is a complex business with a large number of players involved, as shown in Figure 1.1. A central position is played by the grid operator, owning and operating the network.

All players have wishes and set requirements affecting the behaviour of the electric power system:

- Generators need to be connected to the network at all times in order to be able to generate the electric power. They need the network to be operated within technical limits to ensure the proper working of their generating units. Their relation to the society is often on the field of politics, where it concerns the environment and economy. This also affects the policy for constructing new generating units.
- The consumers also need to be connected to the network at all times for their processes. These processes include conversion of electric energy into labour, heat and light, as well as electricity generation. The consumers are related to society because society determines safety and reliability requirements.
- The society sets requirements to generation, grid operator and consumption players. The requirements for the generation players are mainly in the environmental field. The requirements towards the grid operator are in the field of reliability, environment, politics (economical) and safety. The requirements towards the consumption players are mostly in the field of the environment and safety. Very often the regulator is used to set the requirements.
- The grid operators must enable the transmission and distribution of electrical energy. This must be done in a reliable, safe and economical way, while at the same time the environment must be saved. They will adopt new technological features to be able to cope with new requirements.
- Technology players develop new components, processes and ICT-solutions for generation, grid operator and consumers. Driven by economical, environmental and sociological signals, they carry out research and development. Players are, amongst others, universities, technological institutes, manufacturers and engineering consultants.

1.1 Changes influencing the electricity system

In early days electricity systems started as local isolated networks, with small-scale load and generation. Later these networks were linked in order to benefit from economy of scale and to ensure a better reliability by making use of each other's reserves. In this way there was no longer a need for generation and load to be in the same area. Generation moved to locations where it was more economical and efficient to generate. This resulted in an increase of the size of the generation plants and of the distances between generation and load. The increase of power and distance led to higher voltage levels and separated networks for transmission and distribution. In this way a one-directional power supply chain was formed. The generation and transmission system is on top of this chain and the distribution system and consumption on the bottom. Energy traditionally was transported top-down. But as the world changes, also the wishes and products of the players involved in the field of electricity supply change, leading to new requirements and changing the traditional schemes. These changes have an impact on the various players shown in Figure 1.1.

Society

Society increasingly depends on a reliable electricity supply while the demand keeps growing. As a result black-outs bring about enormous economical disasters. On the other hand political, social, economical and environmental matters have great consequences for the whole system from power supply to consumption. The following consequences can be noted:

- The liberalisation of the electricity market resulted in a diversity of different generators, traders, brokers and sellers.
- The Kyoto protocol and other environmental concerns were driving forces for sustainable energy sources. Efficient use of primary sources resulted in the development of combined heat and power plants (CHP) for customers desiring both heat and electricity.
- Regulators set rules for network operators like economical efficiency, reliability and quality.

Generators

The introduction of co-generation and sustainable energy resulted in a change in the way the electricity is generated. The scenery of electricity generation with centralised large-scale generating units got mixed up with smaller-scale units spread over the area, the so called dispersed or distributed generation (DG).

Distributed generation units can be distinguished by their size. In this thesis the following definition is used:

- Micro-scale generation. These are stand-alone units with a power less than 100 kW. Examples are micro combined heat and power (μCHP) and PV systems.
- Small or mini-scale generation. These are stand-alone units or clusters with a power between 100 kW and 10 MW. Examples are CHP units at greenhouses, and wind generators.
- Medium-scale generation. These are stand-alone units or clusters with a power above 10 MW. Examples are CHP units used for district heating and wind farms.

The electricity generation with distributed generation depends on external matters. Wind and solar power generators depend on the availability of natural resources. CHP power generators depend on the demand for heat generation. So the amount of generated power is variable and difficult to predict.

Liberalisation of the electricity market results in generators acting on market opportunities. This not only happens with large-scale generation units but also with smaller units, if they are capable enough to operate on the market. Sometimes these units are combined in "virtual power plants" (VPP) that for example consist of small CHP units at greenhouses. All these aspects cause extra variations in the power flows.

Consumers

The processes of the consumers more and more rely on sophisticated electronic equipment. Some examples are:

- Electronic equipment used to control industrial processes.
- Electronically controlled lighting.
- Energy saving processes using (power) electronics.
- Electronics in new domestic appliances like computers and TV-sets.
- Electronic equipment used to minimise the effects of inrush currents caused by large equipment like motors and generators.

Electronic equipment, however, is sensitive for fast and slow voltage variations, especially voltage dips. Furthermore, the harmonic current injections of this equipment result in higher harmonic voltage levels, which may disturb other electrical apparatus. As a consequence, new power quality (PQ) requirements may be defined or sharpened.

Due to the introduction of distributed generation, consumers can also act as generators.

Technology

Technology has a large influence on the electricity system. Industrial innovations result in other or better equipment and components. Also, technological solutions that were too expensive in the past may become feasible in the future.

The development of power electronics introduced power converters, resulting in many new customer appliances. Many of the distributed generation units generate power on a different frequency than the grid and must be coupled by means of a converter system. Many electrical devices are not only connected to the electricity network but also to networks of other services providers like telephone, television and internet companies, which causes possible problems with electromagnetic compatibility (EMC).

Technology influences power system components like oil and paper insulated cables that were replaced by PVC and XLPE insulated cables. Components are equipped with extra tools for diagnostics like optical fibre in power cables. Equipment for storing electrical energy in batteries or flywheels is introduced in the power system, enabling the development of new ways to control power flows and network voltage.

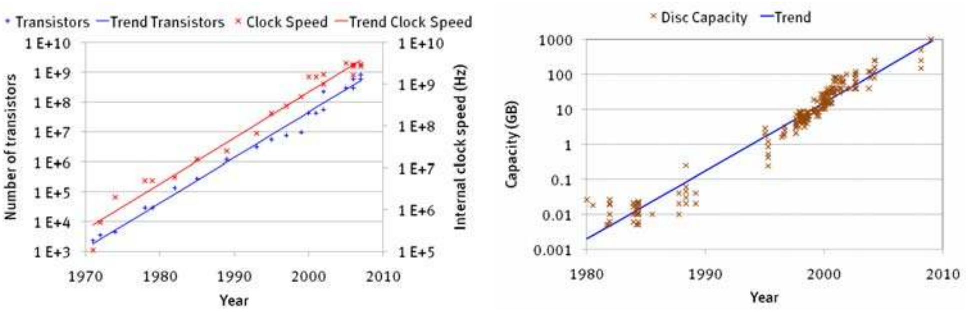


Figure 1.2 Development of personal computer systems
(data based on information from [INTE 001] and [HIST 001])

Also computers get more and more powerful. In 1965 the director R&D of Fairchild Semiconductors stated that the amount of transistors on integrated circuits would double every 1.5 year [MOOR 001]. This effect is known as "Moore's Law" and is still valid. This exponential growth is not only noticed for the number of transistors but (Figure 1.2) also for clock frequency and hard disk capacity. The latter is known as "Kryder's Law" [KRYD 001].

This achievement has resulted in the development of new analysing tools. In the past network analysing tools (load-flow, short-circuit and transients) were only developed for meshed HV networks, comprising relatively few nodes and having a high degree of simultaneity. At this moment also analysing tools for MV and LV networks are available. These networks are often radially operated networks with many nodes and a large diversity of loads. The algorithms developed for HV networks cannot be directly translated towards MV and LV networks, so new algorithms had to be developed. Also new items for network analysis like asymmetry, safety, harmonics and dips have to be treated. When analysing asymmetry and safety aspects multi-conductor models are necessary. The extending computer capacities made it possible to automatically perform lots of calculations, resulting in tools to facilitate the work of the network operators [PROV 001]. Examples are "safe coupling of MV networks" [NUIJ 001] [GROO 001] and "intelligent fault location" [OIRS 001] [PROV 002].

The rapid growth of possibilities of ICT equipment not only enabled fast complex calculations on large network models. It also enables the storing and processing of large amounts of measurement and control data from the networks and connected apparatus. These data grow thanks to developments in electronics and remote metering. At this moment many substations have 5-minutes average values of voltage and current of every feeder and grid operators have information of large-scale customers and DG. The introduction of "smart" meters for the domestic customers will also result in an increase of data. All of these data has to be transmitted from the customer or substation to the computers at the grid operators where they will be stored. This not only sets requirements to the communication but also to the philosophy for data storage. How much has to be stored, for how long and for what purposes.

The possibility of processing lots of data in a short time has resulted in a change of network operation. Substation functionality is automated and remotely controlled. Mechanical relays are replaced by electronic ones with a larger functionality and more features. In literature also the concept of agents is described as a future possibility for network operation and protection [SAMI 001] [MIN 001].

The developments in components and automation generate possibilities to operate the power system closer to its limits.

1.2 Challenges for the network

The grid operator has to operate the network in an economical, safe (regarding people and apparatus) and reliable way without violating technical limits for voltage and current. Additional loads and generators for new or existing customers must be connected bearing this in mind. The changes described in the preceding paragraph cause challenges for the grid operator like:

- Dealing with distributed generation.
- Balancing load with the generation that becomes less predictable.
- Dealing with new components and equipment.
- Keeping the reliability of the supply within the requirements.
- Guaranteeing the power quality level.
- Assuring safety for people and apparatus.
- Designing and operating the network in a technical and economical way.

In this paragraph these challenges will be described. The severity of a problem depends on the network structure, applied voltage levels, earthing philosophy and standards. Solutions may be found in an alternative network configuration and operation, network components and controls. It must be observed, that a good solution for one aspect may have a negative impact on one or more of the other aspects. Complex studies may be necessary. Here the increase of the computer capacities (processor, speed, data storage) is of great help.

Distributed generation

Distributed generation has several challenges for the network operator as described by amongst others [HAIG 001] [HATZ 001] [LAKE 001] [LEES 001] [PEPE 001] [SAKI 001] [TRAN001]. Some are mentioned here:

- Variations in power flow. Distributed generation often uses energy from sustainable sources like wind and sun. These sources have fluctuations that are not easy to predict and control. Also other distributed energy sources have a behaviour that is not easy to predict and control. The electric power generated by μCHP is primary based on heat demand from consumers. Greenhouses with CHP units normally generate electricity based on the heat demand of the crops, but nowadays in the Netherlands they also generate electricity based on the short time electricity market. The fluctuating generation results in varying power flows. In medium and low voltage networks these varying power flows result in varying voltages. This may result in extra control actions of the on-load tap changers of the transformers, having effect on the ageing of this component. The variation of power flow can also result in extra ageing of other equipment like cables and cable joints. The influence of variations in power flow is greater in radially operated than in meshed operated networks.

- Prediction and planning. As the amount of power delivered by the DG varies partly randomly in time, it becomes harder to predict the net load of a network. This influences day ahead planning. Distributed generation also influences the measurement of the peak load in a substation, since the actual maximum load might not be “visible” during periods of high generation. This influences the planning of network extensions [PROV 003].
- Short-circuit current and protection. The increase of DG results in changes of the short-circuit behaviour and the protection philosophy of the network. Both an increase and a decrease of short-circuit currents is possible. Rotating generators will contribute to the local short-circuit currents that will become larger. These generators will also contribute to faults further away in the network. This may result in unnecessary tripping of protection devices, influencing the reliability of supply. When a fault occurs between the substation and the generators, the short-circuit current of these generators may activate the short-circuit indicators in the network, resulting in a false indication of the fault. The increase of local distributed generation may on the other hand result in a decrease of large-scale generation and thus limit the amount of short-circuit current from the HV network. Especially when the local DG is equipped with power electronics this may result in fault currents being too small to trip the protection.
- Behaviour of DG in case of islanding. If islanding occurs due to a fault in that network, safety reasons require that it must be prevented that the generators supply energy to the fault location. When the network is intentionally islanded, care must be taken of keeping the frequency within limits and of (asynchronous) reconnection to the main network.

Balancing load and generation

The traditional way of balancing load and generation is basically through controlling large-scale generation units. They act on changes in set points and adapt their generated power automatically to changes in frequency. Another traditional way to balance load and generation is to control typical loads like electrical heaters and boilers.

Nowadays unbalance can be traded on power markets. Virtual power plants (like co-operations of greenhouse owners with CHP) act on market prices. On smaller scale domestic µCHP units may both be driven by heat demand and price structures. Also the amount of controllable domestic loads, like electric cars, controlled washing machines and refrigerators increases, strongly influences the power flows in the network.

The combination of these controlled and autonomously behaving devices that generate and consume electricity on scheduled or apparently random basis, will lead to alternative power flows in the distribution network. As a result, the power quality in general and the voltage level in particular will change, while they must be kept within specified limits.

Components and equipment

New or other types of components in the network bring along new challenges for operating the network. For example, cables with oil and paper insulation are vulnerable to high and varying currents whereas cables with XLPE insulation are vulnerable to steep voltage transients and over-voltages.

Many industrial processes as well as electronic domestic equipment are vulnerable to voltage dips and harmonic voltages. Voltage dips are often the result of short-circuits elsewhere in the network. Harmonic voltages are a result of harmonic current injections of all equipment.

Many communication devices and IT equipment use signals from more than one provider. This means that in or close to the equipment the earthing of the different supplier systems come together. This can cause malfunctioning due to a disturbance in one of the networks. A good EMC and earthing concept is necessary to prevent dangerous situations [WAES 001].

Power electronics and electricity storage can be used to improve the performance of the network. In high voltage networks there are many examples of improving power quality with the help of power electronics. Stand alone solutions on lower voltage levels are often too expensive (regarding both investments and additional losses) compared to standard network extensions. One of the possible approaches is to combine the solution for several problems in one piece of equipment. Storage of electrical energy can be useful in many occasions [CHOI 001] [DAES 001] [TSIK 001] for instance for:

- Balancing load and generation.
- Mitigating the variation in electric power of fluctuating loads and distributed generation.
- Mitigating dips and improving power quality.
- Marketing purposes: store when prices are low, generate when prices are high.
- Supply a part of a network in case of a black-out.

Reliability

The reliability of the electricity supply depends on the number of disturbances in the network and the time it takes to re-energise the customers. Challenges regarding reliability concern the reduction of the number of outages, the minimisation of the number of affected customers and the reduction of the outage time. Outages can have a natural cause (lightning, ageing) and a human cause (digging). The number of affected customers depends on the part of the network being switched off. Outage time depends on redundancy, time for locating the fault and time for restoration of the energy supply. The number of outages can be reduced by reducing the risk for their causes. These risks might be increased due to more stress on the network. The number of affected customers can be reduced by selective switching and by redundancy.

Selective switching however can increase the duration of the deep dips caused by faults close to the substation. The outage time can be reduced by improving the redundancy, decreasing the time for fault finding and fast network restoration. Distributed generation can influence the time to find the fault location in a negative way when changed short-circuit currents falsely activate the short-circuit indicators.

Power quality

Regulations set requirements to the power quality in the network, whose indices have to be within specified limits. Some of the problems are:

- Distributed generation can increase the slow voltage variations in the network.
- Electronic equipment increases the harmonic current injections in the network, resulting in higher harmonic voltages.
- Dips are influenced by the protection philosophy.
- Selective switching can have a negative impact on dips.
- Switching large loads, motors and generators can cause flicker problems, especially in long networks with small conductor diameters.
- Flicker can also be caused by DG due to the effect of moving clouds on the production of PV systems and due to the tower shadow effect influencing the power production of small wind turbines [VU T 001].

Earthing and safety

The earthing of the network and the customer appliances influence fault voltages and fault currents. Fault voltages can cause safety problems to human beings and apparatus. Steep voltage transients have impact on ageing of several insulation materials. Fault currents can damage apparatus. Faults occurring on one voltage level can have an impact on other voltage levels. When electrical equipment is also connected to networks of other service providers, like cable television, a fault in one network can cause damage in that equipment and even in the network of the other supplier. The introduction of distributed generation can cause new safety problems in islanding situations.

Network configuration and operation

Increasing the amount of decentralised generation causes alternative power flows. As a result of this new situation the network voltage may violate specified requirements. It should be investigated if it is possible to cope with this situation by changing the network configuration and operation.

One of the possible solutions is to operate the distribution networks in a meshed way. The influence of strongly fluctuating power flow is less in meshed networks than in radially operated networks. It might therefore be considered to operate networks with large amounts of distributed generation in a meshed way.

Changing the network configuration from radial to meshed operation has consequences for the protection of the network [CELL 001]. These consequences should be part of the investigation.

Changing the protection schemes influences power quality aspects, since changes in selectivity influences the duration and depth of the dips. The protection system should therefore not be seen as an independent process. Automation of substations and other strategic points in the network can help in more selective switching and faster fault location, both reducing outage times.

Economical constraints

In solving all challenges stated above, the network operator is limited in the amount of money to spend. Society and regulation require efficient operation against reasonable costs. This limits the investments and forces the operator to exploit its assets to their technical and economical limits.

1.3 Research questions and objectives

1.3.1 State of the art

It is a general consensus that the current design and operation of distribution networks is not sufficient for solving the challenges stated above. Solutions can be found in reinforcement of the network, changing from radial to meshed operation [CELL 001], additional voltage control [BONH 001] [CHOI 001] [HIRD 001] [WALA 001], more automation and supervisory [RIET 001] and in applying new equipment like power electronics and storage [DAES 001] [OHTA 001] [OKAD 001] [TSIK 001] [UEMU 001].

It must be noted however that the problems and their solutions depend on the type of network, the kind of load and the penetration level of distributed generation. Problems and solutions for distribution networks with long overhead lines cannot simply be translated towards relatively short networks that consist of underground cables. Distribution networks without active elements like controllable loads, generators and storage systems, cannot be operated autonomously.

1.3.2 Research question

It is inevitable that power systems undergo changes as a result of social and technical innovations in the field of electric power generation and consumption. Generation moves to a certain extent from centralised locations on the transmission level towards the dispersed locations on the distribution level. Furthermore large-scale generation connected to the transmission network will be more and more based on fluctuating resources like off-shore wind farms is. As a result the electricity generation appears to behave increasingly randomly, both at the central level and for sure at the distribution level, bringing new challenges for the balance with the load. Furthermore, any alternative power flow will result in changes of the loading of the network and the associated voltage profiles.

It should be investigated in what way these developments enforce intelligent distribution network design and new engineering tools. It should also be investigated how a new design and control strategy can contribute to meet the power quality and other performance requirements in distribution networks of the future.

1.3.3 Goal of the research

The goal of the research is to develop design criteria for future networks containing a large amount of distributed generation in order to have a performance as good as nowadays networks without DG or even better. It should be investigated which problems can be solved with state of the art solutions and which solutions are available in the near future.

Examples of future developments are: power electronics, storage and control functions. When controls are used, it must be investigated whether they can work autonomously based on local measurements of the behaviour of the network and the equipment connected to it. Such a network can be seen as an autonomously controlled network.

When power electronics and storage are considered, investigation will be done on the technical requirements to enable these new developments. The economical and technical properties of nowadays storage facilities and power electronic equipment like size and price will not be a part of this research.

1.3.4 Research approach

This research focuses on MV and LV distribution networks. These networks will be described in detail and an investigation will be made on the operation during normal operation and during disturbances. The network parameters to be considered are voltage, current, safety and reliability.

Simulations must be performed in order to understand and investigate the behaviour of a network during various operating conditions. From this also the possibilities and shortcomings of nowadays network evaluating tools and the network simulation models become clear. Solutions to overcome these shortcomings must be developed.

The future design strategy will be driven by innovations in the field of network automation. For that reason a short investigation of the state of the art will be made. This investigation includes the influence of automation on protection and fault location.

Distributed generation influences network performance. This influence must be investigated and solutions for possible problems must be found.

Finally, the possibilities for autonomous controls to improve the performance of networks containing large amounts of DG, electrical storage and power electronics will be evaluated.

The research uses network simulations and results of measurements, both from experiments and from daily operation. The network simulations will be performed with standard calculating tools and will be based on realistic models of typical Dutch distribution networks.

1.4 Relations to other work

In order to cope with the challenges concerning distributed generation several research programs started worldwide. Some of them are described in this paragraph.

1.4.1 National programs

IOP-EMVT

In the Netherlands a research program called IOP-EMVT (Innovation Oriented research Program – Electro-Magnetic Power Technology) was started in 2002 and the last tender for projects was in 2008. As this thesis research has been performed within the framework of this research program, it will be discussed in the next paragraph.

EOS

The goal of the research program EOS (energy research subsidy) is to improve the quality of research and knowledge in the Netherlands by stimulating new technologies in order to realise a sustainable energy supply [EOS 001]. This knowledge must be the basis for an affordable, reliable and clean energy supply in the future.

Ongoing research projects are:

- Stability and controllability of the future national power grid.
- System architecture of a smart power grid at district level.
- Voltage quality in future infrastructures.
- Electrical infrastructure of the future.
- Intelligent electricity-transport management.
- Dynamic state-estimation and voltage stability of distribution grids with a large share of distributed generation capacity.
- Control and reserve power: pivot in a sustainable energy supply.
- Transition roadmap energy infrastructure in the Netherlands.
- New components and smart management systems for the power grid of the future.
- Grid control with the use of a high temperature superconducting fault current limiter.

1.4.2 International programs

DISPOWER

DISPOWER is an abbreviation for “Distributed Generation with High Penetration of Renewable Energy Sources” The project started in 2001 and has been coordinated by ISET e.V., Kassel/Germany. The consortium consisted of 38 different partners from utilities, power industry, service companies, research centres and universities from 11 European countries [DISP 001].

The broad European basis of the consortium facilitated an intensive exchange and dissemination of national knowhow and experience.

The project DISPOWER has significantly contributed to the further development of knowledge as well as to the European exchange of experience in the field of integrating small and distributed generators into the electricity distribution grid. The central question was as follows: “what technology has to be developed so that the growing number of decentralised energy resources can be further integrated into the European electricity grids in the future, without losing reliability, safety and quality?”

CERTS

The Consortium for Electric Reliability Technology Solutions (CERTS) was formed in 1999 to research, develop, and disseminate new methods, tools, and technologies to protect and enhance the reliability of the U.S. electric power system and efficiency of competitive electricity markets [CERT 001].

CERTS is developing technology solutions that support competitive markets while protecting the public interest in reliable electricity service. CERTS' electricity reliability research covers five areas:

- Real-time grid reliability management. Developing and prototyping software tools that will ultimately enable the electricity grid to function as a smart, automatic, switchable network.
- Reliability and markets. Performing science-based analysis and demonstrations of options for increasing the effectiveness of market-based approaches for managing reliability.
- Distributed energy resources (DER) integration. Developing tools and techniques to maintain and enhance the reliability of electricity service through a cost-effective, decentralised electricity system based on high penetrations of distributed energy resources.
- Load as a resource. Performing analysis and demonstrations to enable meaningful participation of load in competitive electricity markets, including experimental economics analysis of the effect of price-responsive load in reducing market prices and price volatility.
- Reliability technology issues and needs assessment. Monitoring and identifying technology trends and emerging gaps in electricity system reliability research and development (R&D) to anticipate what R&D efforts are in the public interest to enable the grid of the future.

FUTURED

In Spain, the Spanish Technological Platform of Electrical Grids FUTURED was created for the purpose of integrating all of the agents involved in the electricity sector to define and promote strategies at the national level to allow the consolidation of a much more advanced network, capable of responding to the challenges of the future [FUTU 001].

FUTURED was formed in October 2005 as a meeting point and a common forum for dialogue to allow greater mutual understanding among its member organisations and bodies, identify potential opportunities for collaboration, define a shared vision, and if necessary, defend a common position in relation with their target audiences (society, national and European administrations, etc).

IRED

"Integration of Renewable Energy Sources and Distributed Generation into the European Electricity Grid" is the theme of a large European cluster of RTD projects. IRED is funded by the European Commission and represents over 100 stakeholders in the electricity networks sector [IRED 001]. The cluster is co-ordinated by ISET, Germany.

The activities of the European research cluster started in 2002 under the initiative and guidance of the European Commission – DG Research with the aim of coordinating the European projects in the fields of RES and DG through a high level steering group. Since 2004 the EC has funded the cluster in the framework of the IRED Coordinated Action for four years. During this time the cluster membership has been expanded by including representatives of new European projects in the area.

The vision of IRED is stated as: “A major contribution coming from renewable energy sources and other sources of Distributed Generation (DG) to the European electricity network within the first quarter of this century”.

Their mission is: “To facilitate the integration of renewable energies and distributed generation into the future European electricity network and to create a competitive European industry for a sustainable and reliable future power supply”.

The main objectives are:

- Increase stakeholders’ awareness of the growing importance of RES and DG.
- Contribute to remove technical, economical and regulatory barriers for the grid connection of RES and DG.
- Create a favourable environment for socio-economic acceptance of intermittent RES and DG without risks to quality or safety.
- Create a knowledge infrastructure for design, realisation and operation of the future European smart electricity grid.

MicroGrids

The project more MicroGrids as a follow-up of the FP5 project on MicroGrids, started in 2006 and will investigate, develop and demonstrate the operation, control, protection, safety and telecommunication infrastructure of MicroGrids and will determine and will quantify their economic benefits [MICR 001]. Operation and control concepts in both stand-alone and interconnected mode on laboratory and pilot scale will be demonstrated.

This project aims at the increase of penetration of micro generation in electrical networks through the exploitation and extension of the MicroGrids concept, involving the investigation of alternative micro generator control strategies and alternative network designs, development of new tools for multi-MicroGrids management operation and standardisation of technical and commercial protocols.

Smartgrids

During the first “International Conference on the Integration of Renewable Energy Sources and Distributed Energy Resources” held in December 2004, industrial stakeholders and the research community suggested the creation of a Technology Platform for the Electricity Networks of the Future [SMAR 001].

The European Commission Directorate General for Research developed the initial concept and guiding principles of the platform with the support of an existing FP5+6 research cluster (IRED - see above), which represents over 100 stakeholders in the electricity networks sector.

The SmartGrids European Technology Platform for Electricity Networks of the Future began its work in 2005. Its aim is to formulate and promote a vision for the development of European electricity networks looking towards 2020 and beyond.

1.5 The IOP-EMVT project

The research presented in this work has been performed within the framework of the 'Intelligent Power Systems' project. The project is part of the IOP-EMVT program, financially supported by SenterNovem, an agency of the Dutch Ministry of Economical Affairs. The 'Intelligent Power Systems' project is initiated by the Electrical Power Systems and Electrical Power Electronics Groups of the Delft University of Technology and the Electrical Power Systems and Control Systems Groups of the Eindhoven University of Technology. In total 10 Ph.D. students are involved and work closely together. The research focuses on the effects of the structural changes in generation and demand taking place, like for instance the large-scale introduction of distributed (renewable) generators [REZA 001]. The project consists of four parts, which is illustrated in Figure 1.3.

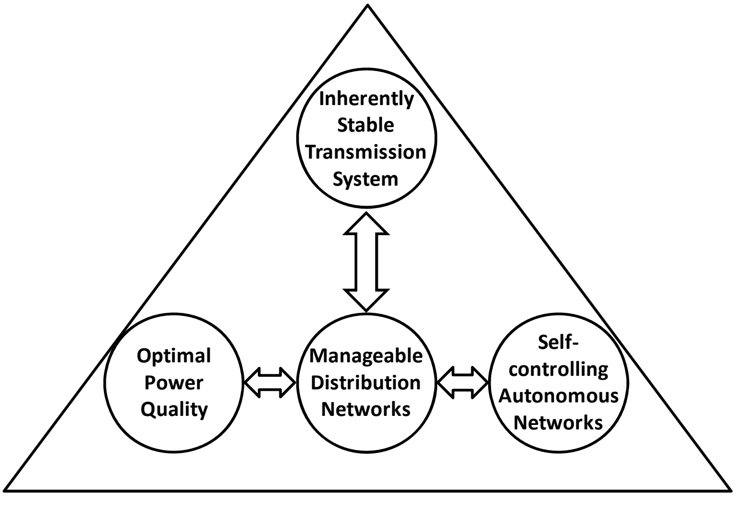


Figure 1.3 Structure of the IOP project

The first part (research part 1), 'inherently stable transmission system', investigates the influence of uncontrolled decentralised generation on stability and dynamic behaviour of the transmission network. As a consequence of the transition in the generation, less centralised plants will be connected to the transmission network as more generation takes place in the distribution networks, whereas the remainder is possibly generated further away in neighbouring systems. The investigated solutions include the control of centralised and decentralised power, the application of power electronic interfaces and monitoring of the system stability.

The second part (research part 2), ‘manageable distribution networks’, focuses on the distribution network, which becomes ’active’. Technologies and strategies have to be developed that can operate the distribution network in different modes and support the operation and robustness of the network. The project investigates how the power electronic interfaces of decentralised generators or between network parts can be used to support the grid. Also the stability of the distribution network and the effect of the stochastic behaviour of decentralised generators on the voltage level are investigated.

In the third part (research part 3), ‘self-controlling autonomous networks’, autonomous networks are considered. When the amount of power generated in a part of the distribution network is sufficient to supply a local demand, the network can be operated autonomously but actually remains connected to the rest of the grid for security reasons. The project investigates the control functions needed to operate the autonomous networks in an optimal and secure way. The research described in this thesis is within this research part.

The interaction between the grid and the connected appliances has a large influence on the power quality. The fourth part (research part 4), optimal power quality, of the project analyses all aspects of power quality. The goal is to provide elements for the discussion between polluter and grid operator who has to take measures to comply with the standards and grid codes. Setting up a power quality test lab is an integral part of the project.

More information and results can be found on the homepage of this project [IOP 001].

1.6 Outline of the thesis

This introductory chapter will be followed by 6 chapters, as illustrated in Figure 1.4.

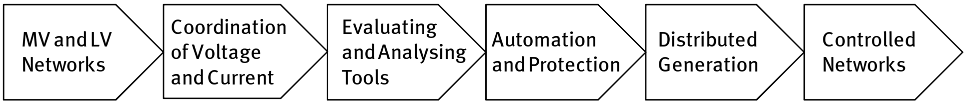


Figure 1.4 Outline of the thesis

Chapter 2 describes the structure of MV and LV networks in the world in general and in the Netherlands in particular. Items to be discussed are design, operation, performance and challenges for future networks.

Chapter 3 describes how to coordinate voltage and current in the network. Both in normal and in disturbed operational situations they must be manageable. The aspects treated are:

- Managing voltage under normal operational conditions.
- Current carrying capacity of components like transformers and cables.
- The consequences of disturbances.

In Chapter 4 the development of tools and methods for evaluating and analysing LV and MV networks is described. The layout of the networks and the diversity of loads set new requirements for the calculating tools. The aspects to be discussed are:

- Applications based on a combination of standard methods.
- Differences for various power system structures and voltage levels.
- New developments like stochastic load-flow.
- The available data and required accuracy.

Chapter 5 deals with protection, automation and fault location. Protection of MV and LV networks has always been based on robustness and selective switching off. The introduction of digital protection gives possibilities to introduce more settings for maximum current relays. Cheap sensor equipment opens the possibility to introduce MV substation automation, intelligent protection and fault location in the network. This is not limited to the substation but can also be introduced at strategic points in the feeders. In this way outage times may be reduced. Aspects to be discussed in this chapter are:

- The different protection philosophies and their developments in the future.
- Requirements, developments and implementation of MV substation automation.
- Development, implementation and practical experience with fault location in MV networks.

In chapter 6 the influence of distributed generation on a number of aspects regarding network performance and planning, and possible solutions to problems are described. Aspects to be discussed are:

- The increase of voltage variations and the consequences for network layout and control mechanisms.
- The influence on short-circuit currents and protection.
- The influence on other planning and operational aspects like load profiles, ageing and reliability.
- Common practice solutions and possible solutions for the future.

Chapter 7 describes the possibilities for an intelligent autonomous voltage control in underground cable distribution networks with large penetration of DG. A constraint is that the number of controls has to be limited. Aspects to be discussed are:

- The operation of the grid (meshed, radial) and the possibility for island operation.
- Necessary points for the controls in the network.
- Various proposals and evaluations for control actions.

The optimal voltage profile is first calculated with knowledge of the voltage in the network. The results of that calculation are used to find the control parameters. Finally, calculations are performed based on these control parameters and the results are compared with the optimal situation.

The thesis ends with a chapter containing the conclusions, the main scientific contributions and some proposals for future work.

2 MV and LV network design and operation

Electricity networks transfer electrical power from generation to load. For a long time the role of the MV and LV networks was to distribute the power from the HV/MV substation top-down to the customers. Distributed generation and the changed behaviour of the various players have their influence on many aspects of the electricity networks. The various consequences for the network structure and design are the main research items in this chapter.

This chapter starts with a description of the development of MV/LV network structures in the world. Next, the focus is set on Dutch MV/LV networks, because Dutch MV and LV networks almost entirely exist of cables, in contrary to many other countries where overhead lines are being used. After this the following paragraphs describe requirements, performance and operation of the networks. The last paragraphs describe the challenges for the network and give some ideas for future networks.

2.1 Network structures throughout the world

Throughout the world different voltage levels and frequencies are used. The reason for this variety is based on tradition more than on optimisation of the system.

Edison started with DC generation and distribution around 1880. Later AC replaced DC for central power generation and power distribution, enormously extending the range and improving the safety and efficiency of power distribution. Edison's low-voltage distribution system using DC ultimately was replaced by AC systems proposed by others, such as Tesla's poly-phase systems.

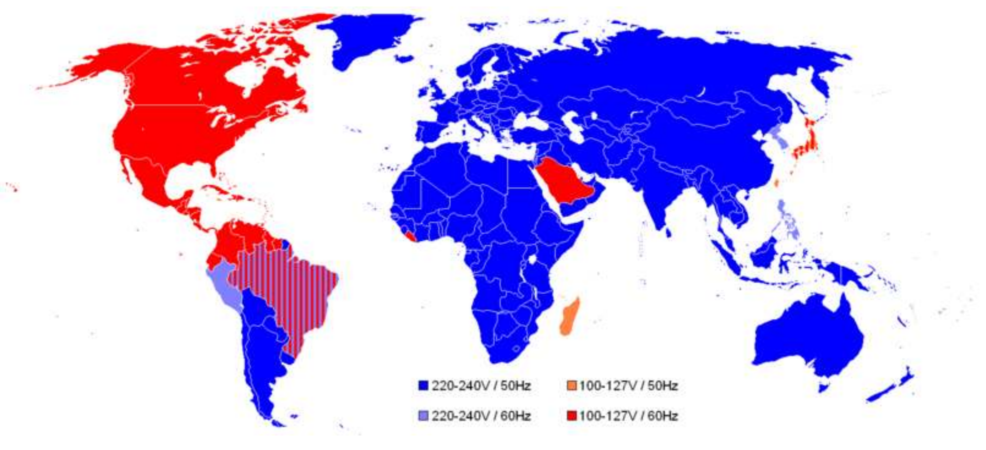


Figure 2.1 Variety of LV levels and frequencies [WIKI 001]

Figure 2.1 shows the world-wide variety of voltages and frequencies. In Europe and most of the Asian and African countries a supply voltage of around 230 V is applied whereas North America, Japan and some countries in South America use a voltage between 100 and 127 V.

The 110 V level was chosen, because in the 1880s carbon filament lamps were designed for a voltage level of around 100 V. Later, metal filament lamps, having a higher voltage capability (220 V), became feasible. In 1899 the Berliner Elektrizitätz-Werk (BEW) was the first utility to switch to 220 V. The replacement costs of the customer's equipment were less than the savings in distribution costs. This became the model for electricity distribution in Germany and the rest of Europe where the 220 V system became common.

The history of power frequencies used is described in [OWEN 001]. Many different frequencies were used in the 19^{th} century. The first units at the Niagara Falls generating station produced 25 Hz power and some early systems used 25 Hz. As the 20^{th} century continued, more power was produced at 60 Hz (North America) or 50 Hz (Europe and most of Asia). Standardisation first allowed international trade in electrical equipment. Later, the use of standard frequencies allowed international connections of power grids. The German company AEG (descended from a company founded by Edison in Germany) has built the first European generating facility to run at 50 Hz, allegedly because 60 was not a "preferred number". At that time, AEG had a virtual monopoly and their standard could be spread out to the rest of the continent.

Electrification started in the large cities. Later came the electrification of rural areas. [OWEN 002] describes the history of electrification of rural areas in the USA.

Networks in Europe and North America have developed themselves in different ways [CARR 001] [GHIJ 001]. It is interesting to see that also the nomenclature in North America and Europe differ for certain distribution system elements. Some of these differences are shown in Table.2.1.

Europe	North America
High Voltage	Subtransmission Voltage
Medium Voltage	Primary Voltage
Low Voltage	Secondary Voltage
Earth, Earthing, Earthed	Ground, Grounding, Grounded

Table.2.1: Differences in nomenclature between Europe and North America

The differences in network structures between Europe and North-America are shown in Figure 2.2. In Europe the MV/LV transformers feed a large amount of LV customers. The three-phase LV networks, which are operated on a voltage level of 230/400 V, are relatively extended; the MV networks have relatively simple structures. In North America the two-phase LV networks are operated on 120/240 V. This lower supply voltage and the relatively higher demand per customer significantly constrain the loadability of North American LV networks. Consequently, when compared to Europe, a much larger amount of transformers is required to feed the same amount of customers. Every MV/LV transformer feeds just a small amount of customers. The LV feeders are rather short and often single-phase. The MV networks are more complex.

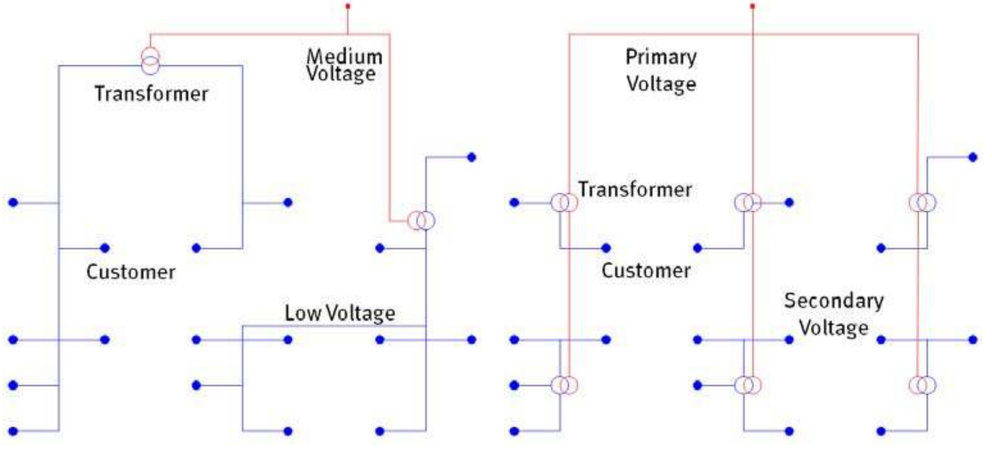


Figure 2.2 Typical structure of MV/LV grids in Europe (left) and North America (right) [CARR 001]

Also, the layout of the MV/LV connections differs (Figure 2.3).

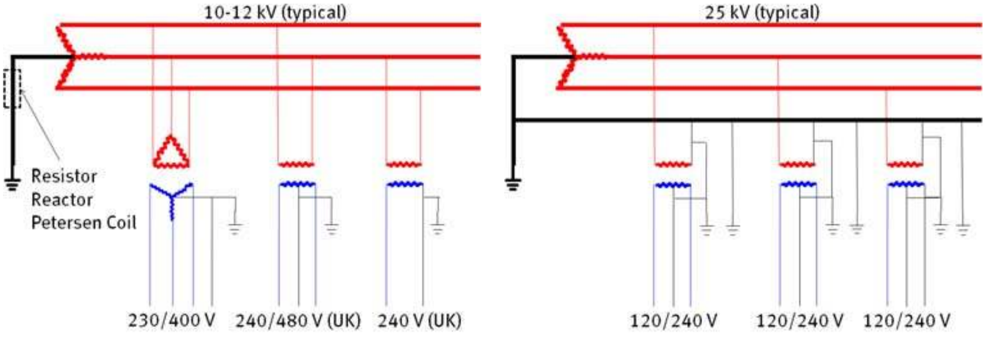


Figure 2.3 Different concepts of overhead distribution systems
North American (left) and European overhead (right) [CARR 001]

In most of Europe the MV/LV transformers are three-phase. The primary Δ winding of the transformer converts the asymmetrical LV currents into symmetrical MV currents, preventing zero-sequence currents to penetrate into the MV network, so that no neutral conductor is needed. Each LV network has its own earthing.

In North America an MV system containing 3 phase conductors and one neutral conductor is used. The primary winding of the single-phase transformer is connected to one phase and the neutral. At each transformer the LV neutral is earthed and connected to the neutral of the MV network. In general one can say that European networks have 3 conductors on MV and 4 on LV whereas North American networks have 4 conductors on MV and 3 on LV.

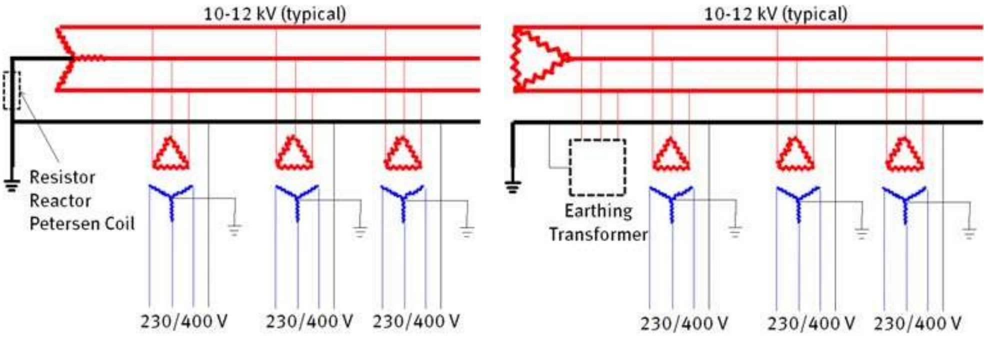


Figure 2.4 European distribution systems with underground cables

There are variations on the European concept. The secondary of the HV/MV transformer can be connected in Δ for instance. In cable systems the cable sheaths of the MV cables are connected to the earthing systems of the HV/MV substation and to the earthing system of the MV/LV transformers (Figure 2.4). In this way a multi-earthed system is created. In the case where the secondary windings of the feeding HV/MV transformer are connected in Δ, an artificial Y-point can be created by means of an earthing transformer.

There are several interesting books regarding nowadays MV and LV distribution networks: [LAKE 002] describes the networks developed throughout the world, whereas [ENER 001] is focussed on Dutch distribution networks. Networks in the rest of the world are based on the concepts of the countries introducing electricity. An example of guidelines for electrification of South African residential areas is given in [ESCO 001].

To prevent undesired situations like electric shocks or malfunctioning of equipment, a proper earthing system is necessary. The earthing concept depends on the type of network and the required performance during earth faults. Therefore various earthing methods are applied throughout the world. Appendix A gives a detailed overview of earthing methods and concepts.

2.2 Distribution network structures in the Netherlands

Dutch MV and LV networks entirely consist of underground cables. Only on a few locations overhead lines are used because of too wet soil conditions. MV networks are mainly operated on 10 kV. But also other voltage levels (6, 12, 20, 25 kV) exist. LV networks are operated on 230/400 V.

2.2.1 MV networks

MV networks may have a transmission function in addition to the distribution function. MV transmission networks mostly consist only of several parallel cables feeding a main MV distribution substation (see Figure 2.5). In these substations a booster transformer may be installed for compensating the voltage drop in the transmission network.

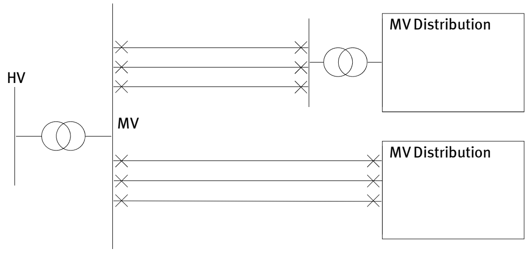


Figure 2.5 MV transmission network between an HV/MV substation and an MV distribution network

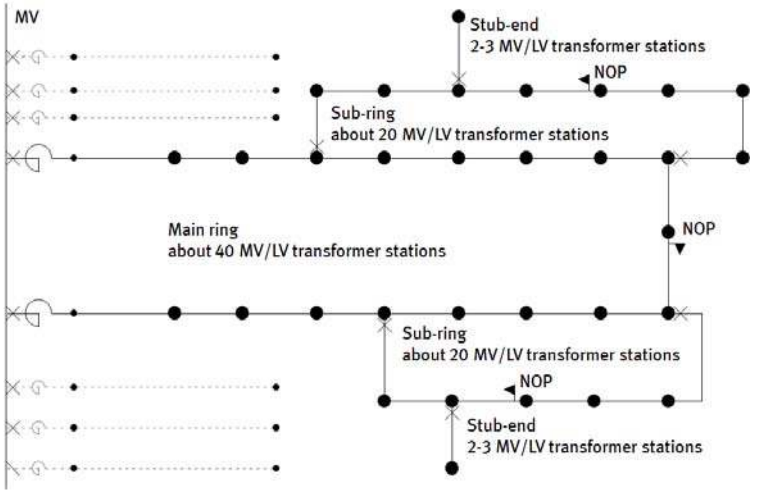


Figure 2.6 Typical structure of a Dutch MV distribution grid

MV distribution networks mostly have ring structures [ENER 001]. To the main ring a sub-ring and some stub-ends may be connected. These networks are fed either directly from an HV/MV substation or by an MV substation, fed by an MV transmission network.

The LV networks are connected to the MV grid by means of MV/LV transformer substations, also known as ring main units (RMU). In practice, the main ring contains about 40 units, the sub-ring about 20. Stub-ends contain only 2 or 3 units. The cable diameter of the sub-ring is smaller than the cable diameter of the main ring. Sometimes the off going feeders in the substation are equipped with reactors which limit the short-circuit currents especially at the ring units close to the substation. Figure 2.6 shows an example of this structure.

When the distribution networks are operated radially, there is a so called normally open point (NOP) somewhere about half way of every ring and sub-ring. In the NOP, the phases are interrupted by means of a circuit breaker or a disconnector. The cable sheaths, however, are not interrupted. In case of maintenance or disturbance on a cable section, the load of the feeder beyond that cable section towards the NOP will be supplied by the other feeder connected to that NOP. In case of maintenance or disturbance in a stub-end the load can only be taken over by a mobile generator.

2.2.2 LV Networks

LV networks can have a radial, a ring or a meshed structure, but are mostly operated radially. In case of disturbances (faulted cable section or maintenance), it is often possible to connect to other feeders, fed by either the same MV/LV transformer or in some cases by another MV/LV transformer. If such a temporary connection is not possible, the loads have to be supplied by a mobile generator.

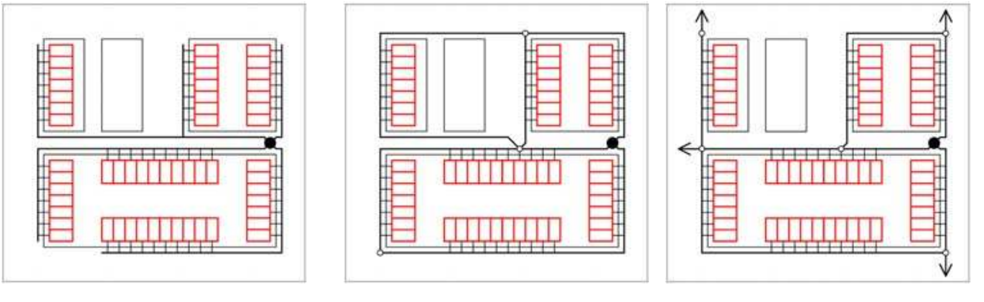


Figure 2.7 Typical structures of Dutch LV grids [ENER 001]

Figure 2.7 shows the various structures of LV networks. Changing the cable connection is possible in the nodes represented by an open circle. The left picture shows a radial configuration. Here it is not possible to connect to other feeders. The middle picture shows a radially operated ring and partially meshed network. Here it is possible to reconnect within the own network. The most right picture shows a radially operated meshed network with connections to other networks. Closing the NOPs in meshed networks will in general result in lower losses. However, it also creates larger short-circuit currents, and a more complex protection scheme will be necessary. Therefore radial operation of the network is preferred. Also, from PLC communication point of view a radial operation is preferred, because in this situation a unique communication path is established. However, the earth wires/conductors (PE) and the neutral wires/conductors will be connected in the NOPs, since this reduces step and touch voltages [VEN 001].

2.3 Operation and performance

In this paragraph network operation and performance will be described in short.

Network structure and its components

Most of the MV distribution networks have a meshed layout but are operated in a radial way. Some networks, especially in cities, are operated in a meshed way, resulting in lower losses and a better voltage profile. With a good and selective protection philosophy, the number of customers affected in case of a fault can be minimized. This way of operation, however, also has several drawbacks like a relatively complex protection structure and an increase of short-circuit currents.

The network consists of various components like cables, transformers and switchgear. Appendix B gives an overview of these components.

Reliability

The reliability of the various European networks is reported on an annual basis [CEER 001] [CEER 002]. These reports show that the reliability of Dutch networks is one of the highest in Europe.

The average number of interruptions per customer is about 0.4 per year. The average outage time per customer is about 25 minutes per year. Reasons for this good reliability are, amongst others, the use of underground cables and the relatively short distances in Dutch MV and LV networks. Since underground cables are not subjected to weather conditions like storms, lightning or growing trees, the reliability of underground cable networks is high [PULT 001]. The replacement of PILC cables by XLPE cables in MV networks increases the reliability even more.

Appendix C deals with the various items regarding reliability in more detail. It also describes the influence of specific network components on reliability.

Voltage, current and power quality aspects

For proper functioning of network components and apparatus connected to the network, voltage and currents must comply with standards. Under normal operating conditions the voltage limits are derived from power quality requirements and current limits are derived from the thermal behaviour of components. Power quality standards and requirements in Europe are based on the IEC 50160. Sometimes regulators set extra requirements, for instance in case of dips. Aspects to be considered in case of faults are: the short-circuit capacity of the network components, transient over-voltages and safety aspects like ground potential rise and step and touch voltages.

Managing voltage and current will be treated in chapter 3.

Protection

The main reason for protection is to prevent damages and safety risks for both equipment and people due to a fault in the network. The radial operation of the MV networks results in a simple protection philosophy. Circuit breakers are located in the off going (ringed) feeders at the substations and at the beginning of the sub-rings. These circuit breakers can be operated by simple maximum current-time relays. The parameters for switching-off current and switching-off time are based on the maximum allowable short-circuit current in the cable and selectivity in switching. Faults and disturbances in the network may not lead to unnecessary switching off network parts or customers as this impacts the reliability of supply.

A fault in a sub-ring is switched off by the circuit breaker in the same sub-ring. A fault in a main ring is switched off by the circuit breaker in the main ring. For the sake of selectivity, the fault currents in the main ring must have a longer duration than fault currents in the sub-ring.

In case of meshed operation the protection becomes more complex. A fault has to be switched off by at least two protection devices. This has to be performed in a selective way, so that a minimum of customers is affected. The selectivity of protection requires distance protection and complex calculations for the determination of set points for impedance, current and dead time.

The protection in the radial LV networks is simple. All off-going feeders at the MV/LV transformer are equipped with a fuse. In TN earthed LV networks the protection has to switch off the fault, not only for protecting the cable, but also to protect the customer against too high touch and step voltages. Meshed operated LV grids are mostly also protected with fuses.

Protection is one of the main items treated in chapter 5. Furthermore Appendix I summarises some specific items regarding protection in distribution networks.

Earthing

The earthing concept of MV and LV networks depends on the network design as described in appendix A. However, the applied earthing concept also depends on the requirements regarding the network performance during earth faults. The desired earthing concept might result in specific settings for protection and in requirements regarding network components like cable length and size.

Network performance during earth faults involves aspects like the possibility of continuation of energy supply, as well as the allowable levels for fault voltages and fault currents. Therefore, this aspect is treated in chapter 3 which deals with managing voltage and current. The consequences for the protection will be treated in chapter 5.

2.4 Challenges and future networks

This section describes the increasing challenges of network management and the consequences for future networks. The solutions will be elaborated in later chapters.

2.4.1 Distributed generation

Distributed generation has its influence on network performance and might result in a changing network topology. As described in chapter 1, more variations in power flows and voltage levels can be expected. This might result in extra ageing of components and an increased number of control actions by the voltage regulating equipment. The planning of network extensions is influenced, because the actual maximum load might not be "visible" due to high local generation. The short circuit contribution of the generators might result in too large mechanical and thermal stresses of components and in false tripping of the protection, influencing reliability. Also, unintentional islanding resulting in dangerous situations, is possible.

In chapter 6 measures to reduce the impact of distributed generation are described. Some related to the network topology are mentioned here:

- Other components. Compared with PILC cables, XLPE cables are less vulnerable for fluctuating load and are allowed to be overloaded during a certain period of time. Dedicated short-circuit current limiters (SCCL) must be used to reduce the impact of short-circuit currents. Power electronic devices and storage can be used to limit the impact on voltage and current.
- Changed network configuration. Meshed operation reduces the fluctuations in power flow and corresponding voltages. This, however, has impact on the short-circuit currents and the protection philosophy.
- Proper planning procedures. The impact of a generator can be limited by connecting it to a voltage level which is feasible both in a technical and in an economic way. In order to further limit voltage fluctuations, it is necessary to reduce the cable impedances, resulting in cables with larger diameters.

2.4.2 Sensitive equipment

Sensitive equipment leads to more stringent requirements for power quality aspects like harmonic levels and dips, and therefore also influences the protection philosophy and the earthing concept. Dips are mainly caused by two- and three-phase faults. The depth of a dip depends on the magnitude of the fault current, which is related to the location of the fault. The duration of a dip depends on the switching-off time of the protection. The protection philosophy is often based on selective switching. As a result faults close to a substation have the longest duration.

These faults, having large short-circuit currents, also cause the deepest dips. Minimizing the effect of dips may therefore result in the use of short-circuit limiting devices and a changed protection philosophy.

Sensitive equipment also requires a good earthing in the customer's installation. This may influence the way of earthing of the LV and MV networks. The introduction of TN earthed LV networks and the transition from isolated towards earthed MV networks result in new safety aspects. A phase to earth fault in both the LV as in the MV network results in step and touch voltages in the LV network. The magnitude and duration of these voltages must be limited to their permissible values.

2.4.3 Features of cables

The introduction of new components influences the design and operation of the network. As stated in appendix B, PILC cables and their joints are vulnerable for high currents and daily changes in current. XLPE cables are less vulnerable for these aspects and may even be overloaded for a long time. This may result in an increase of load in radially operated networks. In case of a disturbance close to the substation the total load of the affected feeder has to be transferred to another feeder. In case of PILC cables the total load in a ring may therefore not exceed the capacity of the cables. Since the repair of a faulted cable is limited to a few days it is allowed to overload the XLPE cables by a certain margin. The use of XLPE cables, however, sets requirements regarding transient over-voltages. Transient over-voltages due to self extinguishing single-phase faults and switching actions must be prevented. This has consequences for the earthing of the network.

2.4.4 Data and communication

The growth of ICT results in more possibilities for measuring in the network. This results in more data coming out of the network. These data are not limited to voltage, current and power, but also to the condition of strategic equipment. From these data it is possible to operate the network closer to the limits. Based on historical and expected data the ampacity of components can be dynamically calculated.

Data from the network can be used in applications supporting the work of the network operator. Examples are: on-line load flow, fast location of faults, improved network restoration and save remote switching.

The growing role of communication makes it possible to introduce more sophisticated protection systems and ways of operation. For example, when protection devices in the network are able to communicate with protection devices in the substation, the selective switching scheme can be adapted to shorter tripping times.

2.4.5 Future networks

Measurement and data handling can help to obtain better knowledge, and to improve design and operation of the network. These data make use of a two-way traffic between the control centre and various monitoring and switching devices, like remote readable energy meters, power quality meters, recorders and automated switchgear. Data transfer is possible over the electricity network and by other modern communication methods. On strategic points the data sent through the network will be concentrated and transferred to separate communication lines with more capacity.

The increase of distributed generation and other new user applications may result in a different design and a more complex operation of MV and LV networks. Local control systems may be implemented to manage their impact on network performance. These controls make use of power electronics and storage devices and may switch non-critical load and generation. The functionality and complexity depend on the type of network. The controls may use a lot of measurement data, requiring fast and effective data handling and communication. The question is whether the controls have to communicate continuously or that they can work as local autonomous controls.

2.5 Autonomously controlled networks

This paragraph describes the general idea behind autonomously controlled networks. Chapter 7 of this thesis describes a detailed proposal for a simple and robust autonomous control system to limit voltage deviations in cable networks.

2.5.1 Structure and behaviour

Autonomously controlled networks (ACN) are parts of the total grid but in principle they are self-controlled [PROV 004] [PROV 005]. Such a network remains an inseparable part of the total electricity network but may exhibit a rather autonomous behaviour as shown in Figure 2.8. These networks are characterised by a large penetration of DG. Therefore, the network is subject to large variations in load and especially in generation. Nevertheless, their performance must be at least as good as nowadays networks.

The autonomous local network in the scope of this thesis is not necessarily an island grid but its behaviour is more or less independent. The aim is to operate autonomously within stated limits during all operational conditions. The grid must function adequately during the normal daily changes in load and generation, but also during disturbances and changes of the network configuration. Important functions of these networks are: operating the network within power quality requirements, maintaining predefined energy exchanges and adequate network restoration after a fault.

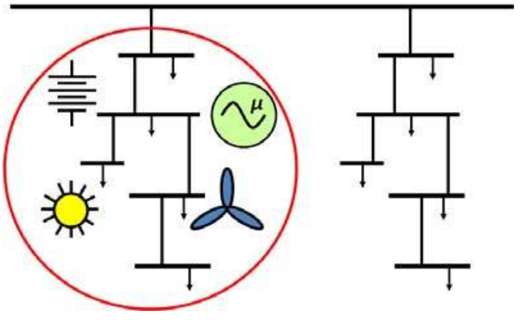


Figure 2.8 Autonomously controlled networks form a part of the total electricity system

At first glance there is some similarity between autonomously controlled networks and micro grids. There are however differences. Micro grids normally are LV networks connected to (weak) MV networks [LASS 001] [SAKI 002] [OVER 001]. Such grids have a rather limited size and complexity. One of their major concerns is to function in island mode when a fault in the MV grid results in loss of connection.

The autonomously controlled network described here will be larger in size and more complex. These networks consist of a combination of LV and MV networks, which are connected to a meshed operated high voltage network. The risk of being isolated due to a fault in the HV network is negligible because these HV networks are always n-1 or n-2 safe. Therefore, the performance of the autonomously controlled networks is not focussed on power balancing and island operation, but on optimized network operation during normal circumstances and maintaining network stability followed by effective network restoration in disturbed situations.

Important conditions for activities in the autonomously controlled networks are the design and operation of the network and aspects such as applied voltage level, types of cables, topology and modes of switching.

The introduction of autonomously controlled local networks is a promising way to manage the expected challenges regarding the operation of future networks. The overall system will then consist of a number of interconnected autonomously and non-autonomously controlled networks.

2.5.2 Controls

The control system will be based on a combination of autonomous local controls (L) and a central control (C) as shown in Figure 2.9.

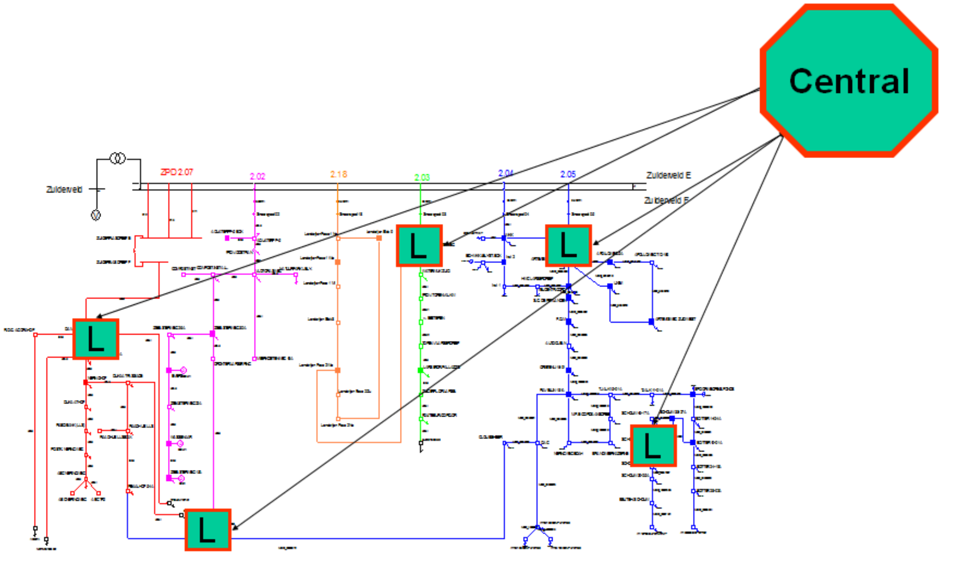


Figure 2.9 Central and local controls in an autonomously controlled network

These local autonomous controls can be seen as so called “intelligent nodes”, located at strategic points in the network. Examples of strategic points are:

- Nodes with controlled load or generation.
- Nodes where switching activities can take place such as normally open points and splitting points in the network.

Control strategies will be based on predictions of loads and generation and on knowledge of the network. If necessary, the settings of the local controls will be calculated and adjusted by the central control.

2.5.3 Intelligent nodes

Intelligent nodes are nodes to which one or more controllable components are connected [PROV 004] [PROV 006] [PROV 007]. The autonomous control of these components uses specific knowledge like network status and prediction of load and generation. The controls are able to communicate with other intelligent nodes and with the central control. Examples of components connected to such a node are controllable loads, controllable generation, storage and dedicated power electronic equipment. The control has a dedicated set of inputs and outputs:

- The input consists on the one hand of local electrical variables like voltage and current, and on the other hand of settings for control parameters that can be received from other control systems.
- The output consists of local controlling activities and of data to be used by other control systems.

The control is not limited to the operation of the component itself, but also to network variables like node voltage and power flows in the connected cables.

Figure 2.10 shows the principle of an intelligent node connecting two feeders. The intelligent node consists of two separated internal nodes (A and B). The internal node A is connected to feeder A and has a specific component C_A connected. The internal node B is connected to feeder B and has a specific component C_B connected. The two nodes A and B are connected by a specific component C_{AB}. Examples for the components C_A and C_B are controllable loads, controllable generation and storage. Examples for the connecting component C_{AB} are circuit breakers and power flow controllers.

The electrical input variables for the control process consist of:

- The voltage of the nodes (U_A, U_B).
- The currents in the connected feeders (I_A, I_B).
- The current towards the components (I_{CA}, I_{CB}, I_{CAB}).

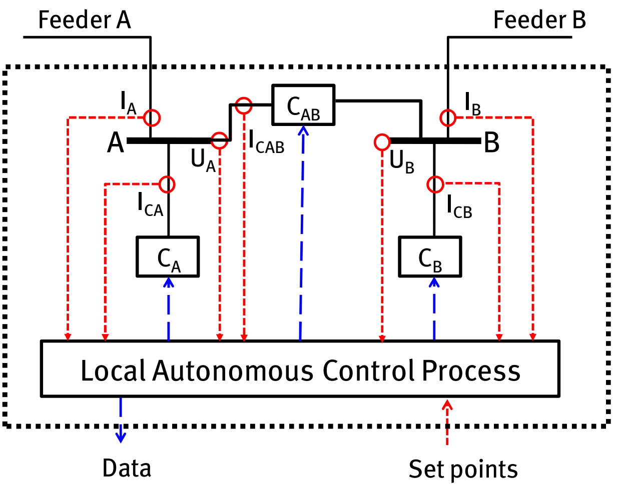


Figure 2.10 The principle of an intelligent node

From these voltages and currents the various momentary active and reactive powers (P_A,Q_A, P_B,Q_B, P_{CA},Q_{CA}, P_{CB},Q_{CB}, P_{CAB},Q_{CAB}) can be calculated. The autonomous control process influences the active and reactive powers in C_A, C_B and C_{AB} in such a way, that the requirements (like specific set points) can be met. Parameter settings may be changed by information from other control systems (like the central control). The control can also communicate specific information towards the central control.

Depending on the requirements of the node, several components can be left out. In case of a controlled generator, only one of the components C_A or C_B is necessary. The component C_{AB} can be replaced by a solid connection between the internal nodes A and B.

This system can be expanded in case more feeders are connected. Every feeder is connected to its own internal node. These nodes are connected by specific components where necessary.

The components needed for creating an intelligent node already exist. However, they are either developed for higher voltage levels (power flow converters) or have a limited size (storage). Further research is necessary in order to adapt these components towards the requirements of the intelligent node.

2.5.4 Operational aspects

There are several ways to observe and define the operational aspects of the ACN [PROV 005] as shown in Figure 2.11. One can differentiate between the normal operation and the operation during disturbances. It is also possible to differentiate between the internal and external behaviour.

The internal behaviour is defined to aspects inside the ACN. The external behaviour describes the interaction between the ACN and the network to which it is connected. Towards that network, the ACN must operate as an “intelligent grey box” with a well defined behaviour.

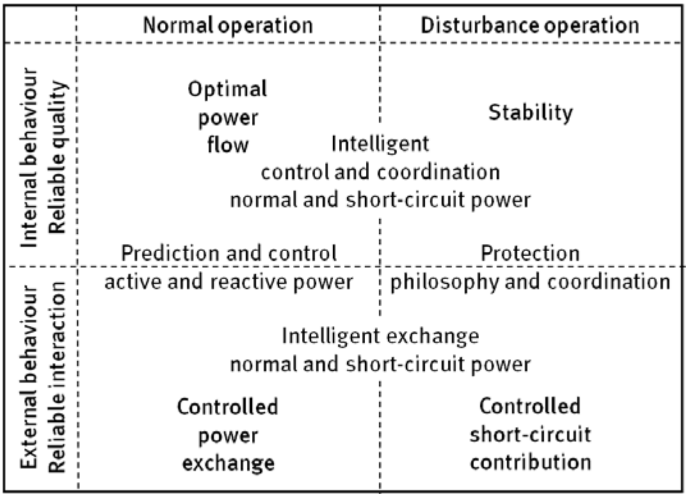


Figure 2.11 Tasks of the autonomously controlled network

Normal operation, internal behaviour

During normal operation, the internal behaviour is based on the optimal power flow. The control activities must focus on:

- Power quality aspects like voltage and harmonic levels.
- Cable loading.
- Network losses.

The activities, however, are not limited to normal operational aspects. Also, measures for limiting the impact of disturbances can be taken. The knowledge of the network status can be used for defining network restoration strategies and for adaptive protection settings.

The intelligent nodes can on the one hand contribute to redirect power flows and on the other hand can send information about specific local parameters, like voltage and current, towards the central control. The central control has to calculate the network status, restoration programs and protection settings and send adjustments for set points towards the various intelligent nodes.

Normal operation, external behaviour

During normal operation the external behaviour of the ACN focuses on the defined exchange of active and reactive power. The network can behave as a reliable market player. The power exchange can be based on market prices and depends on the availability of controllable load and generation in the network. When the ACN contains a large amount of generation and eventually storage it might operate as a virtual power plant (VPP). The local control receives information of market prices and possibilities of the controllable loads and generation. Based on predictions of non-controllable loads and generation new set-points for the controllable elements are sent to the intelligent nodes to which these devices are connected.

Disturbance operation, general

In case of a disturbance either inside or outside the ACN, its impact must be minimized. Therefore attention must be paid on fault ride-through requirements and intentional islanding. In case of intentional islanding the ACN needs its own local autonomous control for frequency, power balance and synchronous reconnection.

Disturbance operation, internal behaviour

In case of a fault in the ACN switching activities are performed to clear the fault and to restore the network. To limit customer outage and the impact of voltage dips, these switching activities must be both selective and fast. In order to reduce outage times, accurate calculation of the fault location and remote (autonomous) switching activities for network restoration is necessary. The network restoration must happen according to the calculated restoration programs. The intelligent nodes can help by reducing short-circuit current contributions and by performing switching actions to clear the fault and to restore the network.

Disturbance operation, external behaviour

When regarding the external behaviour during disturbances, two types of disturbances must be considered: a disturbance inside the ACN and a disturbance outside the ACN. A disturbance inside the ACN may not result in cascade effects outside the ACN. In case of a disturbance outside the ACN, the controls must limit the internal consequences and if possible support the external network. These support actions may consist of temporary intentional islanding or in case of a VPP support of active and reactive power. The intelligent nodes must help to maintain stability in the ACN.

2.5.5 Possible control actions

Based on the operational requirements of the ACN headlines of autonomous controlled activities are given in Table 2.2:

Activity	Normal	Disturbed	Internal	External
Keeping optimal voltage profile	X		X	
Minimizing network losses	X		X	
Keeping internal stability during internal disturbances		X	X	
Keeping internal stability during external disturbances		X		X
Support other networks during external disturbances		X		X
Maintaining predefined exchange of active and reactive power	X			X
Minimizing harmonic distortion	X		X	
Adaptive protection		X	X	
Intelligent fault location		X	X	
Post fault network restoration activities		X	X	
Predefine network restoration strategies	X		X	

Table 2.2 Possible control actions in the ACN

These activities will be considered in the research of autonomously controlled networks managing the impact of distributed generation, to be treated in chapters 6 and 7.

Within the IOP project on intelligent networks, several of these items are being studied in other research. The item of predefined power exchange, for example, has been studied in [JOKI 001]. Stability items for distributed generation are described in [ISHC 001] and power electronic interfaces are treated in [MORR 001].

2.6 Conclusions

Because of their design MV cable networks combine the benefits of symmetrical loading, typical for European systems, with the multi-earthing concept, typical for North American systems.

Because distribution networks in the Netherlands are mainly constructed with underground cables, the reliability of these networks is rather good when compared to the networks in the rest of the world.

New developments in distribution networks, like the increasing penetration of distributed generation and the introduction of new sensitive equipment, lead to more stringent requirements for nowadays and future networks. Innovations and developments in ICT techniques pave the way for solutions regarding the expected challenges. A proposed solution is to develop an autonomously controlled network concept, based on intelligent nodes. Most of the innovative techniques are already developed but must be adapted for the distribution voltage level and should meet the requirements of network operators and the customers connected to these networks.

3 Coordination of voltage and current

Components and apparatus connected to the network are designed to operate within specific limits for voltages and currents. Operating outside these limits may result in breaking down, malfunctioning or extra ageing. When the voltage gets too high apparatus can be damaged. When the voltage is too low apparatus does not work properly or may even break. When the current is too high extra losses and heat are produced. This can result in ageing or damaging.

The network must be operated and protected to minimize violations of the limits, both in magnitude as in number of occurrences. In the past, much effort has been put on isolation coordination to prevent over-voltages which might harm network equipment. This has developed towards a general interest in the quality of the power supply. In this chapter causes of over-voltage, under-voltage and over-current will be described, as well as their influence on performance of equipment and apparatus. Both normal and disturbed operation is considered. The focus will be on MV and LV networks.

3.1 Normal operation

3.1.1 Requirements

Voltage

During normal operation the voltage in European LV networks must comply to standards based on the IEC 50160. In the American countries the standard ANSI C84.1 is used. These standards cover many of the power quality aspects. Most of these norms are based on the 10 minutes average value of the item treated. In Europe the requirements for the phase to neutral voltage in LV networks are:

- Lower than 253 V (230 V +10%) for all of the time;
- Higher than 207 V (230 V -10%) during 95% of the time;
- Higher than 196 V (230V -15%) for all of the time.

The value of 230 V is chosen to obtain a European standard. Until 1995 the voltage requirements for European countries differed. In countries like the Netherlands and Germany the standard was 220 V +10%/-10%, in the UK this was 240 V +10%/-10%. During the transit period, values of 230 V +6%/-10% and 230 V +10%/-6% were used for the 220 V and 240 V networks respectively. The possibility to operate the network below 207 V is intended for cases where a network has to be temporarily reconfigured due to maintenance or repair.

Current

The transport of electrical current always involves electrical losses, resulting in a temperature rise in the components involved. The effects of the heating are influenced by:

- The cooling caused by the environment (air or soil).
- The effect of cyclic load. During low load there is less heating.
- The thermal time constants. It takes time to heat and to cool down.

The temperature rise can result in ageing of components. The temperature also influences other phenomena. When using underground transmission, there is a risk of drying out the soil. In case of overhead transmission the temperature rise results in an increase of the line sag and an increase of the mechanical stresses on the suspension points. Due to the cyclic behaviour of the loading of components the temperatures will vary. This variation in temperature results in expansion and shrinking of materials. In overhead systems this results in a variation of the mechanical stresses. In cable systems this may result in dielectric weak points of the insulation. These weak points are either due to voids in the insulation (which are filled with air) or are due to the penetration of water and other contaminations. Air filled voids occur in systems with insulation of impregnated paper. The difference between the relative permeability of air (ε_r=1) and the insulation material (ε_r=2.5) causes high electrical field strengths over this void, which results in discharges and finally in insulation break down.

Thermal time constants depend on the component. For overhead lines these time constants are short (minutes). For underground cables most time constants are large, especially for heating up the soil (days). For transformers an important time constant is the heating of the oil (hours).

Requirements for the allowed currents of cables are based on IEC 60287 and IEC 60853 standards. The IEC 60287 standard is used for calculation of the continuous cable current rating. The results are the basis for the dynamic calculations according to the IEC 60853 standard. Using this standard, the cyclic and temporary current ratings can be calculated.

The IEC 60287 standard describes the calculation of cable losses and thermal resistances for the cable and its environment. The stationary cable current rating depends on a large number of input variables. Starting point for the calculation is always the cable construction. These data can be obtained from the manufacturer's data sheets. Other factors that influence the calculation results are:

- Sheaths bonding method;
- Laying configuration;
- Depth of laying;
- Underground cables: thermal resistivity of the soil and drying of the soil;
- Cables laying in free air: solar radiation.

The IEC 60853 standard describes the methods for: “calculation of the cyclic and emergency current rating of cables”. This standard uses the calculated cable losses and thermal properties according to IEC 60287.

The IEC 60853 standard is based on the fact that a cable, not conducting 100% of the maximum continuous current for a longer time, has not reached its maximum temperature. Thanks to the dynamic properties of cable and soil, the temperatures respond slowly to a step change in current, enabling the operator to overload the cable during a short time in emergency situations.

3.1.2 Coordination of voltages

The voltage in a distribution network varies due to the transport of active and reactive power. These variations depend on the amount of power, the network components (transformers, cables, overhead lines) and on the network layout (radial or meshed). Figure 3.1 shows the regular voltage variations at different nodes in a typical radial distribution network structure.

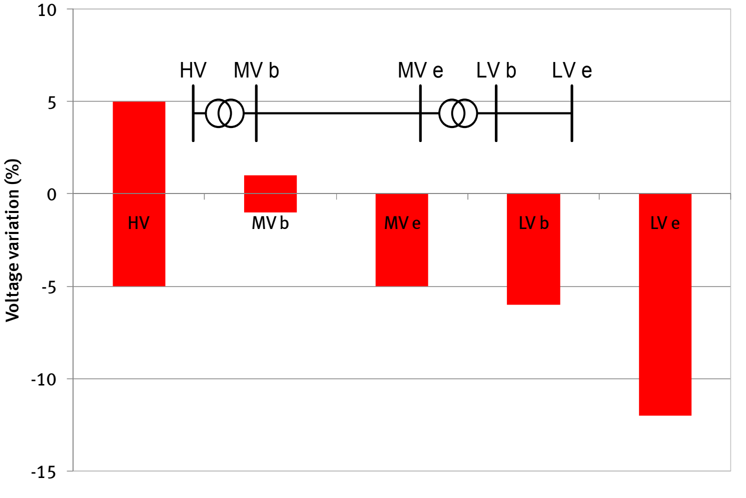


Figure 3.1 Typical voltage variations in a radially operated MV/LV network

Due to the continuous voltage control of the HV/MV transformer, the large variations in the HV network are not much noticed in the MV network. The voltage variation on the MV side of this transformer (MV b) is limited to the dead band of the control. Towards the end of the MV network (MV e), the voltage variation increases due to the variation of the power flow in the MV network. In general the MV/LV transformer does not have any voltage control; the setting of the taps is fixed. Therefore, the voltage variation noticed on the LV side of this transformer (LV b) will almost be the same as on the MV side. In reality, this variation will be slightly more due to the voltage drop across the MV/LV transformer.

The variation in power flow in the LV network will result in an increase of the voltage variation noticed at the end of the LV network (LV e). All voltage variations must be coordinated in such a way that no voltage limits are exceeded. In MV and LV networks the voltage level may be controlled by proper setting of transformer taps and (in case of overhead lines) by switching capacitor banks. Distributed generation will influence the transport of active and reactive power and will therefore also influence the voltage profile.

In nowadays networks the HV/MV transformer is the only component that is able to control the voltage. Since there is no other controlling component in the MV and LV networks, the MV voltage variations will add on the LV voltage variations. Therefore the MV network behaviour must be taken into account when planning and studying LV networks. On the other hand, the voltage limits in the LV network will set requirements for the MV network. As a consequence MV and LV networks can not be seen separately.

Influence of impedances

The voltage drop in a network depends on the impedance of the network in combination with the transport of active and reactive power. The left plot of Figure 3.2 shows a one-phase representation of a connection with resistance R and inductance X. Here U_b and U_e are the phase to earth voltages (given as complex numbers) at the beginning and the end of the connection. An amount of active and reactive power (P,Q) is transported over this connection.

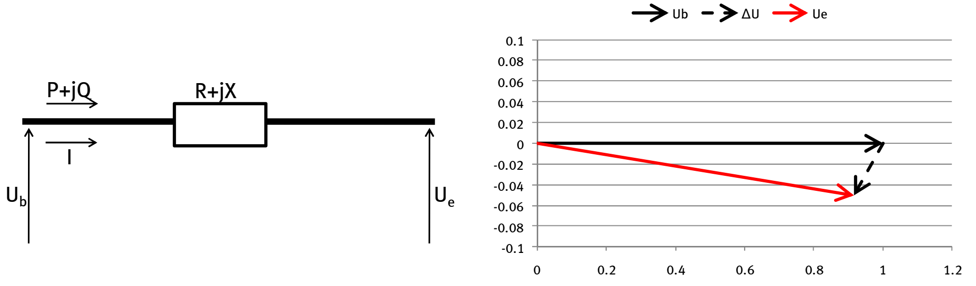


Figure 3.2 Example of voltage drop over an impedance

If the voltage U_b is considered to have a phase angle equal to 0^0, the voltage drop over this connection can be written as:

$$\Delta U = -I \cdot Z = -\frac{S^*}{U_b} \cdot Z = -\frac{P - jQ}{U_b} \cdot (R + jX) = -\frac{(P \cdot R + Q \cdot X) + j(P \cdot X - Q \cdot R)}{U_b} \qquad (3.1)$$

And the voltage at the end of the connection can be calculated:

$$U_e = U_b + \Delta U = U_b - \frac{(P \cdot R + Q \cdot X) + j(P \cdot X - Q \cdot R)}{U_b} \qquad (3.2)$$

As can be seen in the right plot of Figure 3.2, the real part of ΔU results in a voltage drop in the same direction of U_b. And the imaginary part of ΔU results in a voltage drop perpendicular to U_b. If the real part of ΔU equals 10% of the magnitude of U_b and the imaginary part of ΔU equals zero, then the magnitude of U_e will also differ 10% from the magnitude of U_b. On the contrary, if the imaginary part of ΔU equals 10% of the magnitude of U_b and the real part of ΔU equals 0, then the magnitude of U_e will differ only 0.5% from the magnitude of U_b. Therefore, the voltage drop depends mainly on the real part of ΔU.

$$U_e \approx U_b - \frac{(P \cdot R + Q \cdot X)}{U_b} \tag{3.3}$$

The influence of active and reactive power on the voltage drop depends on the X/R-ratio. From the ratio and formula 3.3 it can be concluded whether the voltage drop is mainly caused by active or by reactive power. Table 3.1 shows some typical values for various types of networks.

Voltage Level	Type	X/R	Main cause
HV	Overhead line	››1	Q
MV	Cable large conductor	0.75	P,Q
MV	Cable small conductor	‹0.5	P
MV	Overhead line	›1.5	Q

Table 3.1 Main cause of voltage drop for various types of networks

In HV networks (which mostly consist of overhead lines) the value of X is much larger than the value of R. Therefore the voltage drop depends mainly on the transport of reactive power.

In MV networks with cables, the X/R ratio is less than 1. Cables with a large conductor diameter have an X/R ratio of about 0.75. The voltage drop in these cables depends therefore on both active and reactive power, but the influence of an active power will always be larger than the influence of reactive power. Cables with a small conductor diameter have an X/R ratio between 0.5 and 0.25. The voltage drop in these cables depends therefore mainly on the active power. In MV networks with overhead lines, the X/R ratio is larger than 1.5. The voltage drop will be influenced by both active and reactive power. The influence of reactive power will be larger than the influence of active power in this case. It should be stated that in cable networks the values of R and X as such are much lower than in networks containing overhead lines. Therefore, the voltage drop for transporting a certain amount of power in case of cable networks is less than in case of overhead lines.

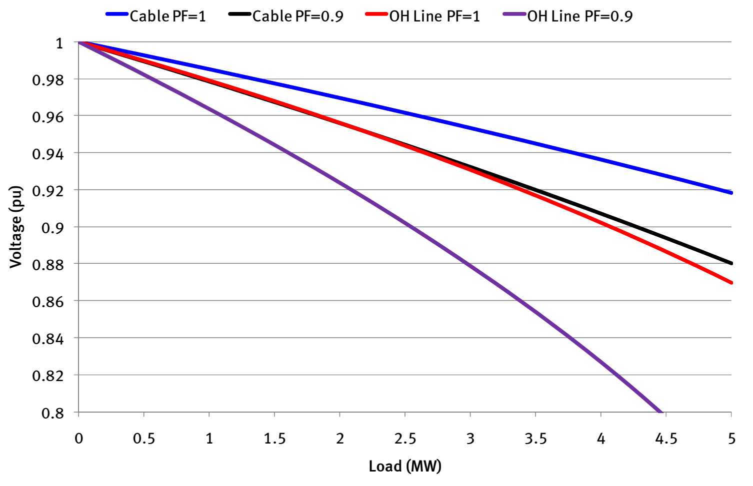


Figure 3.3 Calculated voltage at the end of a 10 km MV circuit (cable vs overhead line) due to a load at the end of the circuit

Figure 3.3 shows the voltage at the end of a 10 km MV circuit (either cable or overhead line) due to the transport of power with a power factor 1 and 0.9. The impedance of the cable is 1.2 + j1.6 Ω, the impedance of the overhead line is 2.2 + j3.1 Ω. The length of the circuit is typical for a long MV feeder in the Netherlands. In this example the influence of the low impedance of cables is clearly visible. The voltage drop for the line is about 50% larger than for the cable. It is also visible that the impact of the power factor is larger for overhead lines than for cables. A transport of 5 MW in a cable circuit (which is the maximum rating of a typical MV cable circuit) results in a voltage drop of 8.2% in case of a power factor equal to 1, and 12% in case of a power factor equal to 0.9. This is an increase of 46%. In the network with overhead lines the values for the voltage drop are 13% and 23.8% respectively. This is an increase of 82%.

The above example is typical for MV transmission networks. In distribution networks the loads are distributed over a feeder. This will reduce the voltage drop with about 50%. In radially operated meshed networks, a feeder also has to take over the load of another feeder, in case of a problem in that feeder. Therefore, the maximum load of a feeder is about half of the maximum allowed ampacity. In case of a cable network it means, that even with power factor 0.9 the voltage drop will be less than 3%.

In LV networks the resistance is much larger than the inductance. The voltage drop therefore is a function of active power and the feeder resistance. For transporting a certain amount of power, the voltage drop mainly depends on the circuit length and the type of conductor.

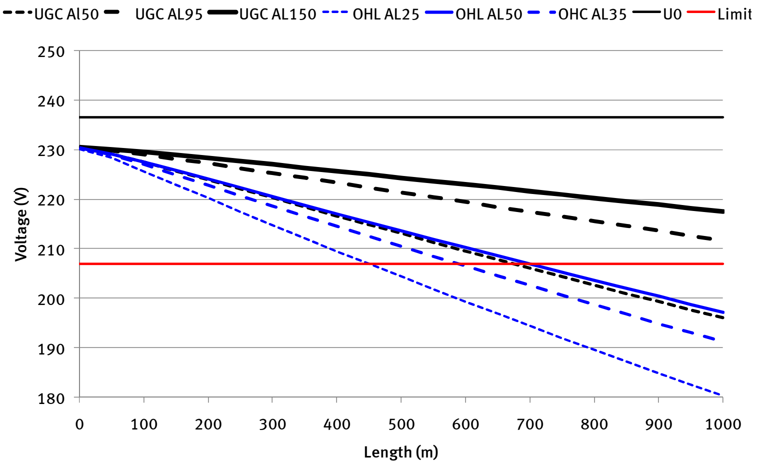


Figure 3.4 Calculated influence of circuit length on the voltage in an LV network for different types of cable and line

Figure 3.4 shows the influence of the circuit length on the voltage in an LV network for some typical conductor configurations like underground cable (UGC), overhead line (OHL) and overhead cable (OHC). Each feeder consists of 42 domestic loads (of about 1 kW each) with a power factor of 0.9. Most of the LV distribution networks in the Netherlands have a length of less than 500 metres. When using 150 Al underground cable, the voltage drop for such a length is about 4%. This figure also shows the voltage of the transformer during no-load conditions (U0, upper straight line) and the lower limit requirement for the voltage (Limit, lower straight line).

It must be noted, that also the transformer introduces a voltage drop. In this example the voltage drop is 6.5 V, which is about 3% of the voltage. Figure 3.5 shows the voltage drop over two typical Dutch MV/LV distribution transformers for different loadings and power factors. Even at power factor 1 the voltage drop is about 1% at full load. At power factor 0.8 the voltage drop is 3.5% for both transformers. The small difference between the curves for the same power factor is the result of a different transformer resistance.

It can be concluded, that systems consisting of underground cables show relatively small voltage drops as long as the lengths are limited to about 10 km for MV and 500 m for LV network. These values are typical values for MV/LV distribution networks in the Netherlands. In networks consisting of overhead lines, problems occur at shorter lengths, and measures to control the voltage drop are necessary. The advantage of cable systems for maintaining a good voltage profile is further described in [PROV 008].

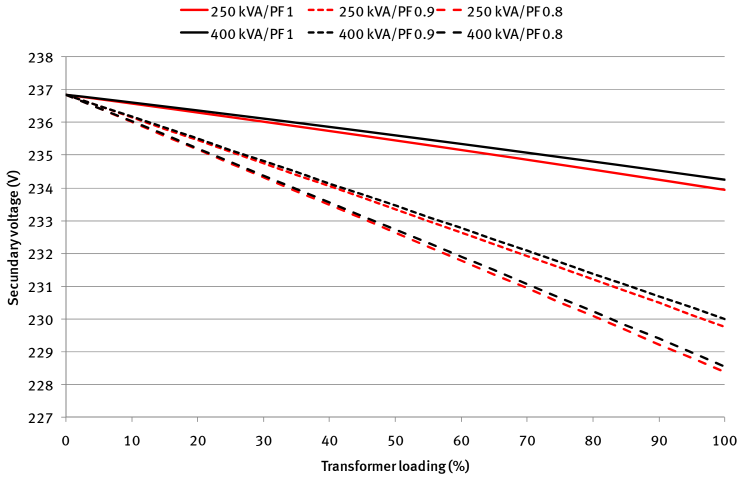


Figure 3.5 Calculated voltage drop over typical dutch MV/LV transformers for different loadings and power factors

It is normal to economically choose a cable which is large enough to maintain the desired voltage profile, but not too large in relation to the investment costs. However, in practice the price of laying a cable is higher than the cable costs for commonly used cable types. The voltage drop in a cable network is inversely proportional with the cable diameter. Choosing 240 Al cables instead of 95 Al cables in an MV network results in a more than 60% reduction of the voltage drop for only 25% extra investment costs. Choosing 150 Al cables instead of 50 Al cables in an LV network results in a more than 65% reduction of voltage drop for 30% extra costs. In relation to the expected lifetime of more than 40 years for a cable, it is often wise to choose a larger diameter in order to prevent future upgrading costs.

Influence of operation mode

Networks can be operated radially or meshed. Meshed operated networks generally result in better voltage profiles and lower losses.

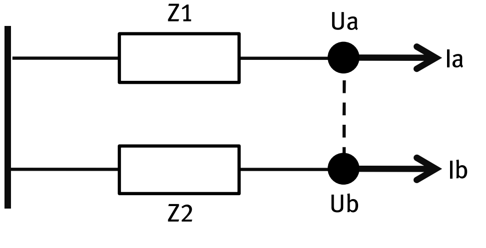


Figure 3.6 Example network showing the influence of operation

Consider the network of Figure 3.6. In a radial configuration the voltage drops over the impedances are:

$$\Delta U_a = I_a \cdot Z_1 \tag{3.4}$$

$$\Delta U_b = I_b \cdot Z_2 \tag{3.5}$$

The mean voltage drop in this radial configuration can be calculated by:

$$\Delta U_r = \frac{\Delta U_a + \Delta U_b}{2} = \frac{(I_a \cdot Z_1 + I_b \cdot Z_2)}{2} \tag{3.6}$$

In a meshed operation the voltage drop over the impedances is:

$$\Delta U_a = \Delta U_b = \Delta U_m = \left(I_a + I_b\right) \cdot \frac{Z_1 \cdot Z_2}{Z_1 + Z_2} \tag{3.7}$$

This voltage drop is always lower than the largest voltage drop in the radial configuration. In many cases this voltage drop is also less than the mean voltage drop in a radial configuration, resulting in a better overall voltage profile.

The impedance Z_2 can be expressed in terms of the impedance Z_1 by:

$$Z_2 = c \cdot Z_1 \tag{3.8}$$

It can be proven that the voltage drop in the meshed configuration is less than or equal to the mean voltage drop in the radial configuration when:

$$\left(c-1\right) \cdot I_b \geq \frac{(c-1)}{c} \cdot I_a \tag{3.9}$$

To evaluate this formula three cases have to be distinguished:

- Both impedances are equal (c = 1)
- Z_2 is larger than Z_1 (c > 1)
- Z_1 is larger than Z_2 (0 < c <1)

If the two impedances are equal (c = 1), the voltage drop in the meshed network equals the mean voltage drop of the radial configuration. Compared to the radial configuration, the voltage in the feeder with the highest voltage drop improves, but the voltage in the feeder with the lowest voltage drop worsens.

If the impedance Z_2 is larger than Z_1 (c > 1), a better overall voltage profile is obtained when:

$$I_b \geq \frac{I_a}{c} \tag{3.10}$$

If the impedance Z_2 is smaller than Z_1 (c < 1), a better overall voltage profile is obtained when:

$$I_b \leq \frac{I_a}{c} \tag{3.11}$$

Both cases describe the situation where in the radial configuration, the largest current flows through the largest impedance and the smallest current flows through the smallest impedance. In the meshed configuration, the current in the largest conductor decreases compared to the radial configuration, resulting in a lower voltage drop over that impedance. The voltage drop over the smallest impedance increases, but this increase is less than the decrease over the largest impedance.

Influence of distributed generation

Considering voltage, in normal steady-state operation, distributed generation can be seen as a negative load. As long as the amount of generation is lower than the load, the voltage profile will improve. When the amount of generation is larger than the amount of load, the voltage in the network will rise. This rise will be noticed mostly in the LV networks. Such situations may occur, since load and generation do not always happen simultaneously.

In LV networks distributed generation consists of solar power modules, µCHP and micro wind turbines. Bigger solitary wind turbines and relatively small CHP units can be connected to an existing MV feeder. The influence of such a generator on the voltage profile depends on the layout of the MV network. In MV networks that consist of underground cables of a large conductor cross-section, the influence is low, because of the limited power of the generation and the low impedance of the network. Wind farms and larger CHP units have a higher power output and are therefore connected on separate MV feeders coming from the HV/MV substation. They will therefore not influence the voltage on LV level.

The influence of distributed generation will be discussed in more detail in chapter 6.

Controlling voltage with reactive power

When controlling voltage with reactive power, a sufficient amount of inductance in the network is necessary. Overhead lines have a larger inductance than cables. Therefore voltage regulation with reactive power is more efficient in networks with overhead lines. When injecting reactive power, care must be taken with the rating of the components. In radially operated meshed networks, the maximum loading of a feeder, for redundancy reasons, is less than half of the maximum ampacity. This creates margins for reactive power injections, but care must be taken when re-arranging the network openings.

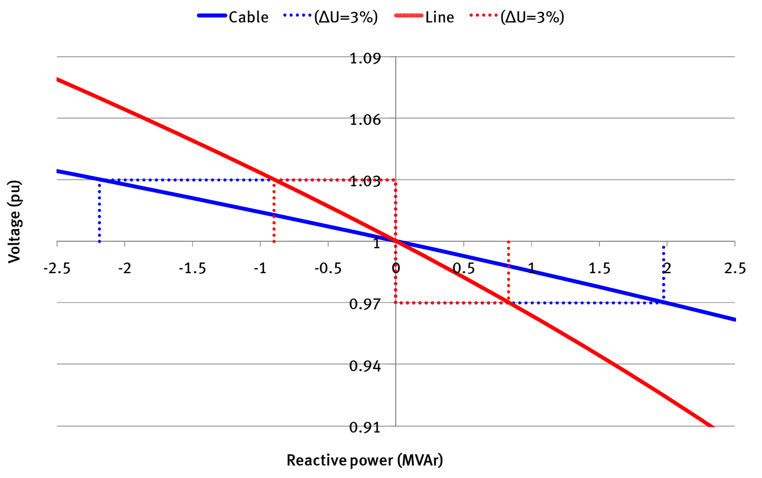


Figure 3.7 Voltage regulation with reactive power for cables and overhead lines
Calculated influence on voltage

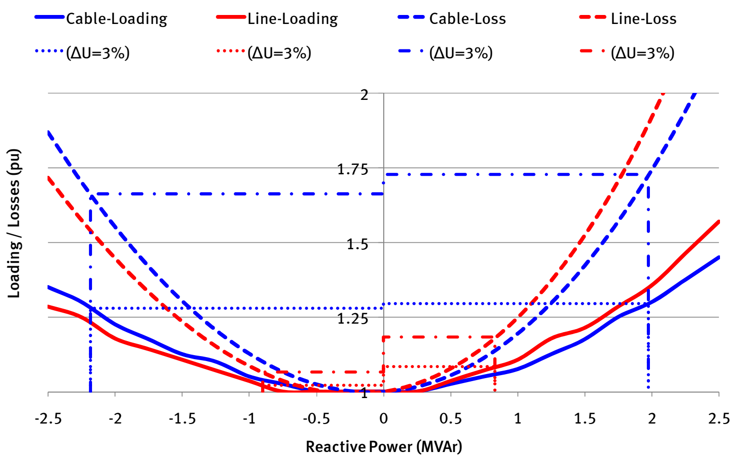


Figure 3.8 Voltage regulation with reactive power for cables and overhead lines
Calculated influence on loading and losses

Figure 3.7 and Figure 3.8 show the influence of reactive power for two 10 km long MV feeders, one being a cable and the other being an overhead line. The active load in both feeders is 2.5 MW, concentrated at the end of the feeder. The reactive load at the end of the feeder can be varied between -2.5 (injecting) and +2.5 (absorbing) MVAr.

Figure 3.7 shows the influence on the voltage. In this plot, the solid lines show the voltage variation at the end of the feeder as a function of the reactive power, relative to the situation in absence of reactive load. This clearly shows that the influence of reactive power on the voltage for a cable feeder is smaller than for an overhead line. The dotted lines in this plot show the reactive power necessary to obtain a voltage difference of 3% at the end of the feeder, when compared with the situation without reactive power injection. In order to increase the voltage by 3%, a cable feeder requires a negative load (injection) of more than 2 MVAr, an overhead line requires less than 1 MVAr. In order to decrease the voltage by 3%, the reactive power of the load must be 2 MVAr for the cable and 0.8 MVAr for the overhead line configuration.

The influence on the loading and the losses is shown in Figure 3.8. The solid lines show the loading of the feeders as a function of reactive power relative to the situation of no reactive load. The dashed lines show the losses in the feeder relative to the situation of no reactive power. The dotted lines show the loading for a voltage deviation of plus or minus 3%, caused by the injection or absorption of reactive power as mentioned above. The dash-dotted lines show the losses for a voltage deviation of plus or minus 3%, caused by the same reactive power. In a cable network, the large injection or absorption of reactive power results in a more than 25% increase of loading, and a nearly 75% increase of the losses. In overhead networks a voltage rise of 3% results in an increase in loading of 2%, and an increase of losses of 6%. Reducing the voltage with 3%, results in an extra loading of 8%, and an increase of losses of 18%. From this it can be concluded that in overhead networks voltage drop/rise may well be compensated by reactive power. This can be obtained by switching capacitor banks or from local generation. In cable networks, however, voltage control with reactive power is not recommended. Furthermore, the voltage drop in a cable network is relatively low, and controlling it, is often not necessary.

Controlling voltage with transformer tap changers

Controlling the voltage with tap changers is possible at the HV/MV transformer, the MV/LV transformer and, in case of an MV transmission network, at the MV/MV booster transformer. Both on-load and off-load tap changers are used. When considering the choice between the use of on-load and off-load tap changers, the following aspects have to be considered:

- On-load control with tap changers requires space and switching activities inside the transformer. This switching influences the lifetime of the tap changer.
- Off-load tap changers can be made very cheap and robust.
- In a normal MV distribution network there are only a few HV/MV or MV/MV transformers and a lot of MV/LV transformers.

Furthermore:

- The operational margins for the voltage at LV level are large.
- In MV networks with cables, the voltage drop along the feeder is relatively small.
- In MV networks with overhead lines, the voltage drop along the feeder is relatively large, but this can be improved by capacitors or re-arranging the feeders.

It is normal to use a voltage control on the HV/MV transformer to keep the MV network voltage within specified limits. As a consequence, control of the LV voltage by means of continuously controlling the MV/LV transformer is not necessary, as long as the MV voltage of the MV distribution network can be controlled within reasonable margins. Therefore, most of the MV/LV transformers can be equipped with an off-load tap changer, which is adjusted only when the transformer is put into service, and when the loading situation changes structurally. On-load tap changers for MV/LV are seldom used. They are expensive and require extra maintenance, which means that the transformer has to be taken out of service and the LV customers have to be supplied with the help of a mobile generator or a spare transformer.

In one particular situation in the Netherlands, where voltage problems for LV customers were expected, a transformer equipped with power electronic tap changers has been introduced as an experiment [ROGG 001]. Such a transformer is expensive, requires more space and does not fit in the standard compact ring main units concept, so it needs to be installed in a specific building.

In remote rural areas with long lengths of LV cable or overhead line, a booster transformer is used to compensate for the voltage drop. This transformer may be constructed with a zig-zag configuration [OIRS 002], which mitigates the asymmetry of the current as an extra feature. Also, these transformers can be equipped with power electronics. Booster transformers in LV networks tend to disappear in the Netherlands, due to the relatively low costs of MV network extensions.

The voltage in the LV network has to be managed by a proper control of the voltage in the MV network. In the HV/MV (or MV/MV) substation, the transformers are equipped with an on-load tap changer, controlled by an automatic voltage regulator (AVR). This regulator compares its input signal with a reference voltage U_{ref}. When these voltages differ, the taps of the transformer are adjusted. There will always be a certain dead band (ΔU), due to the fixed step width of the tap changer. Often also a time delay is used.

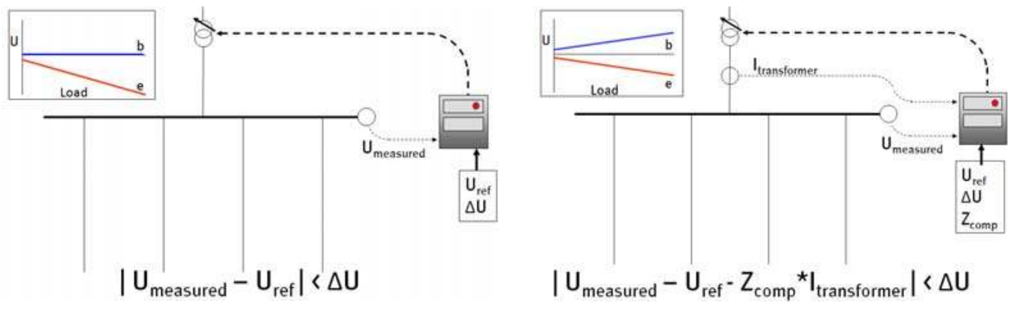


Figure 3.9 Transformer control for constant voltage (left) and for line drop compensation (right)

Figure 3.9 shows two ways of voltage control. The two small plots show the voltage at the beginning of a feeder connected to the busbar (b) and at the end of that feeder (e) as a function of the transformer and feeder load.

The most simple control (see Figure 3.9 left) is to keep the voltage of the MV busbar on a constant level:

$$\left|U_{measured} - U_{ref}\right| \leq \Delta U \tag{3.12}$$

As a result, the voltage at the beginning of the feeder does not change when the load changes. The voltage at the end of a feeder decreases as the load increases.

A more complicated control uses a so called line drop compensation (see Figure 3.9 right). The voltage is controlled based on the loading of the transformer:

$$\left|\left|U_{measured} - U_{ref}\right| - I_{transformer} \cdot Z_{comp}\right| \leq \Delta U \tag{3.13}$$

At high load conditions the input voltage for the control will be lower than at low load conditions. This results in a higher voltage on the busbar. In this way the transformer compensates for the voltage drop on the outgoing feeders. As a result, the voltage at the beginning of the feeder increases as the load increases. The voltage at the end of a feeder decreases as the load increases, but this decrease is less than in the situation without line drop compensation. This reduces the voltage variation due to load variations in the MV network. Distributed generation disturbs this type of control. As long as the penetration of DG is limited, this influence can be neglected [PIGA 001]. At higher penetration the influence of the DG production has to be included in the control. This has been developed already by some manufacturers [HISC 001] [LEIT 001].

Conclusions on voltage control

The design of the MV and LV network influences the voltage variations and the needs for control. In cable networks the influence of active and reactive power is limited, especially when cables with sufficient conductor diameter are used.

The voltage in the MV network and the connected LV networks can be controlled by the HV/MV transformer. Line drop compensation can limit the voltage deviations in case of high loads. In networks with overhead lines, additional control actions using reactive power injection may be necessary to keep the MV voltage within limits.

Costs and lifetime of controls have to be compared with costs and lifetime of network components. The total investment costs for modern LV and MV cables do not vary much on diameter. Therefore, it is mostly wise to invest in thicker cables rather than in extra controls.

Distributed generation influences the voltage profile of the feeders it is connected to and needs extra attention when defining the control concept.

3.1.3 Coordination of currents

The main reason for managing the current is to prevent overloading and to limit the losses in the network and components. Currents result in heating, which influences both components and their surrounding environment. In this paragraph the effects of current on two main components (transformers and cables) are described. Currents also cause electromagnetic fields. This item is described in appendix D.

Transformers

Transformer windings are isolated by paper. The transformers are filled with oil that transfers the heat towards the outside of the transformer. When the temperature of the paper reaches an upper limit value, the ageing of the isolation accelerates. Temperatures above this level therefore have to be avoided. Most distribution transformers only have natural cooling. This means, that cooling of the transformer depends on the conditions of the air around the transformer. Normally distribution transformers have a fluctuating load, which makes it possible to cool down during the low load and low temperature periods in the night. According to IEC 60076 heating and cooling of the oil have a time constant of approximately three hours.

Many distribution transformers are located indoors. The convectional cooling occurs in a relatively warm environment. In summer periods the sunshine results in an extra heating. Due to the warm environment it is not possible to cool the oil sufficiently during the evening and night and the transformer will heat up easier during high load situations. This results in higher mean and maximum temperatures.

Transformers in generation units, for instance in wind generators, do not have cyclic behaving currents. They may be subject to high currents during a long period of time. These transformers are also located indoors, so care must be taken when dimensioning these transformers [DECL 001].

Cables

When looking at cables, two aspects have to be considered. The first one is the drying out of the soil; the second is the effect of heating on the insulation.

The heat of the cable will dry out the soil. This effect is noticed when the temperature on the outside of the cable reaches 50^0 C. Drying out of the soil is a relatively slow process. In the Netherlands this takes about one or two weeks. Rainfall will normally restore the natural amount of humidity around the cable, but this also is a slow process. In certain types of soil (clay and peat) the process of drying out is irreversible, because the drying out of this soil results in a solid compound with a high thermal resistivity. When laying cables, improvement of the soil can be made, so that a thermal resistivity (ρ_e) of 0.75 K.m/W for elements surrounding the cable can be reached. With this value the temperature of 50^0 C is reached at a heat flux of 150 W/mm^2. From this value critical loading of cable types can be calculated.

When cables are laid in ducts the outside diameter will increase, so that more heat can be exchanged. This may increase the critical current loading of the cable, but care has to be taken, because the air inside the duct is a bad conductor for heat, increasing the thermal resistance. In single-phase cables the current will not only flow in the cores, but dependent on the connection of the sheaths, also in the sheath. This reduces the allowed current, compared to a three-phase cable. In distribution networks the cable sheaths are mostly interconnected at both sides. Cross-bonding (which limits currents in the sheath) is expensive and not much applied.

The degradation of insulation increases with increasing temperature. The maximum allowed temperature for the insulation of PILC cables is 50^0 C, for PVC insulated cable this is 70^0 C and for XLPE insulated cable 90^0 C. In case of an XLPE insulated cable, there is a large difference between the maximum allowed core temperature and the maximum allowed outside temperature (for preventing drying out). This makes this cable convenient for fluctuating loadings even above the rated current. Examples are radially operated ring structures, parallel cables, cables connecting wind farms and other fluctuating generation.

Dynamic loading

The values for maximum loading of cables and transformers are based on continuous load. However, most of the loads are not continuous, but have a cyclic behaviour of high and low load. Therefore, the components are not always loaded to the maximum value. These considerations make it possible to allow temporary overloading. In this way a dynamic maximum value is obtained. Since many temperature effects have long time constants, the history of loading and temperature is important. Dynamic overloading of components is described in [TRIP 001] [TRIP 002] [THEE 001] [NUIJ 002].

High currents coincide with high losses. The consequences of these losses (financial and environmental) have to be considered, when structural overloading is compared with investments.

Conclusions on currents

The maximum current in cables and transformers depends on the maximum permissible temperature inside the components. The environmental temperature is an important external factor. Distribution transformers are often situated indoors. In summer periods, the high environmental temperature may limit the cooling capacity of the transformer oil, and in this way reduce the allowed loading of the transformer.

The thermal limit of underground cables is based on insulation temperature and drying out of the soil. Drying out of soil is a slow process. XLPE cables have a large difference between the core temperature causing drying out of the soil and the core temperature causing insulation problems. This allows temporary overloading and makes this type of cable useful for cases with fluctuating and peaking loads.

3.1.4 Power Quality

When looking at voltages and currents not only the 50 Hz phenomena must be considered, but also other characteristics, generally known as power quality aspects. In the Netherlands a Power Quality Monitoring (PQM) program started in 1996. Every year about 150 points in the Dutch network were monitored during one week.

In the first years the measuring points were equally spread out over HV, MV and LV. In later years such measurements were only performed on MV and LV. The results of the PQM program are published every year [ENER 002] - [ENER 006] [ENBI 001].

In appendix E some results are discussed. The main conclusions from this appendix are:

- Power quality depends on network design, the type of components like cables and overhead lines and the interaction with the connected devices and installations.
- In cable networks the power quality is mostly good.
- Limiting the network impedance (thicker cables) decreases the impact of flicker and reduces harmonic levels.
- In TN networks the interconnection of the neutral and the PE conductor reduces the impact of switching of single-phase loads.
- The number of faults in cable networks is low compared to overhead lines. This limits the amount of dips in these networks.

3.2 Operation during disturbances

3.2.1 Requirements

Due to disturbances in the network, short-circuit currents, over-voltages, dips and earth potential rise (EPR) may occur. This has the following consequences:

- Short-circuit currents result in extra heating and mechanical stresses. Dips may cause malfunctioning of apparatus and processes.
- Over-voltages cause damage to apparatus and insulation. Negative-sequence voltages introduce negative-sequence currents, which may damage rotating machines.
- EPR may cause safety problems.

Components in the network and the connected devices are designed for specific voltages and currents. They should be protected against violations of these limits.

Short-circuit currents

Short-circuit currents have a dynamic behaviour. Figure 3.10 shows the profile of a short-circuit current close to a generator, as stated in IEC 60909.

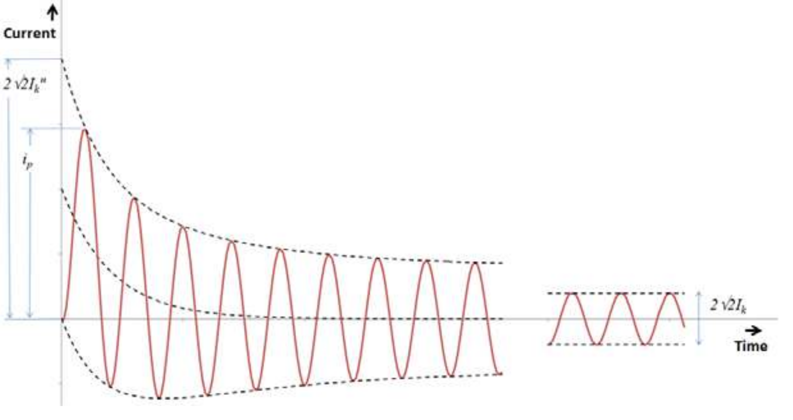


Figure 3.10 The behaviour of a short-circuit current according to IEC 60909

During the first periods, the current is built up from the initial symmetrical short-circuit current I_k” and a decaying DC current I_{DC}. This results in a peak short-circuit current I_p, which occurs after about a half period. The current I_k” contains the contribution of the generator and has a contribution of the rest of the network. The duration of the contribution of the generator is limited in time. After that, the short-circuit current reduces towards the steady-state symmetrical short-circuit current I_k. In the case there is not a generator near to the fault location, the values of I_k”and I_k are more or less equal.

The peak short-circuit current I_p is decisive for the mechanical stresses. The initial and steady-state short-circuit currents are decisive for the thermal heating. Thermal stresses depend on the amount of energy dissipated in the components and devices and are therefore related to the duration of initial and steady-state short-circuit current. These values are specified by the manufacturers.

During a single-phase fault, a part of the fault current will return through the sheath of the cable. This gives extra heating of the cable core and the cable sheath. The amount of current and the maximum allowed time is therefore limited. Also these values are specified by the manufacturers.

Abnormal voltages

Over-voltages (swells) are caused by phase to earth faults. Short-circuits cause voltage dips in neighbouring feeders. The effect of over-voltage and under-voltage on the functioning of apparatus and devices depends on the magnitude and the duration of these phenomena. Requirements are stated in IEC 50160 and in the ITI(CEBEMA) curve.

Safety

During faults earth wires and housings of equipment may unintentionally make contact with (high) voltages. Touching the earth wire or the housing during such an event will result in a current through the body. The current through the human body is a function of the touch voltage. The hazardousness of this current depends on its magnitude and duration. So this touch voltage must be limited in both magnitude and duration. Requirements for safety come from IEC 60479-1 and IEEE Std 80. These requirements are described in appendix A of this thesis.

Faults in the network may also endanger safety of apparatus. Especially when apparatus uses signals from more than one supplier, care must be taken that a disturbance from the network of one of the suppliers (fault voltages, lightning events) does not cause problems, neither in the apparatus itself, nor in the network of other suppliers.

3.2.2 Impact of faults

Disturbances on one voltage level in the network may have impact on other voltage levels in the area. So, in order to investigate the impact of disturbances on the MV and LV networks, not only faults in these networks must be considered, but also faults in the HV networks.

Most of the faults in HV networks have natural causes like lightning, falling trees and effects of storms and ice. Lightning not only causes high transient voltages, but can result also in a flash-over across the insulators, causing single-phase and sometimes multi-phase faults.

Fallen trees, storms and ice, result in single-phase and multi-phase faults, dependent on the number of conductors involved. A proper protection philosophy results in short durations of faults in HV networks often less than 100 ms.

In MV networks both multi-phase and single-phase faults occur. In cable networks faults occur due to ageing of the insulation material and due to human activities like digging. Most faults start as a single-phase fault. In oil insulated joints spontaneous multi-phase faults may occur. The joints of XLPE cables are constructed in such a way, that spontaneous faults at first result in a single-phase fault. Faults due to digging also start as a single-phase fault, which later evolves in a multi-phase fault. Because the cables are underground, the influence of lightning can be ignored.

In overhead networks also faults of natural causes (wind, fallen trees and lightning) are dominating. Lightning often results in a flash-over on one or more insulators. This causes single and multi-phase faults.

Disturbances in the LV network can be caused by short-circuits, loss of the neutral, and by lightning. Most of the short-circuits in LV networks are single-phase faults, with single-phase switching off. In cable systems, direct lightning strokes will not occur. Lightning in the neighbourhood of an MV/LV transformer can cause safety problems, due to the earth potential rise of the transformer neutral, which is transferred towards the customer connections.

Faults can be self-extinguishing and many faults are also self-healing. Self-healing faults occur when the origin of the fault disappears and the network returns in the pre-fault state. Examples of self-healing faults are flash-overs and faults due to lightning. In cable networks self-extinguishing faults are not self-healing faults. Self-extinguishing faults occur due to contamination in the joints and result in a degradation of the insulation, which sooner or later will result in a permanent fault.

A disturbance can have impact on both voltage and current. Limiting the impact on current may increase the impact on voltage and the other way around. Table 3.2 shows, for different voltage levels, the impact of typical disturbances on voltage and current in MV and LV. The next paragraphs describe the effects of disturbances at different voltage levels and their impact on voltage and current in the distribution network.

Voltage Level	Fault type	Effect on MV: D	SW	TV	IV	SA	OC	TC	Effect on LV: D	SW	TV	IV	SA	OC	TC
HV	Lightning					x							x		
	Three-phase	x							x						
	Two-phase	x							x						
	Single-phase	x							x						
MV	Lightning					x	x	x					x		
	Three-phase	x					x		x						
	Two-phase	x			x		x		x						
	Single-phase (direct earthing)	x			x		x		x				x		
	Single-phase (impedance earthing)		x		x		x						x		
	Single-phase (Petersen earthing)		x	x				x					x		
	Single-phase (isolated neutral)		x	x				x					x		
LV	Lightning												x		x
	Three-phase								x					x	
	Two-phase								x			x		x	
	Single-phase											x	x	x	
	Loss of neutral									x			x		

D=Dip
SW=Swell
TV=Transient voltage
IV=Inverse voltage
SA=Safety
OC=Over-current
TC=Transient current

Table 3.2 Possible influence of faults at one voltage level on voltage and current in other voltage levels

3.2.3 Disturbances in HV networks

Dips

Faults in HV networks cause dips in LV and MV networks. Three- and two-phase faults always cause dips. Single-phase faults may result in dips when the network is earthed directly or by an impedance. The impact of a fault can be noticed over a large area. Often the duration of the dip is short (less than 100 ms), due to the fast switching in the HV network. Lightning may cause dips due to flash-overs on the insulators, resulting in single or multi-phase faults.

Safety

Lightning can cause safety problems in MV and LV networks due to local earth potential rise (EPR). A special case is the situation where GSM antennas are placed in HV towers. In order to keep a good EMC, the earthing of the antenna system must be connected to the earthing of the tower. In this way the effect of lightning is minimized. If the lightning stroke results in a flash-over on the insulator, a single-phase to earth fault will occur. A part of the fault current will flow through the tower and will result in a local earth potential rise.

This EPR will also be noticed by the antenna earthing and by the earthing of the LV network connected. This may result in too high touch and step voltages for the customers connected to the same LV network. In [WAES 001] [WAES 002] [WAES 003] this phenomenon is described, including the results of a life test and a solution.

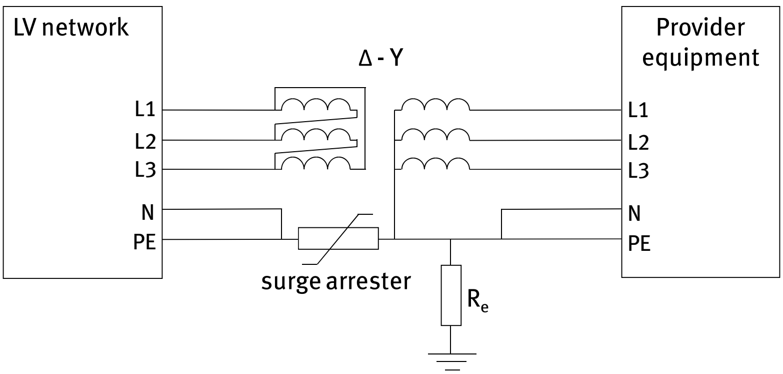


Figure 3.11 Connection of a GSM antenna in an HV tower [WAES 001]

Figure 3.11 shows the solution presented in these papers. The installation and the feeding LV network are electrically separated by means of an insulation transformer. A ZnO surge arrester connects the earthing of the antenna equipment and the HV tower with the earthing of the feeding LV cable. During a lightning stroke, the ZnO arrester conducts and keeps the voltage over the equipment on an acceptable level. During the single-phase to earth fault stage, the voltage over the arrester is so low, that the arrester blocks and the EPR at the tower footing is not transferred to the LV network. This solution has become a standard for the connection of these antennas.

3.2.4 Disturbances in MV networks

Fault currents
Multi-phase faults always cause high fault currents. In directly earthed networks also single-phase faults result in high fault currents. The magnitude of the fault current normally becomes lower when the fault occurs towards the end of the network. The heat production in components and devices carrying the short-circuit current requires a fast clearing of the fault. This limits the feeder length, since the fault currents in long feeders may become too small for the protection to trip. The fault current due to a fault in an impedance earthed network is limited, but also here heat production (both in the phases and in the sheaths) requires the fault to be cleared in a reasonable time.

In networks with isolated or compensated neutral, the single-phase fault current is low. The time for fault-clearing depends on the current in the phases and the sheaths, and may go up to several hours.

Negative-sequence currents

During two-phase and single-phase faults, negative-sequence fault currents occur in the faulted feeder. These currents result in negative-sequence voltages in the network. These voltages are noticed by rotating machines and will introduce negative-sequence currents in these machines, which may result in malfunctioning.

In case of a two-phase fault, the negative-sequence voltage can be calculated from:

$$I_2 = \frac{U_1}{Z_1 + Z_2} \rightarrow U_2 = Z_2 \cdot I_2 = \frac{Z_2}{Z_1 + Z_2} \cdot U_1 \tag{3.14}$$

In case of a single-phase fault, the negative-sequence voltage can be calculated from:

$$I_2 = \frac{U_1}{Z_1 + Z_2 + Z_0} \rightarrow U_2 = Z_2 \cdot I_2 = \frac{Z_2}{Z_1 + Z_2 + Z_0} \cdot U_1 \tag{3.15}$$

Large negative-sequence voltages may be expected during two-phase faults and during single-phase faults in directly earthed networks (where Z_0 is relatively small compared to other earthing methods). The magnitude of the negative-sequence voltages due to single-phase faults in impedance earthed networks, and networks with isolated or compensated neutral, will be much lower because here Z_0 is much larger than Z_1+Z_2.

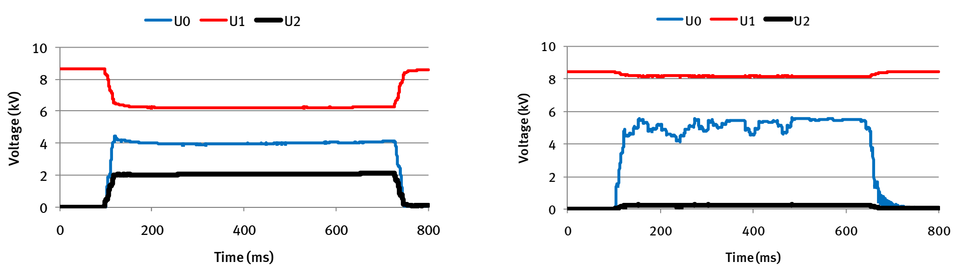


Figure 3.12 Measured negative-sequence voltages during a two-phase fault (left) and a single-phase fault (right)

Figure 3.12 shows the negative-sequence voltages during a two-phase to earth fault in a network with isolated neutral, and during a single-phase fault in an impedance earthed network. From this figure it can be seen that in practice the negative-sequence voltage (U_2) during the two-phase fault is much larger than during the single-phase fault.

Dips

Dips occur when a fault causes a voltage drop on the MV busbar of the substation. Dips can be caused by various types of faults. The impact of the dip depends on the type of fault and the fault location. Based on sequence data, a single-line diagram can be drawn for calculating the fault current and the voltage at the busbar (Figure 3.13).

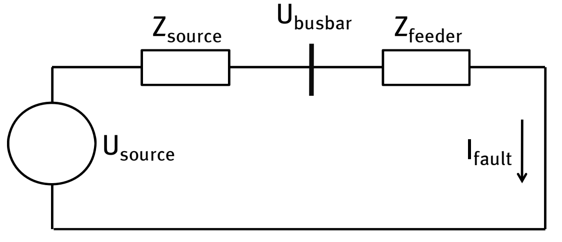


Figure 3.13 General sequence based single line diagram for calculating fault currents and voltages

The impedance Z_{source} represents the sequence equivalent of the circuit feeding the busbar. The impedance Z_{feeder} represents the sequence equivalent of the faulted feeder. The impedance Z_{source} depends on the fault type, but not on the fault location. The impedance Z_{feeder} depends both on the fault type and the fault location. In general, the impedance Z_{feeder} increases as the fault is further away from the substation. The voltage on the busbar can be calculated form:

$$U_{busbar} = \frac{Z_{feeder}}{Z_{feeder} + Z_{source}} \cdot U_{source} \quad (3.16)$$

Severe dips occur when the impedance Z_{feeder} is small compared to Z_{source}. This happens in case of multi-phase faults and in case of single-phase faults in directly earthed networks. These small values of Z_{feeder} result in high short-circuit currents. As a result, high fault currents coincide with deep dips.

The effect of the dip on functioning of apparatus depends on the magnitude and duration of the dip. The magnitude of the dip depends on the electrical distance of the fault to the substation. The duration of the dip depends on the fault-clearing time. MV protection is based on selectivity by time grading. Therefore, the protection at the substation has a certain built-in time delay, so a fault further away in the network can be switched off by local protection. Due to this time delay the largest dips (due to faults close to the substation) last the longest.

Figure 3.14 shows the consequences of a severe dip. The fault occurs in one of three parallel cables in an MV transmission network feeding an MV/MV distribution substation from an HV/MV substation. Due to the time grading of the protection, this cable is switched off 0.7 sec after the beginning of the fault.

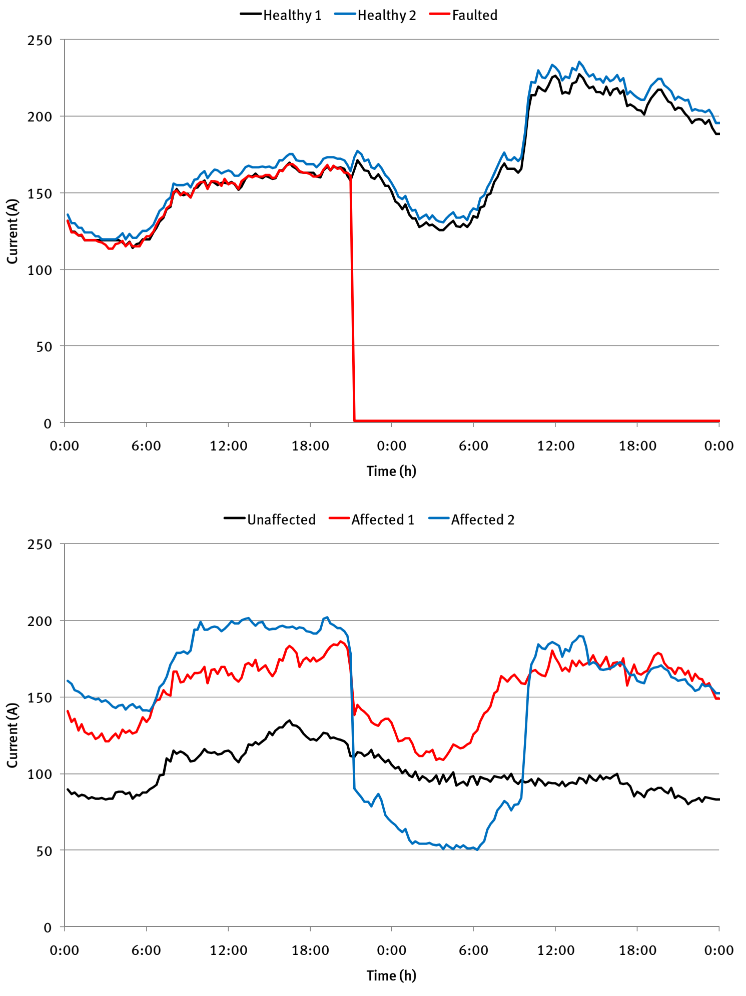


Figure 3.14 Measured currents towards (top) and from (bottom) an MV/MV substation before and after a two-phase fault with severe dip

The residual voltage at the busbar of the HV/MV substation during the fault was about 40%. This dip was noticed in the whole involved MV network, including the network behind the MV/MV substation. Due to this dip, several processes in the network behind the MV/MV substation were switched off, which resulted in a large reduction of the power transport towards that substation. The upper plot of the figure shows the currents towards the MV/MV substation. After the fault, the current in the faulted cable is zero (red curve). In a normal case the two remaining cables should take over the load of the faulted cable after switching off the cable. Here the load in the two remaining cables seems to remain unchanged. This means, that more than 30% of the load is lost, due to this dip.

The loss of load is visible in the lower plot, which shows the currents in the three feeders away from the MV/MV substation. Due to the fault, the current in two (red curve and blue curve) of the three feeders is drastically reduced.

Swells

Swells occur due to single-phase faults. In this case the voltages between the healthy phases and earth at the fault location are raised to the phase to phase voltage. Depending on the applied network earthing, this voltage might decrease towards the substation. In general, all components in the MV network are dimensioned on the possibility of these swells. The swells are caused by the zero-sequence voltage. As the primary winding of the MV/LV transformer is a Δ winding, these swells will not be noticed on LV level. As shown in Figure 3.15 the effect over the network depends on the earthing philosophy.

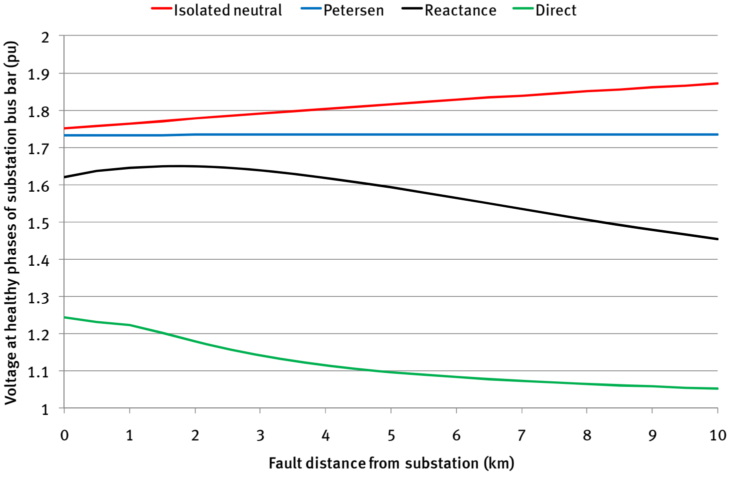


Figure 3.15 Calculated voltage noticed on the MV (10 kV) busbar due to a single-phase fault as function of fault distance for different types of earthing

In networks with isolated neutral or Petersen earthing the voltage (which equals the phase to phase voltage) is almost independent of the fault location. In directly and impedance earthed networks the voltage rise decreases as the distance between the fault location and the substation increases.

Transient voltages and currents

Specific transient phenomena may occur in case of earth faults. One of these phenomena is that when an earth fault happens, transient phenomena can be observed in all phase voltages and in the current of the faulted phase. These transients occur, due to the phenomena of discharging the capacitances of the faulted phase, and charging the capacitances of the healthy phases. The transients have a frequency larger than the normal power frequency.

In networks with isolated or compensated neutral, these transients can be large [NIKA 001]. A large value of a transient voltage may cause high electrical stresses in the insulation material, resulting in extra ageing and possible breakdown. The large value and the high frequency of the transient current can result in a fast zero-crossing of the fault current, which may result in spontaneous fault-clearing. The zero-crossing of the fault current most probably occurs at the maximum value of the zero-sequence voltage. Therefore, a large residual (zero-sequence) voltage remains in the system. The magnitude of this voltage decreases in time, due to leaking resistances, together with the impedances of cables and lines. If the leaking resistances are large, the magnitude in voltage decreases slowly. In case of such a spontaneous fault-clearing, after a half cycle the voltage of the "weak" phase relative to earth will reach a value close to twice the normal line to neutral voltage, added on the remaining zero-sequence voltage. This increases the risk of a re-strike. This re-strike results in new transients, and in case of fast self-extinguishing of the fault, in a larger zero-sequence voltage. If this sequence of re-striking and self-extinguishing repeats, large over-voltages in the system occur [ANGE 001].

These phenomena are in practice observed in the fault location project described in chapter 5. Figure 3.16 shows the current in the faulted feeder and the voltages on the substation busbar, during an extinguishing and re-striking sequence of a single-phase fault in a network with isolated neutral.

The fault starts at t=72 ms. A transient in the current, followed by a steady-state fault current can be observed during the first half period. The busbar voltage of the faulted phase is almost zero. At the zero-crossing of the fault current, the fault extinguishes and the voltage on the faulted phase starts to increase. At t=88 ms, the fault re-strikes. The transient in the fault current results in a fast extinguishing of the fault. At this moment large changes in the voltage can be observed. Five more occurrences of re-striking and self-extinguishing can be observed. In all phases, rapid voltage changes of more than 14 kV in less than 1 ms occur. The phase to earth voltage of all phases reaches values of more than twice the normal phase to earth value. A peak value of more than 20 kV can be noticed. The transients and high voltages will be noticed in the whole MV network and can result in degradation of insulation. This increases the risk for new faults. These faults can occur on a different location, which may result in a cross-country fault.

The effect of earthing on these transients is shown in appendix F. It shows that the risk on these transients is large in case of networks with isolated neutral or compensated neutral. In these networks the leaking resistances are small. In networks with impedance earthing and direct earthing the risk of self-extinguishing and re-striking is limited. In these networks the transient currents are smaller than the steady-state fault current. Therefore, these transients cause no extra zero-crossings, so self-extinguishing of the fault is not possible.

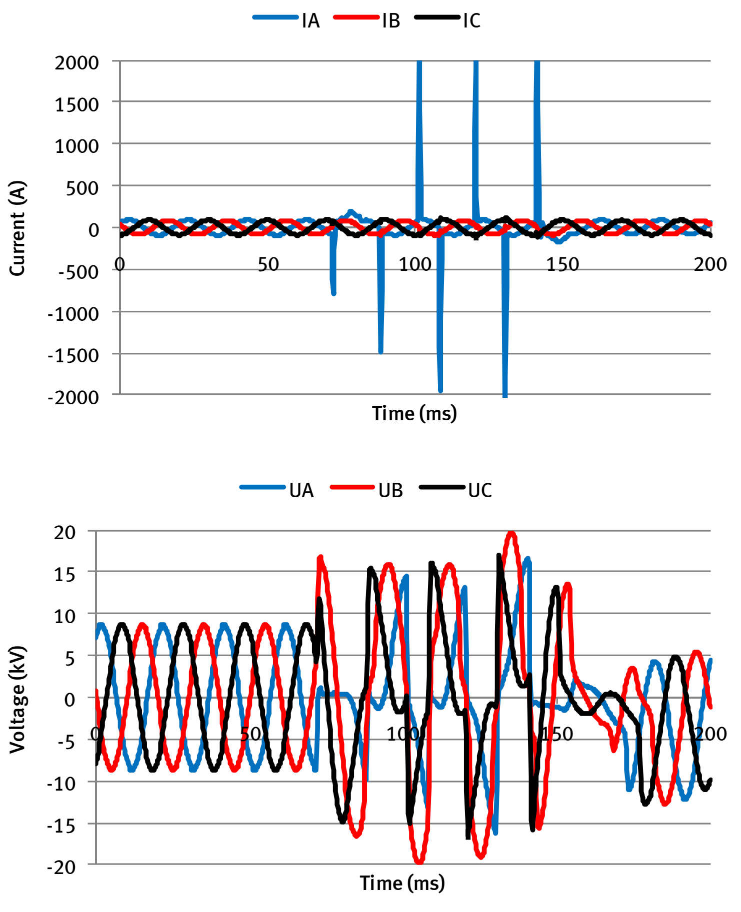


Figure 3.16 Measured current in the faulted feeder (top) and voltage at the substation busbar during a self-extinguishing and re-striking fault in a network with isolated neutral

Safety

When a phase to earth fault occurs in the MV grid, the fault current will return partly through the sheaths of the MV cables and partly through the earth. The current to earth is injected in the earth electrodes of the MV/LV transformers. This will result in a rise of the neutral voltage of the MV/LV transformer, which can cause safety problems in the LV network, especially when a TN system is applied. The voltage depends on aspects like:

- The magnitude of the earth fault current;
- The number of earthing points (MV/LV transformers) in the MV network;
- The resistance of the earth electrodes;
- The type of cables;
- The local (unknown) earth electrodes.

The voltage is the product of the fault current to earth and the impedance of the local earth. This local earth is not limited to the local earth electrode. Many aspects reduce this impedance. Sheaths of MV and LV cables are connected to this point. The sheaths of PILC cables have multiple contacts with the earth and therefore act as extra parallel impedances [BUSE 001]. The sheaths of LV cables are connected to earth points like public lighting. The low-resistance copper sheaths of XLPE cables connect the earth electrodes of neighbouring transformers creating a multi-earthed network. Measurements and calculations ([WAES 001] [POPO 001] [HALK 001] [ERP 001]) show that in these multi-earthed networks safety problems can be managed even in impedance earthed networks.

Influence of distributed generation

Rotating machines like CHP and wind turbines increase the amount of both the dynamic and the stationary short-circuit current. Especially in substations which were designed without taking into account of possible DG, this may cause problems.

Many distributed generators operate on a voltage below 1000 V. They are coupled to the MV network with a transformer. The MV windings of this LV/MV transformer are connected in Δ. This means that single-phase faults in the MV network may not be noticed by the generator protection, and the generators will not switch off. When the fault results in a trip of the circuit breaker in the MV network, island operation is created. This may cause safety problems.

The impact of distributed generation will be discussed in more detail in chapter 6.

3.2.5 Disturbances in LV networks

Short-circuit currents

Short-circuits result in high currents when they appear at the beginning of the network. Due to the direct earthing of the MV/LV transformer the short-circuit current of a single-phase fault close to the transformer can even be larger than the short-circuit current of a three-phase fault, as stated in IEC 60909. When the fault occurs towards the end of the network, the short-circuit current reduces significantly. However, also these faults must be switched off in due time. This may set requirements on both cable length and protection. The protection must switch off faults from the beginning up to the end of the network. The fault current due to a fault in a customer’s installation close to the MV/LV transformer can be much higher than the fault current due to a fault at the end of the LV network. This can result in problems for the protection regarding selective switching.

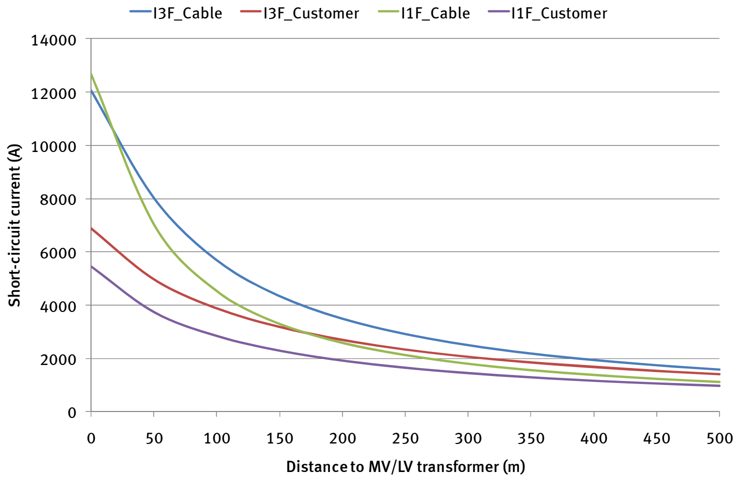


Figure 3.17 Calculated short-circuit current in an LV network

Figure 3.17 shows the short-circuit current due to a fault in the LV network and due to a fault in a customer's installation connected with 10 m of cable to the LV network. The LV cable protection has to switch off faults at the end of the network (1100 A) in due time. A single-phase fault in the customers connection close to the MV/LV transformer results in a short-circuit current larger than 5 kA. Even a fuse with a rated current of 250 A will act on this current in less than 2 periods. This tripping can be avoided by increasing the length of the connection cable for customers close to the transformer. When the network length is increased to 30 meters, the short-circuit current is less than 3 kA and a selective protection is established. This increase of the connection cable length will only have little influence on the voltage quality for the customer.

Safety

In LV networks single-phase faults result in fault voltages on the neutral and/or the PE conductor. In cable networks, the magnitude of these voltages increases with faults towards the end of the network. Fault voltages cause touch and step voltages in the network of a customer connected to a TN network. The higher the magnitude of the touch and step voltages, the faster the fault must be cleared. This means, that for safety reasons, faults at the end of the network must be switched off faster than faults in the beginning of the network. However, the fault current decreases towards the end of the network, resulting in longer times for protection actions (mostly fuses), to clear the fault. This conflict leads to limitation of cable lengths. With the introduction of TN earthing, limiting of the length of LV feeders is of major concern. Developments in fuses made it possible to use lengths of 500 m, which is sufficient for most of the LV networks [WAES 001] [PROV 009].

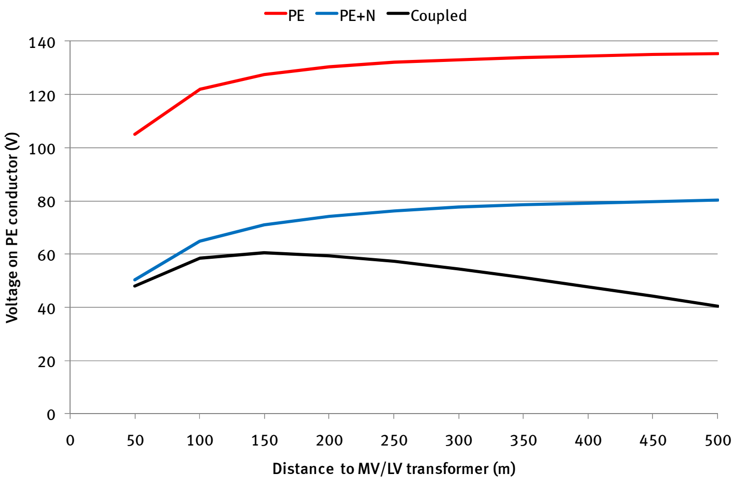


Figure 3.18 Calculated fault voltages as function of distance of single-phase to earth faults in a typical LV cable feeder, for several configurations of the return path of the fault current

The return path of the fault current influences the magnitude of the voltage at the fault location. In Figure 3.18 the distance of the fault location is varied and the fault voltage is given for three different return paths:

- Return through PE (PE);
- Return through PE and neutral (PE+N);
- Return through PE and neutral, in case that the PE and N at the end of the cable are coupled to a PE and N of another cable (Coupled).

When the neutral and the PE conductor are coupled, the fault voltage is lower than when they are separated. Coupling of the PE and the neutral conductor to another cable will reduce the fault voltages even more. This may lead to larger network lengths, but care has to be taken, because longer cable lengths also result in larger voltage variations, and higher harmonic voltages may occur.

It must be noticed that, as will be explained in chapter 4, the fault current itself is hardly influenced by this coupling to another cable.

Loss of neutral

The consequences of a loss of the neutral depend on the earthing of the system. If a local neutral is not otherwise connected to a return system, as is the case in a TT system, this local neutral will be floating. In such a situation single-phase customers will notice an interruption, since the current is not able to return. This can result in high neutral voltages, since all local neutral voltages may maximally become equal to the phase voltage. Three-phase customers may expect both over- and under-voltages, because the customer's neutral is floating and the voltages between the phases and the local neutral are based on the impedances of the different loads.

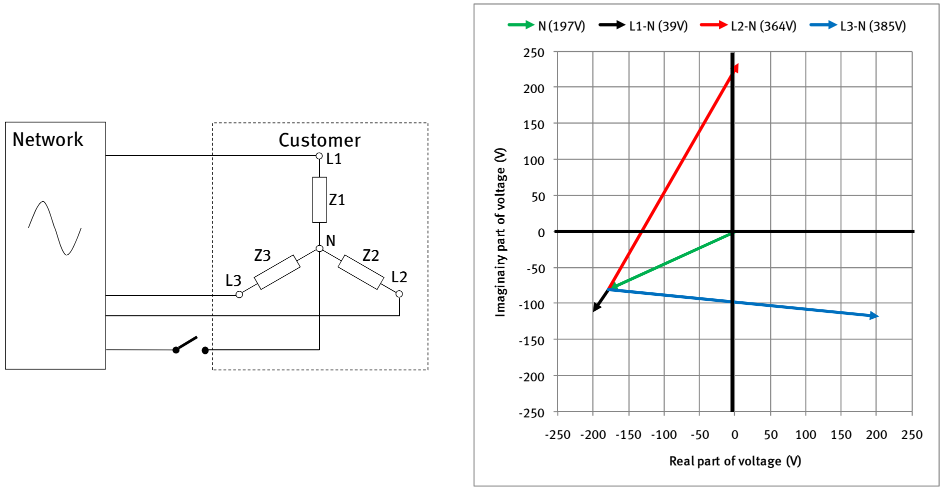


Figure 3.19 Calculated over- and under-voltages at customer's application due to a loss of the neutral

Figure 3.19 shows an example of the effects of the loss of a neutral on the apparatus of a customer with a three-phase connection. In this example, the impedance Z1 connected between L1 and N represents a resistive load of 2.3 kW, the impedance Z2 between L2 and N represents a resistive load of 0.23 kW and the impedance Z3 between L3 and N represents a load of 0.023 kW. This implies that the impedance Z1 has the lowest value and the impedance Z3 has the highest value. In case of a loss of the neutral, the phase voltages on the phases L1, L2 and L3 related to the neutral of the network transformer are hardly influenced. The voltage on the customer's neutral point related to the network transformer neutral is defined from the voltages on L1, L2 and L3 and the 3 impedances Z1, Z2 and Z3. As a result, the highest impedance gets the highest phase to neutral voltage and the lowest impedance gets the lowest phase to neutral voltage. This can be seen from the right plot of Figure 3.19. The voltage between L1 and N reduces to 40 V. The voltages between L2 and N and between L3 and N become larger than 360 V and therefore almost equal the phase to phase voltage.

As a result, in case of a broken neutral conductor, apparatus in standby mode and other low energy apparatus may be damaged, because they are exposed to voltages close to the phase to phase voltage. On the other hand, in case of a broken neutral, apparatus drawing a lot of energy will suffer from a very low voltage. In this case motors will stop due to their characteristics. Electronic equipment will switch off or might be damaged.

In TN networks, the PE and the neutral are interconnected on many locations of the network. In case of a broken neutral, the PE conductor acts as neutral conductor. The risk of a loss of both the PE and the neutral conductor can be neglected [WAES 001] [PROV 009].

Lightning

In case of a lightning stroke close to the MV/LV transformer there will be an earth potential rise of the neutral and the earthing of that transformer. This will cause a voltage difference between the objects that are directly coupled with that point (neutrals) and the objects that are not (local earthings). Local earthing is not limited to the protective earthing system of the customer. Many apparatus like television and computers are also connected to a service supplier with its separate earthing system.

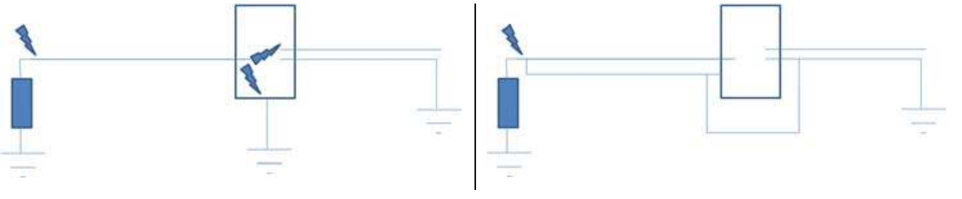


Figure 3.20 Bad (left) and good (right) EMC during lightning

Within apparatus the distance between a high voltage and a local earthing point is short. This might result in a flash-over and will damage the apparatus (see Figure 3.20 left). In TT systems the risk is not limited to television etc. Also apparatus that are earthed, like washing machines and refrigerators, may be affected. This is not the case in TN systems where the earthing and the neutral have the same voltage. When the earthing systems of the various service suppliers are interconnected outside the apparatus, the risk for damage is limited (see Figure 3.20 right). This solution requires cooperation between the different suppliers and their earthing methods. Instead of such cooperation, the different providers in the Netherlands still advise customers to disconnect their supply during lightning as the only possible solution.

3.2.6 Limiting the impact of faults

In order to limit the impacts of faults on voltage and current, the earthing system and the protection philosophy are important. The best approach depends on the type of network. For MV networks containing overhead lines, earthing with Petersen coils has proven to be a good solution. In this way the effect of the self-healing of single-phase to earth faults can be fully achieved. In MV cable networks, however, other phenomena play a role.

Reducing the amount of faults causing severe problems

The best way of limiting the impact of faults is to limit the amount of faults that can cause severe problems like:

- Voltage dips;
- High fault currents;
- Repetitive transient voltages and currents;
- Too high touch and step voltages;
- Degradation of insulation.

Voltage dips and high fault currents occur due to multi-phase faults and due to single-phase faults in directly earthed networks. Most of the multi-phase faults occur due to the fact that single-phase faults are not switched off before they develop into a multi-phase fault, as is the case in networks with isolated neutral. Repetitive transient voltages and currents occur in networks with isolated or compensated neutral. Too high step and touch voltages occur during earth faults in MV and LV networks. The magnitude of these voltages depends on the applied earthing philosophy and is largest in networks with direct earthing.

Single-phase faults in cable networks always lead to a degradation of the insulation of the cable (joint) at the fault location and on the insulation of other components in the network. Therefore, it is desired to switch off earth faults at their first occurrence. This sets requirements on the magnitude of the single-phase fault current.

- The fault current must be large enough to operate the protection.
- The fault current must also be large enough to cause enough damage on the fault location, so that the fault location can be detected by the maintenance crew.
- The fault current must be sufficiently low, in order to avoid too deep dips, to avoid too high touch voltages and to prevent large currents in the sheaths. This low current also reduces the risk of the fault to develop in a multi-phase fault.

In MV cable networks this can be achieved by applying a proper impedance earthing. In LV cable networks the number of faults causing severe problems can be limited through the following measures:

- A fast action of fuses in case of high fault currents prevents single-phase faults to develop in multi-phase faults.
- A fast action of fuses in case of high fault currents limits the duration of a dip.
- A direct earthing limits the amount of transient over-voltages.
- A TN earthing system limits the risk of a broken neutral.
- Too high touch voltages can be avoided by applying a TN earthing philosophy with limited cable lengths.

Limiting fault duration

The effects of short-circuit currents must be limited and for this the duration is an important factor. Therefore, faults have to be switched off as soon as possible. Short-circuit currents can be switched off by fuses and circuit breakers. Fuses have the advantage that they can switch off large currents very fast, sometimes even before the peak value for the short-circuit current (I_p) is reached. Fuses also have disadvantages. Over-currents are switched off relatively slow, because it takes time to heat up the wire inside the fuse.

Circuit breakers always need a certain time (several periods) before they can operate. The operation time however, is independent of the current. Therefore, a circuit breaker can easier handle the thermal stresses than the mechanical stresses (due to I_p). Furthermore, the duration of the fault is determined by the time grading of the protection scheme, leading to compromises. The choice between breakers and fuses with respect to the protection philosophy is discussed in chapter 5. The impact of fault duration is reflected in the duration of the dips in the network.

Limiting fault currents

High fault currents cause deep dips in the network. Limiting these fault currents reduces these dips. Short-circuit limiters can be used to reduce short-circuit currents. When limiting short-circuit currents, the magnitude of the current must be high enough to be detected by the protection. This means that limiting may not have much influence on the magnitude of currents due to faults at the end of the network. The standard solution for limiting fault currents is using short-circuit limiting coils. For instance in MV networks with a relatively large 150/10 kV transformer, these coils are used to limit the short-circuit contribution for the first ring main units.

A new phenomena is the short-circuit contribution of distributed generators. If standard coils are used to limit their short-circuit contribution, their impedance must be very large, which decreases the network performance. So, more sophisticated limiters must be considered. This will be discussed in more detail in chapter 6.

3.3 Conclusions

Regarding the normal operation of a distribution network, keeping the voltage within the specified limits is of major concern. This may be achieved by choosing the right combination of network components and controlling mechanisms. Over-sizing network components may be a technical solution, but it may not always be the most economical solution. In MV and LV networks, cables have a better performance than overhead lines. The relatively small margin in costs makes it possible to choose cables with larger diameters. By choosing larger diameters and reasonable cable lengths, problems with voltage and other power quality items can be reduced.

Disturbances in network parts of one voltage level may have impact on the own voltage level, but also on network parts of lower voltage levels. The impact on voltages and currents has been listed. Short-circuits have their impact on over-currents, transient currents and voltages, dips, swells, increased negative-sequence voltages, and have their impact on the safety of people and apparatus. In LV networks the loss of a neutral may cause voltage problems in customers' installations.

An earthing concept for MV/LV networks with underground cables is proposed in this chapter.

Using impedance earthing for an MV cable network reduces the risk of multi-phase faults causing large fault currents and dips. It also reduces the risk on transient over-voltages due to re-striking of cable faults.

A TN system for the LV network reduces the risk of damaged apparatus and maintains safety for people. However, care must be taken for the earthing of other service providers. This requires a cooperative solution, so that disconnecting cables during possible lightning conditions resulting in temporary non-functioning of apparatus can be avoided.

4 Evaluating and analysing tools and methods

Until the middle of the 1980's hardly any calculations were performed on LV and MV networks. Due to the one-directional power transfer and due to the lack of local computers, the network design was based on simple rules of thumb, since more or less only voltage deviations had to be considered. The introduction of local generation in the MV networks and the change towards TN earthing in the LV networks were the first reasons for the need of more calculations and calculating tools. This led to the development of company specific software such as OPTI [PROV 010].

The introduction of office automation with many personal computers was of great help. Since networks are designed for more than 40 years of operation, also economic aspects (investments, better use of assets, upgrade postponing) became more and more important.

Nowadays network calculation can't be missed for the analysing of network design and performance. These calculation programs are not limited simply to load-flow and short-circuit calculations, but are also of great help for operating and managing the network [PROV 001]. Examples are selective protection, network quality, intelligent fault location and network restoration after a fault.

In the Netherlands commonly used programs are Vision *Network analysis* for MV and HV power systems and Gaia *LV network design*. Developments described in this chapter are implemented in these programs. These programs were used for the calculations that were used in the theoretical experiments described in this thesis.

4.1 Methods for analysis in MV and LV networks

There are many types of calculations in MV and LV networks. A separation can be made between basic calculations and more advanced applications. Basic calculations are used in daily practice of network developing and planning. Applications are extensions of standard calculating tools and developed for a specific topic in network operation or network study.

4.1.1 Existing methods

Load-flow calculations

Load-flow calculations are needed to get information about voltages, currents and power flows in the network. From load-flow calculations, the violations of limits for voltages and currents can be observed. Load-flow calculations are therefore necessary for network planning, network extension and network operation.

Load-flow calculating tools often provide extra functionalities, like motor start, switching network parts, contingency analysis (n-1, n-2) and time-sequence calculations based on patterns.

Short-circuit calculations

Short-circuit calculations are performed in order to investigate the consequences of the possible short-circuit situations in the network. Important results from these calculations are the maximum and minimum short-circuit currents in the network. Maximum short-circuit currents are normally decisive for maximum thermal and mechanical stresses. The maximum and minimum short-circuit currents set requirements for protection coordination. As stated in chapter 3, short-circuits can also cause dips and swells in the voltage. Sometimes, the engineer is not only interested in the maximum and minimum short-circuit currents, but also in the currents and voltages in the network during a specific disturbance.

There are two methods used for short-circuit calculations:

- For a passive network according to IEC 60909. This method is developed for calculating by hand and is based on assumptions and simplifications. The result of the calculation fulfils the objective to have results which are generally of acceptable accuracy.
- Performing of short-circuit calculations on an active network, including generators and motors. In this situation the short-circuit is modelled as a small impedance on the fault location. The calculations are based on an actual power flow situation. As a result, also voltages during the fault can be examined. In this method it is possible to vary the fault impedance and to see its influence on the functioning of the protection. This method can be used to evaluate a sequence of faults at different points, simulating a cross-country event. Also the effect of opening and closing of circuit breakers used for clearing the fault and network restoration can be analysed.

Dynamic calculations

Dynamic calculations are performed in order to study the effects of disturbances like short-circuits and fault clearing on network stability. In daily practice, generally no dynamic calculations are carried out for medium voltage networks. This is due to the fact that:

- Stability problems seldom occur in most MV and LV distribution networks.
- Island operation is not allowed in most cases. Network operators therefore require a fast switching off of the generators in case of a fault.
- Furthermore it is hard to obtain enough information about control parameters and time constants of small generators.

Dynamic calculations regarding a system with many generators (like distribution networks with distributed generation) require a lot of calculating time.

This calculating time can be reduced with intelligent reduction of input data [ISHC 001]. The time consuming process of modelling and performing dynamic calculations often results in simplification of the networks.

Reliability

Reliability calculations evaluate the risk of the occurrence of a disturbance, the consequences of this event, and the time needed for network restoration. These calculations use failure rate of components, duration of fault location and duration of network restoration. In this way the average time of no supply for a certain group of customers can be calculated. The assumptions are not accurate enough to present an absolute figure for a certain type of network. When using the same basic assumptions however, reliability calculations can compare the influence of various aspects like network topology, protection philosophy, fault location and network restoration.

Harmonics

The increasing number of non-linear loads in electricity networks resulted in the need of harmonic calculations. Harmonic calculations can be used to investigate harmonic distortion of voltage due to the injection of harmonic currents by these non-linear loads. Each device has its own harmonic fingerprint, describing the harmonic current injections. Another function of harmonic calculations is to detect possible harmonic resonances in the network.

Normally, harmonic calculations are performed for odd harmonics, where symmetry over the phases is assumed. Therefore these calculations can be performed using the model of positive, negative and zero-sequence. The harmonic calculations for unbalanced networks, as is the case in LV networks, need a full three-phase model including neutral and earth return.

Asymmetry

Asymmetry plays an important role in LV calculations. Most of the loads are connected single-phase to neutral. This results in a current through the neutral conductor causing a non-zero neutral voltage. In dense areas all single-phase loads are divided equally over the three phases, so that this neutral transfer can be neglected. This is not the case in rural areas, feeding just a few (large) loads.

Other typical asymmetrical events are the starting of single-phase motors (causing dips) and the connection of equipment between two phases (welding equipment, motors, cooking apparatus, etc).

The introduction of residential distributed generation (PV, μCHP), connected single-phase to neutral, increases the need for asymmetrical calculations, both for load-flow and short-circuit calculations.

When calculating the influence and possible mitigation techniques, a five conductor model (three phases, neutral and PE) is necessary [OIRS 003].

4.1.2 Advanced applications

Protection coordination

Protection coordination is needed to investigate whether in all circumstances selective switching occurs when a fault occurs in the network. In radial networks this can simply be performed by comparing the different graphs of protection settings. In meshed operated networks the use of a computer is inevitable. Faults are fed from different locations and have to be switched off by more than one device. Computer analysis can help to investigate the effects of a large number of faults with varying fault resistances. Electricity utilities developed own programs to perform these calculations for MV transmission networks [ROMB 001, ROMB 002]. These programs are based on practical experiences within the company. Nowadays more general tools are available. Computer aided protection coordination can simulate different fault locations, different fault types, different values of fault resistance and breaker operation time. In this way a more accurate method is available.

Calculation of dips

Based on reliability of network components and the scheme of protection settings, it is possible to calculate the risk on dips. From the fault current it can be calculated which protection device switches off and within what time, giving the duration of the dip. Based on the reliability figures, the probability of such a dip can be calculated and aggregated for every node.

Intelligent fault location

In case of a fault in a network, its location can be estimated by using measured currents and voltages. From these data, the type of fault and the fault impedance can be calculated. By carrying out a number of short-circuit calculations in the network model, the location can be estimated, by comparing the measured impedance. The system of fault location is described in more detail in chapter 5.

Network restoration

Network restoration after a fault can be divided in several stages. A fault will be cleared by a circuit breaker. After detection of the faulted cable section, it will be isolated by opening the cable separators on both ends. Then the network between the circuit breaker and the isolated cable section will be re-energised by (manual or remote operated) reclosing the breaker. The network part behind the faulted cable section has to be re-energised by closing the separation in a normal open point. When doing this, no over-currents may occur in the rest of the network. In meshed networks this can be rather complicated. In the application an analysis of the closing combinations of NOPs in the neighbourhood of the isolated parts of the network is performed.

The result is the minimum required closing of NOPs. For every step of the program the relevant data like isolated nodes and overloaded branches can be seen.

Coupling of MV networks

In case of disturbance, maintenance or extension in an MV grid, changes in network topology are required. Cable sections have to be isolated, network openings have to be closed and new temporary network openings have to be made. In order not to interrupt power supply to the customers, some normally open points have to be closed before the cable section can be isolated. This means that temporarily two network sections are connected. When these two sections are fed by different HV/MV transformers, this will result in balancing and inrush currents from one network to the other. The magnitude of these currents is amongst others determined on the difference in voltage amplitudes and phase angles in the network and the power consumed in the network parts. The inrush and balancing currents should not trip the protection devices. And in order to create a new open point, the balancing current has to be switched off without safety risks.

By estimating the phase angle and actual loads in the two networks, the expected switching, inrush and breaking current can be calculated. If they are all below safety limits, the switching actions can be performed. In appendix G a description of this application is given.

State-estimation in an MV network with only few measurements available

State estimation is a well known function in transmission network analysis. However, in distribution systems the idea is relatively new and practical applications are not that common. One reason for this is that, contrary to the circumstances in transmission systems, in distribution networks there are no excessive measurements, but one has to rely on both measurements and statistical load models. Activities are performed on so called ‘pseudo state-estimation’ [JALO 001]. In normal load-flow calculations, the load at a certain node is based on the total load divided by the participation or diversity factor. In case of a large variety of loads this factor will vary over a time (depending on the hour, day and month). Pseudo state-estimation is estimating this factor based on the (measured) load curve at the beginning of the feeder and the (measured or constructed) load curves at the nodes. This calculating method results in a more realistic calculation of power flows and voltages in the network [WATE 001]. At this moment, calculations are performed mainly based on load curves for specific types of loads (shops, households, factories, etc). These curves can be extended towards generation profiles (wind, solar, CHP). The challenge is to obtain accurate generation profiles. A description of implementing state-estimation is given in [PROV 001]. A short description of the application is given in appendix H.

4.1.3 Differences for the voltage levels

There are characteristic differences between the networks on HV, MV and LV levels. These differences are the reason for different requirements for the calculating tools dedicated to those voltage levels. Table 4.1 summarises the most important differences. The structure of the networks on HV level is mostly meshed. Also networks on MV level with an important power transmission function may have a meshed structure. These transmission networks will also be meshed operated, ensuring the n-1 redundancy. The structure of distribution networks on MV and LV level, may be meshed, but will mostly be operated radially. This is the result of the choice for the protection system. The computing tools for HV and MV transmission networks must be able to deal with meshed structures, but the distribution network computing tools can be allowed to be developed for radial purposes only. If a distribution network can be operated meshed during short periods, it is wise to choose a computing tool that is able to calculate meshed distribution structures.

	HV	MV	LV
Structure	Meshed	Radial	Radial
Load	Symmetrical	Symmetrical	Asymmetrical
Diversity of load	Small	Medium	Large
X/R	>1	~1	<1

Table 4.1 Characteristic differences between the networks on HV, MV and LV levels

The loads on HV and MV voltage levels will mostly be symmetrical. This allows the computing tools to use a positive sequence system model for the load-flow based calculations. On the LV level, however, both the power system components and the loads may be unbalanced. In those cases a positive sequence approach may not be accurate enough for all engineering questions. When asymmetrical problems are studied, also the neutral of the network has to be modelled. This involves a full model using three phases, the neutral and the earth return.

The X/R ratio of network components such as lines, cables and transformers differ much in the three voltage levels. Whereas this ratio is larger than 1 for HV networks, it is approximately 1 for MV networks and smaller than 1 for LV systems. This means that HV networks behave mainly reactive and LV networks behave mainly resistive. MV networks have a mixed behaviour. As a result, standard load-flow algorithms, developed for use in HV calculations and based on decoupling of active and reactive power, can not be applied in LV calculations because the mainly resistive behaviour of the cables results in a very slow convergence of the traditional algorithms.

The radial operation and low X/R ratio place LV distribution networks in the so called group of ill-conditioned networks for the conventional solution methods. For solving the power flow in these networks several methods based on ladder-networks and iterative backward-forward sweeps have been proposed [JAMA 001] [JASM 001] [RAHM 001].

The asymmetry of loads in the LV networks requires a more detailed model for the cables, loads and generators. In these models the neutrals have to be included. For the neutral, per-unit values can not be used. The neutral voltages may be equal or close to zero. This makes it hard to work with classical per-unit based load-flow solution algorithms.

4.1.4 New developments

Stochastic load-flow

Different papers describe network planning using stochastic parameters [NEIM 001] [ENGE 001]. A summary of early articles (1962-1988) is given in [SCHI 001]. The problem with stochastic calculations is always the extra amount of data and calculations. A good description of how to perform a stochastic load-flow is given in [OIRS 004] [OIRS 005]. This is summarised below.

The load consists of a deterministic part (e.g. daily load profile as function of time) and a stochastic part (e.g. the random variation of the load). A stochastic load-flow calculation focuses on one specific moment, where the deterministic part remains approximately constant. The method of a stochastic load-flow calculation can be described with the example of two current sources i_1 and i_2 (see Figure 4.1).

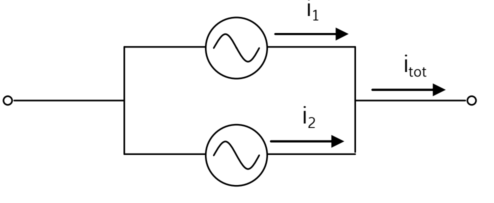


Figure 4.1 Two current sources to explain the model for stochastic load-flow

The total current of the sources equals:

$$i_{tot} = i_1 + i_2 \tag{4.1}$$

Also when the two individual currents are represented as stochastic this equation holds.

The mean value of the total current equals the sum of their mean values (the operator E is used here to indicate the mean values):

$$E(i_{tot}) = E(i_1) + E(i_2) \tag{4.2}$$

The standard deviation of the total current must be calculated from the variance. It can be proven that:

$$\text{var}(i_{tot}) = E(i_{tot}{}^2) - E(i_{tot})^2 = \text{var}(i_1) + \text{var}(i_2) + 2\,\text{cov}(i_1, i_2) \tag{4.3}$$

When both currents i_1 and i_2 are independent of each other the covariance is equal to zero. In this case the variance of the total current equals the sum of the individual variances.

$$\text{var}(i_{tot}) = \text{var}(i_1) + \text{var}(i_2) \tag{4.4}$$

When both currents totally depend on each other, their covariance equals their variance and the variance of the total current is:

$$\text{var}(i_{tot}) = 4 \cdot \text{var}(i_1) = 4 \cdot \text{var}(i_2) \tag{4.5}$$

In case there is some correlation between the currents, the variance will be somewhere in between the two values stated above.

A load-flow based on stochastic loads requires a number of calculations. Therefore the stochastic current i can be divided into a deterministic value E(i) and a stochastic value î with a mean value of zero.

$$i = E(i) + \hat{i} \tag{4.6}$$

With:

$$\begin{aligned} &E(E(i)) = c_1 \qquad \text{var}(E(i)) = 0 \\ &E(\hat{i}) = 0 \qquad \text{var}(\hat{i}) = c_2 \end{aligned} \tag{4.7}$$

The network equations written as current sources in combination with a linear admittance matrix are given as:

$$\underline{i} = Y \cdot \underline{u} \Rightarrow E(\underline{i}) + \hat{\underline{i}} = Y \cdot (E(\underline{u}) + \hat{\underline{u}}) \tag{4.8}$$

Where:

- $E(\underline{i})$ is a vector of the deterministic part of the current.
- $\hat{\underline{i}}$ is a vector of the stochastic components of the current.
- $E(\underline{u})$ is a vector of the deterministic part of the voltage.
- $\hat{\underline{u}}$ is a vector of the stochastic components of the voltage.

From this it can be concluded that the mean values and the stochastic values can be treated separately and combined by using superposition.

As a starting point, the power flow is calculated for the mean values of the current injections. The result is a mean value for the node voltages and branch currents. Next, the stochastic parts are derived. For this calculation, the network model has to be changed into a passive network without sources. All voltage sources have to be replaced by a short-circuit impedance and all current sources must be replaced by an open circuit.

For each load a separate calculation is performed. The load is replaced by a current source, injecting the stochastic current. The magnitude of this current equals the standard deviation of the load current. This results in standard deviations of node voltages and branch currents. These values must be squared in order to obtain the variance. The sum of all these variances per node/branch equals the total variance. The standard deviation is the square root of that variance.

A stochastic load-flow is implemented in the computer program Gaia for LV network design .The mean values and standard deviations of the loads can be calculated from the Strand-Axelsson/Velander values (which will be discussed in section 4.3.2). The results of these calculations are valid in both radial and meshed networks.

Economical optimisation

Once a distribution network is constructed, it has to be sufficient for more than 30 years. It is therefore not only necessary to look at the investment costs, but also to the costs of future operation. The capitalisation of the costs for losses must be taken into account. This may influence the choice for a specific cable type, since thicker cables are more expensive in investment costs, but cheaper in operational costs. As losses depend on the current, an economical break-even current can be calculated. This calculation is described below.

The costs of a cable can be divided into construction costs (C_c) and operational costs (C_o). These operational costs are the capitalised costs for the losses in the cable during the years of operation:

$$C_o = \frac{C_{loss,1}}{1+i} + \frac{C_{loss,2}}{(1+i)^2} + \ldots.. + \frac{C_{loss,N}}{(1+i)^N} \tag{4.9}$$

With i the interest rate and $C_{loss,n}$ the costs for the losses in year n. These costs can be divided in costs per kW (C_{kW}) and costs per kWh (C_{kWh}). The kW losses can easily be calculated from the square of the peak current in the cable and the cable resistance. The kWh losses are often related to the kW losses by the utilisation time ($t_{util,loss}$) of the losses [ENER 001]. The costs for the losses in year n can then be described as:

$$C_{loss,n} = 3 \cdot \left(C_{kW} + C_{kWh} \cdot t_{util,loss}\right) \cdot I^2_{\max,n} \cdot R \tag{4.10}$$

When a yearly growth of the load (a) is assumed, this equation can be written as:

$$C_{loss,n} = 3 \cdot \left(C_{kW} + C_{kWh} \cdot t_{util,loss}\right) \cdot \left(I_{\max,1}(1+a)\right)^{2n} \cdot R \tag{4.11}$$

And the total costs for a cable per kilometre can be written as:

$$C_{cable} = C_c + 3 \cdot (C_{kW} + C_{kWh} \cdot t_{util,loss}) \cdot r_{cable} \cdot I^2_{\max,1} \cdot \sum_{n=1}^{N} \left(\frac{(1+a)^2}{1+i} \right)^n \tag{4.12}$$

This results in so called economic maximum currents for the cables:

$$I_{eq,AB} = \frac{C_{0,B} - C_{0,A}}{3 \cdot (C_{kW} + C_{kWh} \cdot t_{util,loss}) \cdot \sum_{n=1}^{N} \left(\frac{(1+a)^2}{1+i} \right)^n \cdot (r_A - r_B)} \tag{4.13}$$

When the current in a cable section is higher than this value it is more economic to install a thicker cable. These economic maximum currents are smaller than the maximum thermal currents. Figure 4.2 shows some results for typical Dutch LV cables.

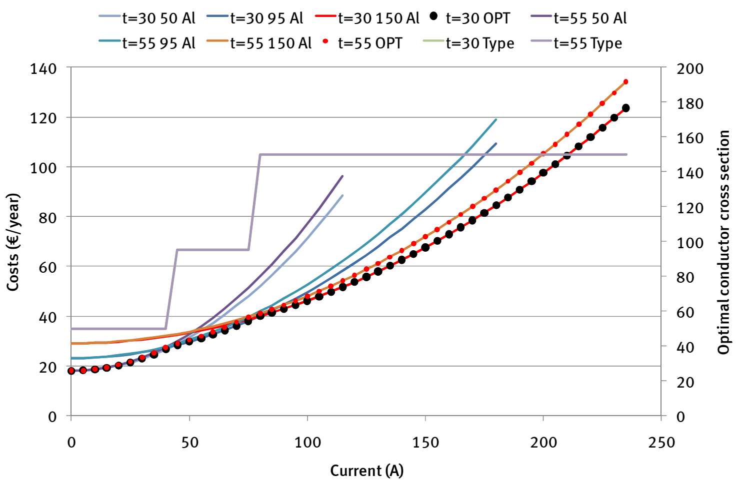


Figure 4.2 Example of the economical maximum current

The figure shows the costs for three types of cable as function of the current. The lowest costs (economical optimisation) are represented by the dots in the figure. The figure also shows the optimal cable type. Since the resistance of cables depends on temperature, the costs are given for a conductor temperature of 30°C and 55°C. The influence of the temperature on the costs is clearly visible. The optimal cable type however is not influenced by the temperature.

Computer programs using economical optimisation are described in [SUGI 001] [LAKE 003] [MACQ 001]. Also network calculation programs used in the Netherlands are based on these methods [PROV 010] [OIRS 006].

Safety in LV networks

In TN networks, the earthing system of the customer is provided by the electricity system. The earthing of the customer is connected to the earthing of the MV/LV transformer by the neutral and the sheath of the LV cable. In this way a low impedance return path for faults is established. This is described in chapter 2 and chapter 3.

In TN networks hazardous touch voltages due to faults in the LV network have to be prevented for the safety of the users. The calculation of these safety aspects is complex:

- The maximum allowed touching time depends on the touch voltage.
- The touch voltage depends on the location of the fault.
- The touch voltage depends on the return circuit of the fault current.
- The switching time of the protection depends on the fault current.
- The fault current depends on the impedances of the cable.

In case of a radial system the simplified cable model using only resistances can be used. In case of multiple return paths for the current, this simplification is no longer valid. When the PE and the neutral of two cable feeders are interconnected, a meshed return path for the current is created. The major part of the fault-current returns through the PE conductor and the neutral conductor of the faulted cable feeder. The other (smaller part) returns through the PE and the neutral of the other cable feeder. This reduces the fault voltage, but the fault current however is hardly influenced [SLOO 001]. Measurements showed that in this case both the fault voltage and the fault current differed from calculations based on the resistance model.

Further studies [VEN 001] showed that the voltage and current were not only depending on resistance, but also (mutual) inductances of the conductors inside the cables play a major role. Calculating these effects requires a complex [5x5] cable model with 3 conductors, the neutral and the PE impedances and their mutual interactions have to be taken into consideration. As utilities in the Netherlands transfer to a TN system, a nation-wide project started for a computer program for the LV network planner [OIRS 006] [PROV 011]. Also in other countries computer programs dealing with safety in networks were developed [GEMM 001].

As an example, two configurations of the same network are calculated (Table 4.2). The network consists of two parallel cables 150 Al each 500 m long. The fault is applied at the end of one of the cables.

	Resistance Method		Impedance Method	
	U_{fault} (V)	I_{fault} (A)	U_{fault} (V)	I_{fault} (A)
1 Cable	90.8	1185	80.2	1118
2 Cables	56.5	1476	40	1126

Table 4.2 Fault current and voltage calculated with a simple and a complex model

In the first case (1 Cable) there is no interconnection between the PE and the neutral of the two cables. In the second case (2 Cables) this interconnection is established. Calculations are performed using only cable resistances (Resistance method) and using the 5x5 cable model (Impedance method). With no interconnection between the cables, the results are quite similar.

The calculation of the fault voltage according to the resistance method gives a somewhat conservative result. In the case of two cables a too high fault-current and voltage is calculated when only resistances are taken into account.

Public lighting combined cables

In cable networks, the conductors used for public lighting can be integrated in the LV network cable (combined cable). The five-conductor models made it possible to calculate safety and voltage requirements for public lighting (PL). However, modelling difficulties occur, because two different cable models must be used (one for public lighting one for the LV network). This can be solved by extending the five-conductor load-flow into a nine-conductor load-flow.

4.2 Future network analysis needs

The developments in user friendly software for MV and LV grids is of great importance for better planning and operation of these networks. Several aspects require further investigation. Items regarding future network analysis are:

- New requirements regarding network design.
- Changes in the behaviour of load and generation.
- Where to find reliable and accurate data.
- Which calculations are needed.

New requirements regarding network design

The purpose of the design of a network is that the network can be operated under expected operational conditions, without exceeding limits for voltage and current. This design method is subject to several constraints like:

- Both investments and future operational costs must be taken into consideration. As a result, the possibility of temporary overloading of components, resulting in postponing necessary network extensions must also be considered.
- Power Quality sets requirements for harmonics, flicker, dips and reliability.
- Safety sets requirements regarding touch and step voltages.
- Reducing outage time puts emphasis on decreasing the time for network restoration. As in most MV and LV networks, remote switching is not common practice, this sets limits for the number of switching actions needed for network restoration.

Changes in the behaviour of load and generation

Load and generation influence aspects as voltage, current and losses. Both load and generation are subject to changes, not only in the amount but also in diversity. Many appliances become less energy consuming, but the number of appliances like computers and television sets in households increases and new appliances like heat pumps and electric transportation become more common. All these changes influence calculation parameters like the maximum load, coincidence factor and annual growth.

Distributed generation has its effect on both planning and operation, as will be described in chapter 6. Regarding network calculation, it strongly influences the worst-case scenarios. It is no longer sufficient to study the case of maximum load. In networks with distributed generation, the worst-case scenarios are full load combined with no generation and no load combined with full generation. Knowledge of coincidence of load and generation can result in less severe extreme conditions, which reduces the need for network extensions or control actions.

Accurate and reliable data

The accuracy of a calculation result depends on the accuracy of the data used. When these data can not be supplied with sufficient accuracy, extra margins must be included in the interpretation of the results. More accuracy can be obtained by a good analysis of data available from various measurement systems.

In case of planning future networks, not only today's reality but also future expectations must be considered. This not only involves expectations in growth of load and generation, but also changes in economic parameters like costs for losses and emissions. The uncertainty of these expectations and, as a result, the uncertainty around the results of the calculation increase as the time span increases.

Number of calculations

Proper design and operation of MV and LV distribution networks needs a large number of calculations. Based on hourly data, almost 9000 calculations are needed when analysing the performance of a network during one year. This number increases drastically when more years have to be analysed under various scenarios. In order to draw specific conclusions, the results of all these calculations must be analysed in depth.

This whole process of calculations and result analysis will be time consuming. The number of calculations can be reduced by introducing some assumptions, like coincidence factors and stochastic behaviour. The effect of these assumptions on the accuracy must be considered and taken into account during the analysis of the results.

4.3 Network model and available data

As stated in chapter 3, the MV and LV networks cannot be seen apart. During normal operation, the MV voltage variations will add on to the LV voltage variations. During disturbed operation, faults in MV networks may cause voltage dips and high touch and step voltages in the LV networks.

Therefore the MV network behaviour must be taken into account when planning and studying LV networks. On the other hand, the voltage limits in the LV network will set requirements for the MV network. It is however not necessary to use detailed models for all voltage levels. Equivalent network representation is allowed, as long as the behaviour of that equivalent performs as might be expected for the type of calculation.

Every type of calculation requires a specific model of the network. In general a network model consists of nodes, branches and elements with some specific features like protection. Elements like generators and loads are connected to the nodes. Branches like lines, cables and transformers are connected to two or more nodes. The amount of parameters and their required accuracy strongly depends on the type of calculation performed.

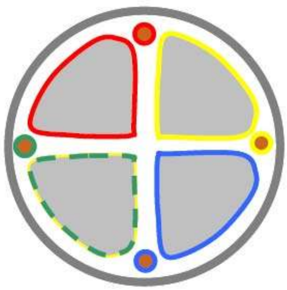
The model for calculations in MV networks can be based on positive, negative and zero-sequence parameters. For load-flow calculations only positive-sequence data are necessary. The model needed for short-circuit calculations depends on the type of fault. Three-phase faults can be calculated with positive-sequence data. Two-phase faults (without connection to earth) require an extension of the network model with negative-sequence data. Only for generators and motors these data differ from the positive-sequence data. Faults to earth (both single-phase and two-phase) require a further extension of the model with zero-sequence data. Typical values for zero-sequence data of network components are given in IEC 60909-2.

4.3.1 Modelling of LV cables

For many calculations in LV networks a model based on sequence data is not sufficient. Therefore it is more convenient to use a model in which all phases, the neutral and the PE are represented. As a result, this modelling is also necessary when combining calculations for MV and LV. In the Netherlands the LV cables may consist of 9 conductors:

- The three phase conductors;
- The neutral conductor;
- The cable sheath;
- Four small additional conductors, used for public lighting and tariff control.

The cable model must represent all these conductors and their mutual interactions (self impedance and mutual impedance). As shown in Figure 4.3, this will result in a 9*9 matrix [OIRS 007].



Z_{f1}	Z_{f1f2}	Z_{f1f3}	Z_{f1n}	Z_{f1PE}	Z_{f1h1}	Z_{f1h2}	Z_{f1h3}	Z_{f1h4}
Z_{f2f1}	Z_{f2}	Z_{f2f3}	Z_{f2n}	Z_{f2PE}	Z_{f2h1}	Z_{f2h2}	Z_{f2h3}	Z_{f2h4}
Z_{f3f1}	Z_{f3f2}	Z_{f3}	Z_{f3n}	Z_{f3PE}	Z_{f3h1}	Z_{f3h2}	Z_{f3h3}	Z_{f3h4}
Z_{nf1}	Z_{nf2}	Z_{nf3}	Z_{n}	Z_{nPE}	Z_{nh1}	Z_{nh2}	Z_{nh3}	Z_{nh4}
Z_{PEf1}	Z_{PEf2}	Z_{PEf3}	Z_{PEn}	Z_{PE}	Z_{PEh1}	Z_{PEh2}	Z_{PEh3}	Z_{PEh4}
Z_{h1f1}	Z_{h1f2}	Z_{h1f3}	Z_{h1n}	Z_{h1PE}	Z_{h1}	Z_{h1h2}	Z_{h1h3}	Z_{h1h4}
Z_{h2f1}	Z_{h2f2}	Z_{h2f3}	Z_{h2n}	Z_{h2PE}	Z_{h2h1}	Z_{h2}	Z_{h2h3}	Z_{h2h4}
Z_{h3f1}	Z_{h3f2}	Z_{h3f3}	Z_{h3n}	Z_{h3PE}	Z_{h3h1}	Z_{h3h2}	Z_{h3}	Z_{h3h4}
Z_{h4f1}	Z_{h4f2}	Z_{h4f3}	Z_{h4n}	Z_{h4PE}	Z_{h4h1}	Z_{h4h2}	Z_{h4h3}	Z_{h4}

Figure 4.3 General impedance model of an LV cable [OIRS 007]

In this matrix 4 blocks can be distinguished. The upper left block (A) is a 5x5 matrix representing the main conductors and the sheath. The lower right block (D) is a 4x4 matrix representing the additional conductors. The upper right block (B) and the lower left block (C) represent the mutual coupling between the blocks A and D. Block C is the transpose of block B. The blocks A and D are symmetrical around their diagonal. For each cable type, such an impedance matrix must be developed. The calculation of all the necessary parameters is a rather complex and time consuming matter and requires specific software.

The resistance of the conductors plays an important role in the calculations and the influence of the temperature effect on the resistance should not be neglected.

4.3.2 Diversity of loads and DG

Statistics of load and generation

For an accurate calculation there is a need for reliable load and generation data. Many load types have predictable patterns. But the pattern of distributed generation is not so easy to predict and it differs from day to day.

A stochastic load-flow might help to solve some of the problems. There are however some challenges like:

- This type of load-flow requires a large increase of the number of calculations.
- When several different types of load and generation have to be concerned, their mutual dependency (covariance) has to be investigated.
- Every load curve consists of a deterministic pattern and a stochastic variation.

For standard loads the deterministic part can be estimated as hourly values over the day. Considering generation, the deterministic and stochastic values differ per type of generation. Sometimes the deterministic part is hard to predict, as is the case for wind and solar energy. Short-term variation in wind however is small when areas covered by an MV network are considered. This means that the stochastic variation for wind is small. The production of solar energy is influenced by clouds. On days with clear sky and on days when the sky is fully covered with clouds, the stochastic variation is small. On the other days the stochastic variation depends on the amount and size of the clouds.

The generation of μCHPs depends on human behaviour and on weather conditions. Especially during the evening hours there is a spread of on/off operation in houses. When using a modulating type of μCHP, the number of starts/stops reduces and the generator runs on lower production for longer time. As a result, the coincidence factor is high as people wake up in the morning and come home in the evening. On other moments the coincidence factor is lower.

The generation of larger CHPs (mainly installed at greenhouses) depends on the production process of the plants. The plants need heat, light and CO_2. This has to be delivered in an optimal day/night sequence. Nowadays also the electricity market becomes important. Co-operations of CHP owners act as virtual power plants on spot and unbalance markets. When electrical energy is not needed for the process and the prices are high, the CHP produces energy for the market. When only electricity is needed and prices are low, the electrical energy is bought from the market.

Stochastic behaviour and coincidence factor

In low and medium voltage networks coincidence and diversity factors play an important role in calculating maximum loading situations [NAZA 001] [SARG 001] [BROA 001] [LIVI 001] [LAKE 001]. The maximum loads do not occur at the same moment. For specific load groups it can be assumed that the various loads during a peak period are normally distributed around a certain mean value. Each load for a certain moment can then be represented with a mean value and a standard deviation.

With c being a factor describing the relation between the extreme value, the mean value and the standard deviation:

$$c = \frac{Value_{max} - Value_{mean}}{\sigma} \tag{4.14}$$

The maximum value for the load of one customer ($P_{max,1}$) can be calculated from:

$$P_{max,1} = P_{mean,1} + c \cdot \sigma_1 \tag{4.15}$$

The maximum value for the aggregated load for n customers ($P_{max,n}$) can be calculated from:

$$P_{max,n} = P_{mean,n} + c \cdot \sigma_n \tag{4.16}$$

The total load of a certain number of customers can be related to the maximum load of one customer or based on the electricity consumption.

The relation based on the maximum load of one customer is described in 1956 by Rusck [RUSC 001].

$$P_{max,n} = n \cdot P_{max,1} \cdot g_n \tag{4.17}$$

Here g_n is the coincidence factor for n loads. This coincidence factor is related to the coincidence factor for an infinite number of loads:

$$g_n = g_\infty + (1 - g_\infty)\frac{1}{\sqrt{n}} \tag{4.18}$$

The relation based on electricity consumption is described in 1952 by Velander [VELA 001]:

$$P_{max,n} = \alpha \cdot \mathrm{n} \cdot \mathrm{W} + \beta \cdot \sqrt{\mathrm{n} \cdot \mathrm{W}} \tag{4.19}$$

With:

- W the yearly energy consumed by one customer.
- α, β emperical based constants

In 1975 this formula was used in a CIRED paper by Axelsson and Strand [AXEL 001]. Dutch literature often refers to this article and therefore Velander's formula is known as Strand-Axelsson in the Netherlands.

It can be shown that the formulas of Rusck and Velander are related [ENER 001].

$$P_{max,n} = \alpha \cdot \mathrm{n} \cdot \mathrm{W} + \beta\sqrt{\mathrm{n} \cdot \mathrm{W}} = n \cdot P_{max,1} \cdot g_n = n \cdot P_{max,1} \cdot \left(g_\infty + (1 - g_\infty)\frac{1}{\sqrt{n}} \right) \tag{4.20}$$

From this it follows that:

$$\alpha = \frac{P_{max,1} \cdot g_{\infty}}{W} \tag{4.21}$$

$$\beta = \frac{P_{max,1} \cdot (1 - g_{\infty})}{\sqrt{\mathrm{W}}} \tag{4.22}$$

Both the formulas of Rusck and Velander are based on stochastic formulas and can be expressed in the equations 4.16 and 4.17 [OIRS 004].

As:

$$\sigma_n = \sqrt{n} \cdot \sigma_1 \tag{4.23}$$

and

$$P_{mean,n} = n \cdot P_{mean,1} \tag{4.24}$$

Equation 4.17 can be written as:

$$P_{\max,n} = P_{mean,n} + c \cdot \sigma_n = n \cdot P_{mean,1} + c \cdot \sigma_1 \cdot \sqrt{n} = n \cdot P_{mean,1} + (P_{\max,1} - P_{mean,1}) \cdot \sqrt{n} \tag{4.25}$$

The coincidence factor g_n is then:

$$g_n = \frac{P_{\max,n}}{n \cdot P_{\max,1}} = \frac{P_{mean,1}}{P_{\max,1}} + \left(1 - \frac{P_{mean,1}}{P_{\max,1}}\right)\frac{1}{\sqrt{n}} \tag{4.26}$$

$$g_{\infty} = \frac{P_{mean,1}}{P_{\max,1}} \tag{4.27}$$

Such relations can also be developed for Velander.

$$\alpha = \frac{P_{mean,1}}{W} \tag{4.28}$$

$$\beta = \frac{c \cdot \sigma_1}{\sqrt{W}} \tag{4.29}$$

Dealing with coincidence factors

When calculations are performed using coincidence factors, Kirchoff's current law cannot be applied, as is shown in Figure 4.4.

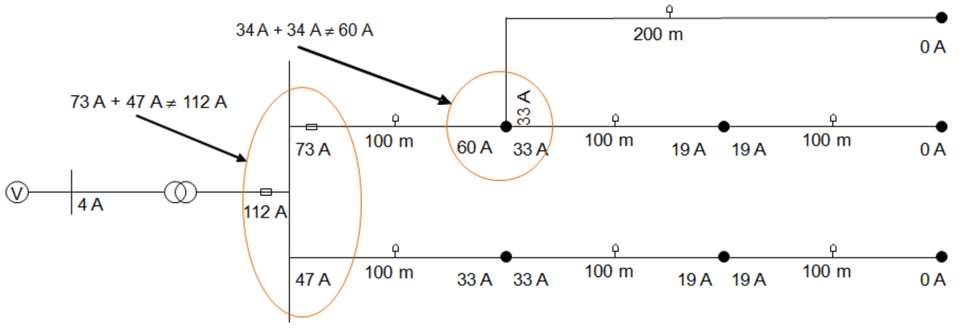


Figure 4.4 Maximum currents in a network when coincidence factors are used

The lower feeder consists of 3 sections with the same length and the same number of 5 houses. In the last cable section the maximum current is 19 A (Velander for 5 houses). In the second section the maximum current is 33 A (Velander for 10 houses). The maximum current at the beginning of the feeder is 47 A (Velander for 15 houses). In the upper feeder, the two sub-feeders after the splitting point each have a maximum current of 33 A. According to Kirchhoff this would result in a current of 66 A towards the node. According to Velander, this would result in a current of 60 A. The maximum in the two feeders is 73 A and 47 A respectively. According to Kirchhoff this would result in a current of 120 A, according to Velander this is 112 A. In order to calculate the correct values for the maximum current, special measures must be taken in the software. Examples are:

- Add invisible (negative) loads in the network. These loads must compensate the differences. This has the advantage that standard load-flow solution methods can be applied.
- Use forward and backward sweeps. First calculate the maximum currents in the network (from the back to the front), then calculate the voltage drop in the network (from front to back). Based on the new voltages the loads are adjusted and the process is continued until convergence is met.
- Use a stochastic load-flow calculation method.

The first two methods can only be applied in radially operated networks. If also meshed operated networks must be considered, as is the case in analysis tools for general purpose, a stochastic load-flow is the only solution to correctly deal with coincidence factors.

4.3.3 Necessary input data

Sequence data

Positive-sequence data for generators, transformers and cables can be provided by the manufacturer. The cable lengths and types can be obtained from geographic information systems.

Some guidelines for the negative-sequence parameters are given by IEC 60909. According to clause 3.1 of this standard, the negative-sequence short-circuit impedance (Z_2) is equal to the positive-sequence short-circuit impedance (Z_1) for network feeders, transformers, overhead lines, cables, reactors and similar equipment. According to clause 2.3.2 of the standard, the values of the positive-sequence and negative-sequence impedances can differ from each other only in case of rotating machines. When far-from-generator short-circuits are calculated, it is generally allowed to take $Z_2 = Z_1$. According to clause 4.2.2, during the initial stage of the short-circuit, the negative impedance is approximately equal to the positive-sequence impedance, independent of whether the short-circuit is a near-to-generator or a far-from-generator short-circuit. Therefore it is allowed to take $Z_2 = Z_1$ in these cases. Only during the transient and steady-state stage, the short-circuit impedance Z_2 is different from Z_1, if the short-circuit is a near-to-generator short-circuit.

Typical values for the zero-sequence data of network components are given in IEC 60909-2. Most generators operate with isolated neutral, so zero-sequence parameters are not needed. Zero-sequence data for transformers and cables can be obtained from the manufacturer. In underground cable systems, however, the zero-sequence resistance and inductance depend on the return path of the current. When the current only returns through the sheath, there is just one return path and a limited area involved. When the current returns through the sheath and earth, two return paths are created and the current can return through a large area. When comparing the return through cable sheath and earth with the return through cable sheath only, the following can be observed:

- The parallel path reduces the resistance.
- The larger area increases the inductance and thus the reactance.

In networks with isolated neutral, the impedance of the zero-sequence capacitance of the network dominates the zero-sequence impedance. Errors in zero-sequence resistance and reactance of cables have minor influence on the result. In directly earthed and impedance earthed networks a good approximation of this resistance and reactance is necessary.

Cable Data

In cable networks the resistance is an important part of the cable impedance. The resistance is a function of the core temperature of the cable. The cable resistance at an actual cable temperature T_{act} can be calculated from the following formula:

$$R_{Cable}(T_{act}) = R_{20} \cdot \left(1 + \alpha_{20} \cdot (T_{act} - 20)\right) \tag{4.30}$$

Here R_{20} is the resistance at 20^0 C and α_{20} is the temperature coefficient of electrical resistivity at 20^0 C. According to IEC 60909 the temperature coefficient α_{20} is approximately 0.004/K, both for copper and aluminium. The maximum temperature for PILC cables is 55^0 C. At this temperature, the resistance is 14% larger than at 20^0 C. The maximum temperature for XLPE cables is 90^0 C. At this temperature the resistance is 28% larger than at 20^0 C.

For load-flow calculations the cable temperature will influence the voltage drop over a cable. Worst-case scenarios are obtained by using the resistance based on the highest permissible temperature.

From short-circuit calculations maximum and minimum short-circuit currents can be obtained. The maximum short-circuit current is necessary for estimating the maximum mechanical stresses. The minimum short-circuit current is necessary for investigating the correct functioning of the protection. Calculating the maximum short-circuit current requires a low resistance. Calculating the minimum short-circuit current requires a high resistance. IEC60909 provides guidelines for cable temperatures to be used. When calculating the maximum short-circuit current, the resistances must be based on a temperature of 20^0. When calculating the minimum short-circuit current, the resistances must be based on the temperature that is expected at the end of the short-circuit period. The influence of cable temperature can be implemented in the calculation software.

Load data

The power and current consumed by a load, may depend on the applied voltage and frequency. Since in load-flow calculations the frequency is kept constant, only the voltage dependency is a part of the load model. Some loads are purely resistive, others draw a constant power and many loads have a behaviour which is a combination of both. In order to cope with this voltage dependency, different models can be applied to the loads.

Standard load behaviours are:

- Constant power: the active and reactive power of the load are independent of the applied voltage. This implies that a decrease of voltage results in an increase of the current drawn by the load.
- Constant current: the current drawn by the load is independent of the applied voltage. The power is linearly dependent of the actual voltage.

- Constant impedance: the power is quadratic dependent of the actual voltage. The current drawn by the load decreases when the voltage decreases.

In general the load representation with constant power results in the most conservative results. However, this representation may cause convergence problems in load-flow calculations, when loads are connected on the secondary side of a transformer. Standard load-flow routines are based on a repetitive sequence of the solution algorithm and an algorithm used for control actions like adjusting tap changers. This means, that the load-flow algorithm has to converge before the tap changers are adjusted. As a result, the calculated voltage on the secondary side of the transformer depends on the voltage at the primary side, the transformer tap at the start of the calculation and the current drawn by the load. When loads are represented with a constant power behaviour, a low voltage results in an increase of the current drawn by the load. This results in a further decrease of the voltage, which might be enhanced by the extra reactive power consumption of the transformer. In this way the load-flow solution might diverge. When the loads are represented as constant impedance, this effect will not occur. In cases where the voltage supplying the load is controlled at a near constant voltage, this representation is allowed. The representation of load behaviour influences the values of the calculated voltages and in this way the need for network extensions. Therefore, investigation of this load behaviour is necessary.

Coincidence factors

The correct values for the coincidence factors are not easy to obtain. A simple approximation can be based on the value of the feeder loading. This value has to be compared with the calculated feeder loading when based on the maximum values of the loads. From these two values the coincidence factor for the nodes in the feeder can be calculated. Towards the end of the network, the coincidence factors tend towards a value of one. Therefore a coincidence factor equal to one can be applied on the last few nodes, in order to obtain a more conservative voltage drop, based on the maximum load at these nodes.

The coincidence factors are based on a few representative sample measurements in the past. These values give a good result when looking at the MV/LV transformer level, but not at the single-customer level. Applying standard values will result in too low currents and thus too optimistic voltage levels. A modernisation of this approach is needed.

Also the daily load profile has changed drastically during the last years. More and more appliances, like computers and television sets, are used in households. The coincidence factor of these appliances is high.

From this it is quite easy to see that large uncertainties occur due to lack of measurements. On the other hand the costs for setting up many simultaneous measurements were too high. The implementation of electronic meters with remote reading opens possibilities for more measurements. These meters are able to store kWh data with 10 or 15 minutes intervals. These data can be used to calculate an approximation of the kW usage in that period. In this way simultaneous values for many customers will become available.

Measurement data and systems

Nowadays measurement systems in substations and in the field create large amounts of data. In many substations five-minutes averages of current, voltage and power of all outgoing feeders are available. Also from other measurement campaigns data is available. In theory it is possible to improve network performance calculation by analysing and combining these datasets. This however requires specific knowledge that is normally not available at electricity utilities.

Another problem can be the way all data is stored. Especially in companies that are a result of several mergers, data are stored in different ways on different systems. In order to make a good model, the user has to obtain information from several data systems like GIS, measurement data, user connection data etcetera, and how to deal with them.

4.3.4 Required accuracy

Calculating in LV and MV networks is associated with large uncertainties. The behaviour of single-phase generators and motors during disturbances is not well known. Formulas of Rusck and Strand-Axellsson/Velander are based on observations in the late 60's of the last century and should be replaced by actual load patterns and must take into account stochastics. Every network contains a large number of customers. In order to limit calculation times these large numbers must be represented by a few customers, resulting in the same behaviour. This reduction might depend on the type of calculation.

Load-flow calculations

The accuracy of load-flow calculations depends on the accuracy of the load data and the cable characteristics. Cables are the result of a well defined production process. Therefore accurate cable parameters per unit length can be provided by the manufacturer. However, the resistance of the cable depends on the conductor temperature. The cable lengths and types can be obtained from geographic information systems.

In order to get "worst-case results" calculations are performed using maximum load and maximum cable temperature, giving the largest voltage deviations.

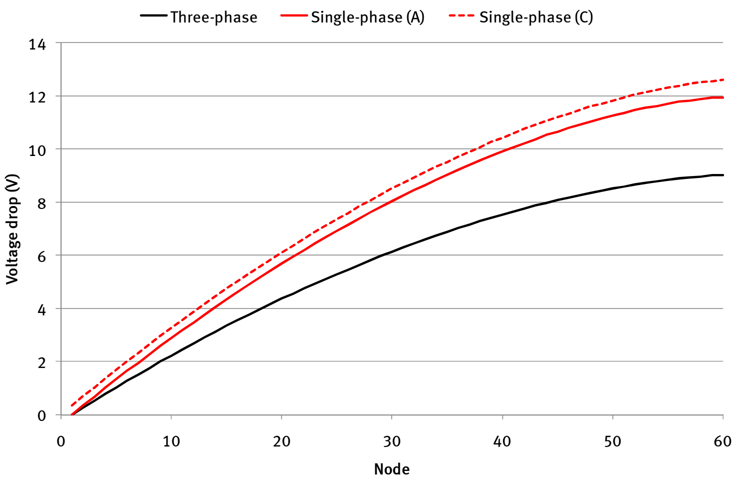


Figure 4.5 Differences in voltage drop for 60 houses connected either three-phase or single-phase.

The representation of loads in LV networks has influence on the voltage profile. When the loads are considered to be connected as three-phase loads, the loading of the cable is based on the Velander factor of N customers. So every phase is loaded with Velander(N)/3. When the loads are considered to be connected single-phase, the loading of every phase is based on N/3 customers, which is considerably larger. This influence on voltage drops is shown in Figure 4.5 for the case of 60 houses.

Short-circuit calculations

As stated earlier, the cable resistance depends on its temperature. This temperature has to be taken into account when performing a short-circuit calculation. The model needed for short-circuit calculations depends on the type of fault. Three-phase faults can be calculated with positive-sequence data. These data are normally available, since they are also used for load-flow calculations. Two-phase faults (without connection to earth) require an extension of the network model with negative-sequence data. Only for generators, these data differ from the positive-sequence data. Faults to earth (both single-phase as two-phase) require a further extension of the model with zero-sequence data

In networks with isolated neutral, the impedance of the zero-sequence capacitance of the network dominates the total zero-sequence impedance. Errors in the zero-sequence resistance and reactance of cables have minor influence on the result.

However, in directly earthed and impedance earthed networks a good approximation of this zero-sequence resistance and reactance is necessary. These values are influenced by the type of soil, neighbouring metallic objects and cables and cannot be determined precisely. Manufacturers can give suggestions, estimating that the current returns only through the sheath or through sheath and ground. Most calculation tools expect that the zero-sequence impedance of a cable is a constant value per km. In reality however these values can change depending on the fault location and the current.

In general, when earthing is involved in the calculations, zero-sequence data are necessary. These data depend on the current return path. If the current returns only through conductors like cable sheaths, the zero-sequence impedance can easily be calculated. When an earth return is involved, calculations become more complex. Several papers describe the calculation of earth return path impedances [PAPG 001] [URIB 001].

- All cable sheaths (both MV and LV) are connected to the earthing system of the MV/LV transformers. This can create return circuits over the LV network.

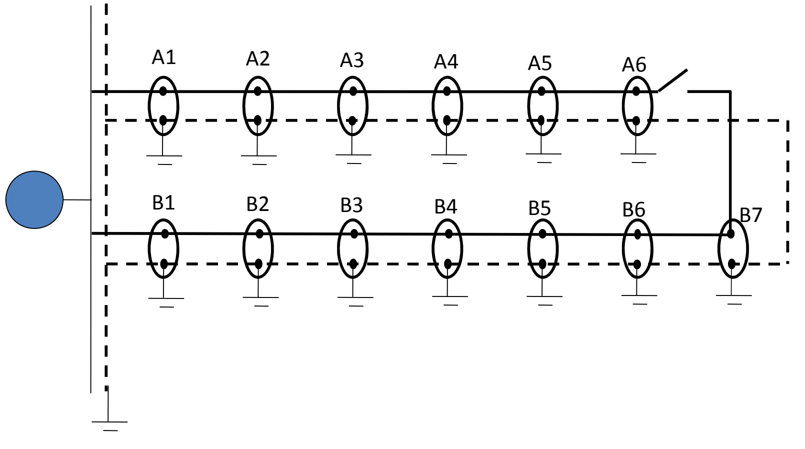


Figure 4.6 Example of a meshed earth grid. The phase (solid line) is open between node A6 and B7. The earth wire (dashed line) is not open

The sheath connections of the MV cables generate a meshed earth grid (Figure 4.6). The current can return over various paths:

- The sheaths of the MV cables. Not only directly back but also over the rest of the meshed network.
- The PE and neutral conductors of the LV network between two transformer houses.
- The earth at all earthing points.

In PILC cables there is a transfer of current between the sheath and the earth everywhere along the cable, making everything even more complex.

The impact of these items depends on the location where the fault occurs. As a result, the zero-sequence impedance of a cable is not a constant value per km, as is always assumed in the calculation models. In general one can say that when earth is involved, the cable model is always wrong. It is hard to predict the exact return current distribution. It is then important to have a proper assumption, which often is the worst-case assumption. It is also necessary to know whether and in which cases the deviation from reality is important.

Safety

When calculating the effects of MV short-circuits on the LV touch and step voltages, it is necessary to know all local parameters. The distribution of the short-circuit current between ground and sheath across the cable length is a bathtub curve [WAES 001]. At the fault location and close to the substation the distribution is based on local earthing parameters. In the middle of the cable there is a kind of equilibrium based on global parameters of the cable and the soil. Measurements [ERP 001] [WAES 004] show the influence of local parameters at the fault location.

Other analysing tools

When developing new analysing tools, the accuracy of cable parameters and other quantities become more and more important. Intelligent fault location in MV networks is based on measured and calculated impedances from the substation to the fault. The inductance of a cable is constant but often low when compared to the resistance. The resistance depends on the loading of the cable (influencing the temperature) and on the arc resistance of the fault. This is described in more detail in chapter 5.

4.4 Future network analysis

The future network analysis and design is characterised by frequent and multiple scenario studies. The types of scenarios and calculations are determined by the desired output data and accuracy. The next scheme appears to be sound:

- Have large amount of data available; for example hourly load data and generation data;
- Filter the necessary data and make near future predictions;
- Determine scenarios for load and generation development;
- Determine network changes in structure, components and operation;
- Define the technical requirements for the network;
- Define the economical requirements for the possible solutions;
- Calculate all scenarios;
- Analyse and evaluate the results;
- Determine bottlenecks and correct the possible solutions;
- Repeat the procedure until the result is satisfactory.

The network engineer has to develop reliable scenarios. The software to be used to analyse the scenarios must be fit for repeatedly processing input data, executing a vast series of calculations and processing the results. A number of analysis, like n-1 and n-2 checks and load pattern evaluation, will be available as standard functions. Also the computing tools must be flexible enough so that repeated actions, alterations and reporting can be programmed by the network engineer.

Ultimately, this also paves the way for intelligent power system operation. An on-line load-flow calculation describes the actual situation. Previous period measurement data and calculation results are used for the estimation of the network components maximum dynamic load. For the prediction of loads and generation, especially μCHP and wind power units, the weather forecast is used to tune the short-term load-flow prediction. All possible congestions and voltage violations have to be signalled in case of normal and disturbed operation. The development of autonomous controlled networks will profit from the availability of relevant input data and fast analysing tools.

In combination with fault location tools, this will speed up also the restoration process, especially in the cases where an emergency current (temporary overload) is needed.

4.5 Conclusions

Calculating methods originally were developed for use in HV network studies. Gradually these methods migrated to advanced tools for MV and LV network models. Power distribution systems have a totally different scope of study than power transmission systems. For example, stability problems seldom occur in distribution systems but power quality problems are of growing importance.

Modern applications are based on the traditional load-flow and short-circuit calculating methods. They combine available data and extended network models in selectively repeated calculations. Their output is tuned to the questions for network analysis, design and operation. New applications are developed for protection coordination, dips evaluation, fault location, network restoration, closing normally open points and MV network state-estimation.

There are characteristic differences between the power systems of HV, MV and LV levels. These differences are the cause of specific calculating tool requirements for each voltage level. One of these requirements for LV calculations, concerning the large diversity of loads, led to the development of a stochastic load-flow. Also economical optimisation is a specific LV calculating tool. The concern of safety for customers and the combination with public lighting led to the development of a new extended cable model. One of the main items was the complexity of understanding the return path in a system with multiple contacts to earth.

5 Protection, substation automation and fault location

The main purpose of power system protection is to prevent damages and safety risks for both equipment and people during a fault in the network. In a well protected network the thermal effects and the dynamic forces of short-circuit currents on the network equipment will be limited.

For adequate protection, data have to be gathered and exchanged. These data are mostly related to specific fault events. While doing this the on-line measurements during normal situations are not processed. However, modern central applications require such detailed information, representing the actual status of the network. Early projects failed economically, because HV techniques were copied in the MV systems. Use of standard equipment in each bay, like has been done in HV substations is an extensive and expensive process. As an example, in the case of the power system of Alliander (a Dutch network operator [ALLI 001]), investments must be made in approximately 200 HV/MV substations with a mean number of 20 feeder bays each.

Substation automation based on an alternative approach, like with the SASsensor technique, makes substation automation feasible for MV and LV power systems. By using a compact and straightforward measuring method, the on-line data become available for processes like protection. Where up to this moment each function in a substation needed its own device, each containing a separate processor, nowadays this automation can be performed on only a few computers.

The data also become available for processes outside the substation. In early days the data communication was a bottleneck, but in time the speed and the reliability have been improved and the possibilities have been increased enormously. Available data can be used for processes like fault location and state estimation. Fault location is an example of an application that uses measured data for protection purposes inside the substation for a totally different application outside it.

5.1 Protection

5.1.1 Protection philosophy

A protection philosophy describes the way to protect the network and its components. There is a mutual dependence between protection philosophy and the design of the network. Aspects to be considered are:

- The way of clearing a fault (fuses, circuit breakers).
- The type of protection to be used (e.g. maximum current, distance, differential).
- The number of set-points for the protection and their corresponding values.
- The application of automatic reclosers (normally not applied in cable systems).
- The maximum number of switching actions necessary to isolate a faulted network section, taking into account malfunctioning.
- The way of restoring (parts of) the network, automatic vs. manual switching.

It is also necessary to know which fault currents have to be switched off. Large fault currents (due to multi-phase faults and earth faults in directly earthed and impedance earthed networks) have to be switched off as soon as possible. Small fault currents (due to single-phase faults in networks with compensated or isolated neutral) do not require switching off, as long as their impact on the network and components is negligible. Temporary over-currents (due to inrush, motor start, switching actions) must not be switched off. Stationary over-currents (above thermal limits of components) must either be switched off by the protection or reduced due to actions by the network operator.

Faults can be switched off by fuses and by circuit breakers. Fuses operate due to the current. Circuit breakers are operated by signals obtained from relays. More details about fault interrupting devices, relays and protection of specific equipment is given in Appendix I.

5.1.2 Protection of MV and LV networks

MV transmission networks

MV transmission networks consist of parallel (cable) circuits and are often configured in a meshed way. This implies that clearing a fault must be performed by at least two switching actions. When the transmission network consists of only parallel cables, a simple protection scheme can be applied. This protection can be based on:

- A differential protection. The currents on both sides of a cable are compared, both in magnitude as in direction. When these currents differ, the protection trips the circuit breakers on both sides of the cable. This type of protection requires fast communication. The reliability of the protection therefore also depends on the reliability of this communication.

- A distance protection. On both sides of the cable a distance protection is applied. The first stage of the distance protection covers about 80% of the cable, so the main part of the cable is immediately switched off by both protections in case of a fault.
- A combination of distance protection and over-current protection. When at the HV/MV substation short-circuit limiting reactors are used in the beginning of the feeders, the protection on this part might be equipped with an over-current protection. The distance protection on the opposite side of the cable has its first stage of protection up to this reactor.

Sometimes a solution based on energy direction relays is proposed instead of distance relays. Practical experience shows that this solution can result in false tripping, especially when a fault occurs close to the protection. In these cases the voltage is almost zero, and the protection cannot decide the proper direction. Distance relays are often supplied with more sophisticated software, that extrapolates the pre fault voltage. In this way a good approximation of the direction is obtained.

When the transmission network has a more complex structure, a standard protection scheme can not be declared. The protection scheme depends on the protection philosophy of the network company. In general the coordination of the protection devices is a complex matter. This can however be supported with computer software as described in chapter 4.

In many MV transmission networks single-core cables are used. Here the most common fault is a single-phase fault. For these types of faults the impedance is not a linear function of the distance, because the fault current can return over several paths. The first path is formed by the sheath of the faulted cable towards the HV/MV substation. The second path is formed by the sheath of the faulted cable towards the MV distribution substation and the sheets of healthy phases and other parallel cables from the MV distribution station back to the HV/MV substation. This might result in improper functioning of the distance protection.

MV distribution networks

The radial operation of the MV rings results in a simple protection philosophy. The main strategy protecting MV-grids is to ensure maximum protection at minimum total cost [ANDE 001]. At the substation, all off-going feeders are equipped with a circuit breaker, which is triggered by an over-current relay. Based on mechanical (fixed time) relays, two sets of currents and corresponding times can be distinguished:

- Large short-circuit currents (I››, t››). The current has to be switched off as soon as possible (t››). If selectivity is not required, a current exceeding I›› may be switched off immediately. The value of I›› is based on the minimum expected fault current due to phase to phase faults in the cable section between the substation and the next protection.

- Small short-circuit currents (I›,t›). Currents exceeding I›, will cause damage to the equipment. The time t› must be chosen in such a way, that temporary currents exceeding I› will not result in switching off. The current I› is chosen, based on the lowest nominal current of the cables being protected. In general, a factor of 1.25 I_{nom} is chosen, in order to avoid tripping due to temporary over-currents and due to harmless fault currents caused by single-phase faults.

When a part of a network is protected by more than one protection device, selectivity of the protection devices is required. This selectivity can be obtained by time grading. As a result, faults being switched off by the HV/MV substation protection have the longest duration. These faults include the faults close to the substation, which have the largest fault currents and will cause the most severe dips.

Modern protection devices may have a third set-point (I›››, t›››). In this way faults close to the substation can be switched off fast. However, selectivity with other protections is required.

In the Netherlands most of the MV ring main units are based on a standard compact unit (Magnefix), having three connections:

- Cable-in;
- Cable-out;
- T-off, for the connection of a transformer or a cable towards a sub-ring.

The cable-in and cable-out bays contain manually operated switches or separators. The switches are able to break normal load currents, but not short-circuit currents. The T-off may be equipped with a fuse or a circuit breaker, capable of switching off short-circuit currents. In this case, a so called protected bay is created. This can be used for the protection of a sub-ring.

LV networks

LV networks can be protected by fuses or by circuit breakers. In most cable networks fuses are applied. This has several reasons:

- Fuses are cheaper than circuit breakers.
- Most faults in LV networks are single-phase faults and most of the connections towards the customers in LV networks are single-phase tappings. Most of the LV circuit breakers use three-phase switching, where fuses use single-phase switching. Finding the fault and repairing it, is time consuming and can last for several hours. When all phases are switched off (three-phase switching), all customers are switched off. When only the faulted phase is switched off (single-phase switching), 67% of the customers can still be supplied.

- The reliability of a fuse is somewhat higher than the reliability of a circuit breaker. A fuse will always blow, when a too large current is applied. Circuit breakers have mechanical parts which have to move. This mechanical operation can be disturbed by the arcing that occurs during the current breaking.

Applying fuses set limits for the length of the LV network. Faults at the end of the network may result in relatively small short-circuit currents. The magnitude of this current depends on the type of cable and the length of the cable. In networks with long feeders and small cable diameters, the fault currents may be less than 5 times the nominal current of the cable. When applying fuses, it may take too much time before these faults are cleared.

In LV cable networks there is normally just one protection per feeder. The nominal current of the fuse is related to the nominal current of the first cable section in the feeder.

In LV networks where a TN system is applied, the protection has to switch off the fault not only for protecting the cable, but (as described in chapter 3) also to protect the customer against too high touch and step voltages.

5.1.3 Future developments

The standard network protection philosophy is challenged by changes in the requirements set by society. Reliability requirements may result in the need for more circuit breakers in the network and the need for remote switching. Requirements regarding power quality, safety and way of operation might result in a change of both the number and the corresponding values of the protection set-points. The introduction of distributed generation will influence the protection coordination.

Reliability requirements

In the Netherlands, faults in the MV networks have a large influence on reliability indicators like SAIDI and SAIFI, etc. Reducing these index figures is possible by:

- Reducing the amount of customers affected by a fault.
- Reducing the outage time of the affected customers.

Reducing the amount of affected customers is possible by applying more circuit breakers in the network, with proper selectivity criteria. Reducing the outage time is possible with remote switching.

The price of protection bays for compact switchgear is decreasing. As a result, not only the T-off but also the cable-out bays can be equipped with protection. In this way more switching facilities can be created.

Remote switching requires communication, which increases the costs. However, this communication can also be used to send more network related information to the control centre, resulting in benefits.

Requirements for Power Quality

Voltage dips due to two- and three-phase faults, were up to now not an issue in protection philosophy. Observations from measurements however show that some dips due to faults close to the substation last longer than the maximum allowable time for that dip according to the ITI(CEBEMA) curve (Figure 5.1). These observations are visualised as dots below that curve.

In general it can be stated that the consequences of a dip will reduce when the depth and/or the duration of the dip reduces. Protection can reduce the duration by reducing the time grading. However, without other measures this may conflict with the selectivity requirements.

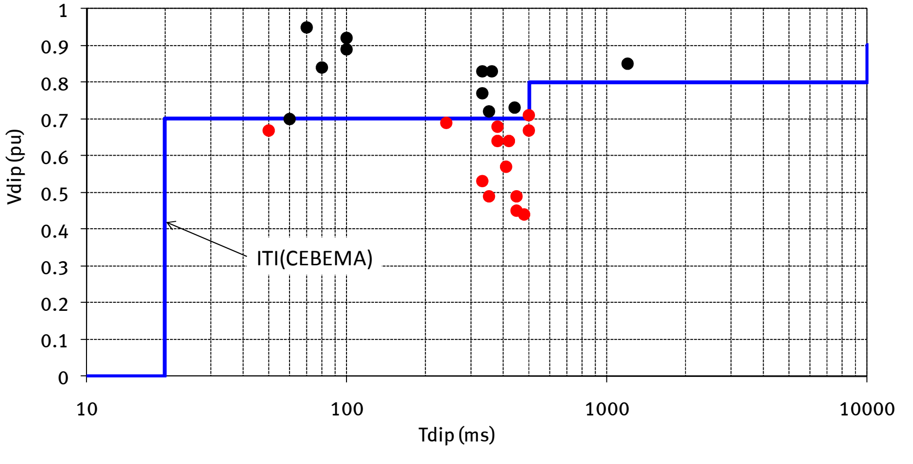


Figure 5.1 Dips recorded at substation Zaltbommel between 1999 and 2004

Requirements for safety

Faults between phase and earth (either single- or two-phase) in an MV network cause step and touch voltages in the LV network. In TN-earthed LV networks the magnitude and duration of these voltages must be kept below their permissible values regarding safety.

The duration is related to the protection setting. The magnitude of the step and touch voltages is related to the fault current. In networks with isolated neutral, the fault currents are relatively low and consequently the step and touch voltages are low. In directly earthed networks the fault currents are large, but they will be switched off fast.

In networks with impedance earthing the fault currents are moderate. Largest fault currents occur due to faults close to the substation. In general this means that earth faults close to the substation are more severe than faults further away, due to a larger value of the fault current and a larger duration due to selectivity requirements. It might therefore be necessary to change the settings of either the over-current or the corresponding duration. Conflicts with selectivity requirements may also occur here.

New requirements for safety and power quality ask for a faster clearing of faults close to the substation, as explained above. When only two set-points are available, this might conflict with the selectivity requirement. When more set-points are available (for example t›››, I›››), they can be used for fast switching of faults close to the substation.

Modern electronic protection devices have the possibility to implement more set-points for current and corresponding time. In this way several specific tripping and warning currents can be defined like $I_{contract}$, I›, I›› and I›››. The choice for these values and their corresponding times must be coordinated with other protection devices in order to maintain selectivity.

Distributed generation

The implementation of distributed generation will influence the protection. This is not only related to the extra contribution of the short-circuit current. In order to reduce voltage problems with distributed generation, meshed operation is often seen as a solution. This will cause a change in the protection philosophy.

The influence of distributed generation on protection philosophy is described in more detail in chapter 6. Some of the aspects that have impact are:

- False tripping of the network protection. This can be prevented by taking the direction of the current into account.
- Blinding of protection. This is most likely in networks with overhead lines and not in cable networks [COST 001].
- False tripping of the generator. Many generator protection settings are set too conservative, in order to prevent unintended islanding due to a fault in the network. A proper fault ride-through philosophy is necessary. A fault in the network may only result in the trip of distributed generation in case of unintended islanding and in case of danger for the generator. The protection of the network must be changed in such a way that fault ride-through conditions can be handled by the distributed generators.
- Meshed operation of MV networks. The fault needs to be switched off by at least two circuit breakers. Simple over-current relays are not sufficient. In some strategic locations of the network distance relays or differential relays must be applied. These relays must be directionally sensitive.

Lifetime of modern protection

New devices for protection and control are often based on electronics. Every application has its own device or combinations are made. There is a rapid development in these devices and in the components used in them. Spare parts are only available during a limited amount of time. As a result a large variety of equipment is used in the various substations. All this equipment has different interfaces, different operational functionalities and different manuals. This impedes the work of service and maintenance engineers in case of malfunctioning or changing parameters, as it can no longer be expected that they know all details.

5.2 Substation Automation

The liberalization of the energy market, the introduction of distributed generation and the increase of vulnerable power electronic equipment lead to an increasing demand for more detailed information on the distribution network performance and behaviour. There is a need for more information processing and for tools to manage and operate the distribution grid. Asset managers require information on historical loads for expansion scenarios. Operators are interested in actual loads for supervision and to support remote switching activities. The outgoing feeders of HV/MV and MV/MV substations are often the borders between different network functions and the relation with customers becomes obvious. Therefore this point is the ideal point for metering, power quality registrations and the monitoring of loads and currents. Due to the large number of feeders, this kind of automation asks for simple, cost effective and intelligent standard solutions. The fast developments in information technology facilitate visionary thinking and ideas for which manufacturers do not have a proper product yet. Several ideas have been published during major conferences [RIET 002] [RIET 003] [RIET 001]. These ideas show that many subjects are related to each other and that only an overall approach will lead to success. The state of the art for this moment is a straightforward intelligent MV automation system, consisting of smart measuring devices that communicate with a smart centralised computer system.

5.2.1 Requirements for MV automation

Power system requirements are defined by operators, customers and management. Customers require a high standard of reliability and quality. This means that outage times have to be as short as possible. Power quality aspects have to meet requirements stated by international standards and by the regulator. Operators need to act as fast as possible and want to have more data from the network in order to monitor the performance of the grid and the behaviour of the customers. Management is mainly interested in economical aspects. Therefore the automation system has to:

- Act fast on disturbances in the network, both regarding protection and restoration.
- Do constant monitoring of power quality parameters and alarming when thresholds are exceeded.
- Provide good communication between substations, dispatch centre and the rest of the world.
- Get more information from the network like loads deeper in the grid and state-estimation.
- Reduce future investments and costs of network operation.

5.2.2 Points of concern

Considering substation automation on distribution level, attention must be paid to several items. These items are not only technical but also economical. Substation automation must be implemented in many substations with many feeders. Network components like cables and substations have a long life time, often more than 40 years. The modern electronic equipment used for protection and control has a life time less than 10 years. This means that in the life time of a substation, the secondary equipment has to be replaced approximately four times.

There is an increasing demand for more detailed information of the distribution network performance and behaviour. The required information can not always be retrieved from the existing secondary installation, so new function boxes are needed. However, the costs for investing, engineering and installation of these boxes are often much higher than the benefits arising from this information.

Many automation systems consist of a large number of separate boxes with their own wiring, set-up protocols, programming language and manufacture specific properties. This will often result in inflexible, complex and expensive solutions. A lot of effort must be put in the conventional copper wiring. Furthermore the configuration and parameterisation tools can be complex, resulting in a lot of mistyping especially during the parameterisation of the built-in protection and other functions. The fact that each system is specific in a total of many substation automation systems, gives problems in maintenance and in solving minor disturbances. The future systems must be less depending on human errors and therefore have simple MMIs.

A proper EMC concept is necessary in order to prevent malfunctioning due to disturbances in the primary equipment. In case of an open arc, the copper wiring can transfer high voltage to the secondary system. This will damage the electronic equipment.

During its lifecycle the substation automation system will be subject to changes. These changes must be tested and accepted. This sets requirements on the design of substation automation systems [BALD 003].

5.2.3 Developments and implementation

Papers [RIET 002] [RIET 003] describe a new way of looking at substation automation. This concept is visualised in Figure 5.2 and based on:

- Long life time of measuring devices.
- Conversion of analogue signals into digital signals as soon as possible.
- Communication over glass fibre instead of over copper.
- Software solutions instead of hardware.
- All protection and control on redundant computers.
- Implementation of specific functionality by means of simple copy and paste.

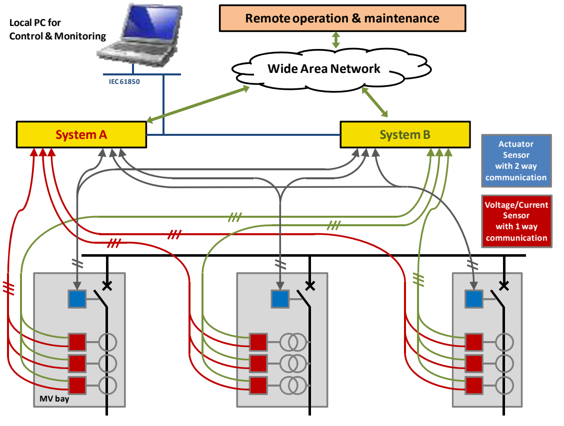


Figure 5.2 Example of tomorrow's substation automation [RIET 001]

The hardware components are smart conventional devices like circuit breakers and switches, equipped with electronics for operating and diagnostics. Smart measuring devices like current and voltage transformers produce digital signals instead of analogue signals. All data are sent to a central system, consisting of two redundant computers (visible as System A and System B), where all required functionality is implemented. The input of the computers consists of information from the smart devices. Each voltage and current sensor transmits its data through a glass fibre connection to both computer systems. The output consists of control signals towards the smart components and information about the network towards the dispatch centre and other interested parties. In this concept there is no longer a clear separation between protection and control.

The glass fibre is not only necessary for EMC purposes, but also to prevent damages to the central system in case of open arcs and other disturbances in the primary installations.

The interface with the primary installation converts the primary signals into digital information. The design of this interface is of major importance for both the life cycle costs of the total secondary installation, as well as its functional performance during the life time. If this interface can have the same functional life time as the primary components, future upgrade or refurbishment will become simple and cost effective. The interface must be future-proof, so that new required functionality can easily be installed without major adaptations to the basis.

The communication interface between the signal converters and the centralised computer system as well as the signal converters themselves, should be designed on cost effectiveness, simplicity and a long life time.

Due to the expected shorter technical life of the central processing devices on which the application functionality is being executed, these devices should be easy to replace. Furthermore, the concept should be in line with the IEC 61850 standard on the data model and the interfaces.

Development of SASensor

Based on the ideas described in the previous paragraph, a new system for substation automation has been developed. This concept is called SASensor. It is implemented and tested in 10 substations. New applications are developed based on the results of this concept. Features of this system are:

- High sampling rates of voltage and current. This makes it possible to perform harmonic analysis.
- Non-linearity in measuring transformers can be corrected with software.
- Malfunctioning of a current measuring device can be corrected by using Kirchoff's law based on all other current measurements.
- Updates can be installed from the office.

This concept is described in several papers like [BALD 001] [BALD 002] [RIET 001] [RIET 002] [RIET 003].

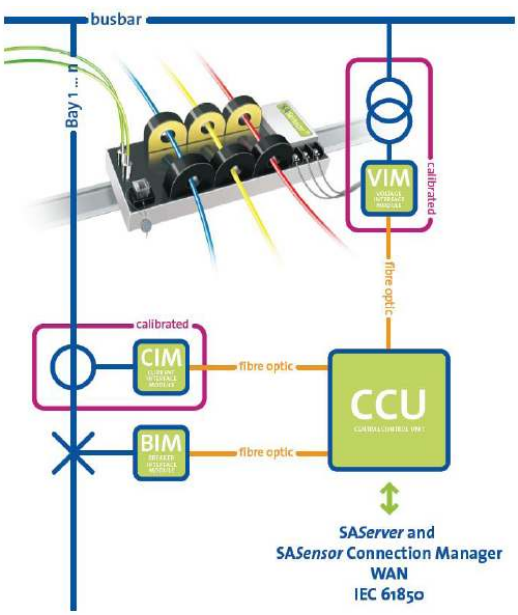


Figure 5.3 Schematic view of SASensor lay out [BALD 001]

The system (Figure 5.3) consists of a central processing unit and three types of process interface modules, one for the three-phase current, one for the three-phase voltage and one for control.

The Current Interface Module (CIM) and the Voltage Interface Module (VIM) are connected to the conventional instrument transformers (CT and VT) and convert the analogue signals from these transformers into high sampled digital data. The Breaker Interface Module (BIM) is used for position indication as well as to open/close the circuit breaker and/or other switching devices.

The central system is a “one-box” device called Central Control Unit (CCU). This CCU has a multiprocessor layout and is equipped with a flexible amount of fibre optic interfaces for sensors, actuators and Ethernet based devices. On the central level all functionality like control, protection, revenue metering and power quality monitoring is implemented.

It is simple to make a duplication of the system by using a second identical CCU. This creates a redundant system for all functionality. The system also creates redundancy for the CIM. Measurements of the current are normally performed in all incoming and outgoing feeder bays. As a result the system can calculate the sum of the currents going to and from the busbar. This calculation can be performed on a sample by sample basis. In case the measurements of one CIM, or even one phase of the CIM, are lost, the system can replace the lost sample stream by the calculated stream. The accuracy of the individual measurements is high enough to replace a missing sample stream by a calculated one. This N-1 situation is improving the availability of data and functions without extra investments in hardware.

The system has been implemented and tested since the end of 2006 in several substations. The first stage of the testing was to proof the data acquisition and to check the added functionality like power quality monitoring and fault location. The next step was the integration with protection and control which was tested in 2008. As from 2009 this system will be installed with substation refurbishment.

The SASensor system opened the way for cost effective applications like:

- Revenue metering: the system uses the CT and VT correction tables to obtain revenue metering accuracy on standard cores of any kind.
- Power quality: the sampling rates of the CIM and the VIM are high, so harmonic measurements can be performed up till the 50^{th} harmonic.
- Digital fault location: fault recording can be started by user defined events and stores sampled data streams and half cycle RMS values of all relevant process variables. The principle of fault location is described in more detail in paragraph 5.3.

- Dedicated protection: the protection system is fast enough to minimise impacts of dips and retains its selectivity with respect to remote protection in the network.
- Measurement of current and voltage: due to the correction tables, there is no longer a need to have separate instrument transformers for measuring and protection purposes.
- A detailed overview of this system including its implementation is given in Appendix J.

5.2.4 Future possibilities

Developments in information technology and (PLC) communication over low and MV networks, makes transition of automation towards LV networks feasible. This involves not only the communication to customers, e.g. automatic meter reading, but also the total grid management from substation to the LV connections.

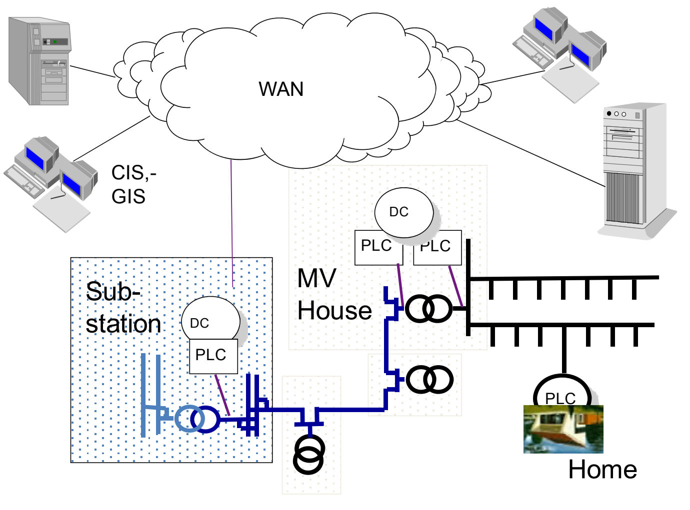


Figure 5.4 Future communication to the customer [RIET 003]

A possible way to communicate with every customer is shown in Figure 5.4. Communication between the dispatch centre and the various substations is performed over a WAN. Communication between the customers and the substations is performed with PLC technology. On various points data concentrators (DC) are installed.

Such a system opens possibilities for:

- Automatic meter reading.
- Outage time registration of every customer.
- Registration of the power quality at every point of connection of the customer.
- Distribution grid management.
- Switching streetlights.
- Load management by switching electrical boilers and other energy consuming applications.
- Generation management by controlling distributed generation.

In such a system also other signals like measurements of the pressure in the gas grid can be communicated.

5.3 Intelligent fault location in MV cable networks

Most of the outage time for Dutch utilities is caused by faults in the MV network. As shown in Appendix C approximately 65 % of all customer minutes lost (CAIDI) originate from faults on this voltage level. The duration of these faults (SAIDI) is about 90 minutes. This duration is determined by the time to locate the fault and the time for switching actions. Only 20 % of the customer minutes lost originate in the HV transmission networks. Because of the redundancy in these networks and the available network automation, these delivery interruptions can be restored quickly. The remaining 15 % originates in the LV distribution networks. The restoration in these networks may take a long time, but the number of affected customers is small. In order to decrease the CAIDI and SAIDI, priority has to be given to the reduction of the duration of faults in the MV network. One of the main items for this is the reduction of the time necessary for fault location.

5.3.1 Development of fault location

When a fault occurs in a radially operated (ring shaped) MV network a circuit breaker in the MV feeder will operate and a part of the network is isolated. The next step is to find the faulted section between two ring main units (RMUs). When this section is localised, it can be isolated by opening the switches in both ring main units. Then the network can be restored by closing the circuit breaker and by closing the normally open point in the ring.

Since the cables are buried, it is hard to tell from the outside where the fault has occurred. Therefore traditionally every ring main unit is equipped with so called fault passage devices. When a fault occurs, the fault current will trigger these devices. The restoration crew has to look in the RMUs whether the fault passage device has tripped or not. This manual finding is time consuming and can be improved by the use of intelligent fault passage devices, that can automatically dial with a dispatch centre when a fault current has triggered the device [SCHO 001]. The disadvantage of fault passage devices is that these devices can falsely trigger in networks with dispersed generation, due to the short-circuit current of the local generators ‘behind’ the fault.

An alternative way is to implement a so called intelligent fault location system that is based on:

- Calculating the fault impedance from the measured voltage and current;
- Comparing this impedance with a value obtained from calculations on a network model.

This fault impedance must be compared with the results of a set of short-circuit calculations on a model of the feeder. For each type of fault short-circuit calculations must be performed on several locations in the faulted feeder and the calculated impedance must be compared with the real fault impedance, so that an indication of the fault location can be obtained.

In high voltage systems fault location based on measured voltages and currents during a fault has been applied for many years. It was thought, that this way of fault location could also be applied in MV systems. However, because of economical reasons, feeder-dedicated fault locators are hardly used in MV networks. Instead, the fault recording function available in digital relays can be used. Under these circumstances, low-cost fault location has become feasible, as described in [ALLE 001] [SAHA 001] [PROV 002].

5.3.2 Differences between HV and MV fault location

Fault location in MV networks is much more difficult compared to the same task in HV and EHV networks. In HV and EHV networks each transmission line may be equipped with its own fault locator (FL). Generally a transmission line is a point to point connection with a well known impedance. This impedance can be implemented in the fault locator. In such a case the FL algorithm is a numerical procedure which converts the voltage and current, given in a digital form, into a single number being the distance to a fault.

Compared to the point to point connection of HV lines, there are several differences for MV feeders:

- MV feeders are multi-terminal and may contain branches. Generally there is no indication of one obvious fault position, often there are more possible alternatives.
- MV feeders contain loads. Seen from the busbar these loads are located both before and beyond the fault point. The value of the loads differs over the day and the year. Since the changes are unknown to the FL, it is difficult to compensate for them.
- MV feeders are not fixed. This means that regularly changes in the network topology occur. The feeder can be extended with new lines or cables. New ring main units may be inserted. Parts of the feeder may be switched to other feeders, either temporary (in case of a disturbance) or continuously (in case of topology changes necessary for better performance).
- MV networks may contain different types of conductors with different impedances. This makes it hard to work with a constant impedance per unit length.

Due to these differences it is not common to apply feeder dedicated fault locators in MV networks.

5.3.3 Fault location in MV distribution networks

As described earlier, an accurate calculation of the fault location consists of two steps:

- Firstly, the signal has to be analysed in order to find the type of fault and the impedance from the substation to the fault location. These elements are calculated from the voltage and current before and during the fault.
- Secondly, the impedance for the feeder and a possible fault is determined from a model of the network, based on the topology of the real network. The result of the first stage is fed into a network model where the fault is simulated in order to find the exact location. In the simulation process the calculated short-circuit currents and voltages are compared with the available measured values. The model uses the pre-fault values for the load and the position of the switches.

Figure 5.5 illustrates the data flows as used in the pilot stage of fault location at Alliander.

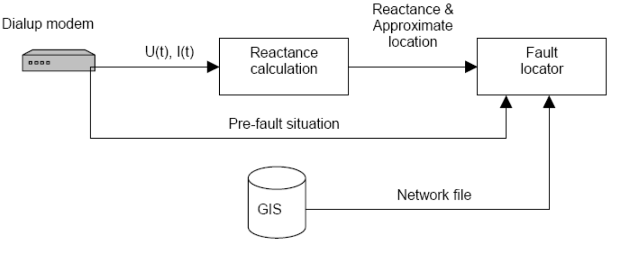


Figure 5.5 Data flows in the dispatch centre [OIRS 001]

The network model must reflect the actual situation at all times. In the ideal situation, all network data are stored in an actual Geographic Information System (GIS). Not only all network nodes and cables are stored in the GIS, but also the actual switch positions in the feeders. Every time a single setting is changed, a new network model is generated automatically by the GIS.

With the actual network model the computer program starts simulating short-circuits on all nodes in the faulted feeder. Also the information on the approximate location (main/sub/dead-end feeder) is used in this step. Depending on the feeder the number of nodes varies from 20 to 60, so this will not be a time consuming process. For all short-circuit calculations the simulated reactances, as 'seen' from the substation into the direction of the feeder, are calculated. After this step it should be possible to point out two nodes for which the value of the measured reactance lies between the values of the simulated reactances.

5.3.4 Algorithms

Several techniques for the location of faults are reported, as for example [SACH 001] [AGGA 001]. The algorithm for the first step of the fault location consists of four stages:

- Processing the signal;
- Analysing the signals;
- Detecting the type of fault;
- Calculating the fault-loop impedance.

Processing the signal

The analysis of the signal can be performed using several techniques like Fast Fourier Transform (FFT), Laplace transform and wavelets. The use of the specific algorithm depends on the sampling rate of the data and the events to be analysed.

In Dutch MV networks, circuit breakers are used for fault clearing. Normally it takes some time before the circuit breakers operate, because the protection must detect the fault and the circuit breakers need some time to operate. Therefore the duration of most faults in MV networks is at least several periods. For these events FFT techniques can be used.

After a fault occurs, the data for voltage and currents are collected in the substation and transmitted towards a computer in the dispatch centre. In order to analyse the sampled data, these data first have to be transformed into complex signals represented by magnitude and phase angle, using Fourier and symmetrical components transforms. The Fourier analysis is performed on a moving window containing a number of samples representing one period. Only the values for the fundamental frequency are needed. Using this method, the complex voltage and current time series are generated for the three phases of the faulted feeder. The resulting signals are then transformed into their symmetrical component signals using well known techniques. After this the following complex signals are available:

- Ua(t), Ub(t), Uc(t) : three-phase voltage;
- Ia(t), Ib(t), Ic(t) : three-phase feeder current;
- U0(t), U1(t), U2(t) : zero-sequence, normal and inverse voltage;
- I0(t), I1(t), I2(t) : zero-sequence, normal and inverse feeder current.

Examples of the process of transforming the measured voltage and current time series towards Fast Fourier and symmetric component signals are given in Appendix K.

Analysis of the signal

From the transformed signals the samples that are representative for the system state during the fault must be detected by analysing the complex phase voltage and phase current signals. The assumption is that all faults and circuit breaker actions generate a transition in the voltage and current signals. Each transition marks the beginning of a new system state. The system state in which the largest short-circuit currents occur, is the state that should provide the voltage and current values for the analysis. The transitions may include a fading transient behaviour, invoked by system dynamics or short-circuit DC components. These transients may disturb the calculation. In order to minimise this effect, the values are selected at the end of the evaluated system state, just before the next transition should occur. By doing this, the influence of transients should be negligible. Since the fault impedances are calculated just before the fault is cleared, local generation in the faulted feeder is assumed to be switched off. Also the influence of motors feeding into the fault may be neglected. Therefore the analysed part of the network only consists of passive elements and there is no need for information of local generation and motors. However, one should be aware of the fact that single-phase faults not always result in tripping of generators.

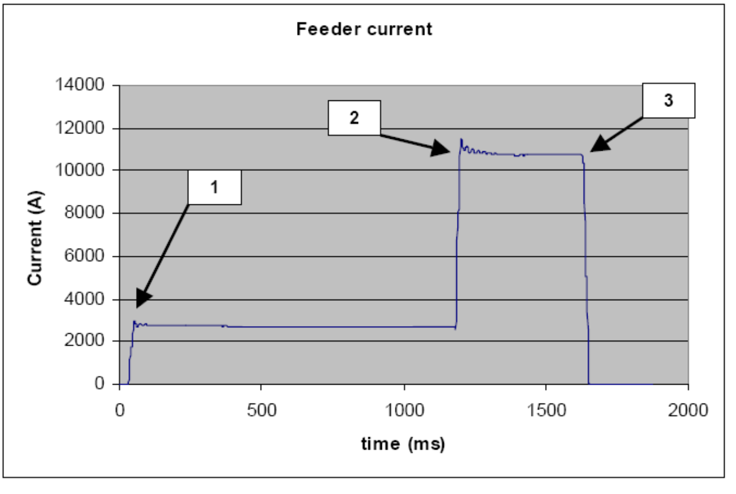


Figure 5.6 Values selection in case of a changing fault [OIRS 001]

Figure 5.6 illustrates the process of identifying the representative values for a changing short-circuit fault. In this figure a single-phase fault turns into a two-phase to earth fault before being switched off. The transitions are:

- Normal state to single-phase fault;
- Single-phase fault to two-phase fault;
- Two-phase fault being switched off.

The representative values are related to the state in which the largest feeder currents occur. The chosen values are those that occur just before transition number three.

Detecting the type of fault

The type of fault should be detected automatically using the representative voltage and current values. This is described in Appendix K. Each type of fault has a characteristic behaviour relating to the normal, inverse and zero-sequence currents. Table 5.1 summarises the characteristic properties of the different types of fault in a theoretical case [OIRS 001]:

Type of fault	$I_1 > I_{1,pre}$	$I_0 > 0$	$I_2 > 0$	$I_1 - I_{1,pre} \gg 0$	$I_2 \gg 0$
Single-phase to earth	yes	yes	yes	no	no
Two-phase to earth	yes	yes	yes	yes	yes
Two-phase	yes	no	yes	yes	yes
Three-phase	yes	no	no	yes	no

Table 5.1 Identifying types of fault [OIRS 001]

Calculating the fault-loop impedance

Opposite to the methods used in HV systems, it has to be taken into consideration that the investigated networks may consist of sections with different cable types. In such a case parameters change from section to section. According to [SAHA 001] this mainly influences the algorithm for the fault location determination. The calculation of the fault-loop impedance can use the same principle, based on voltage and current phasor estimation.

The fault-loop impedance measurement algorithm depends on whether the measurements (voltage and current) are available for the faulted feeder or only are available at the substation level (total current measured at the supplying transformer). Moreover, the algorithm depends on the type of fault.

The principle of calculating the fault-loop impedance is quite simple, especially when radial networks are considered. According to Ohm's law, the impedance from a measuring point to a faulted point is determined by the ratio of the measured voltage and the measured current during the fault. In practice however it is more complicated. It may be important to incorporate the influence of the existing pre-fault load current. Also the resistance of the fault itself is not known. According to [LEHT 001] it is recommended to disregard the resistance part of the fault impedance. Since the reactance of the fault is zero and the cable reactances are well known and not current dependent, the fault locator has to work with the reactance only and the resistance will not be used.

Calculating the reactance is based on a calculated phase angle. Errors in the calculation in this phase angle have strong influence on the value of the reactance. These errors may occur due to errors in the measurement and in the processing of the data.

In appendix K it is shown that a formula for the fault-loop reactance can be derived from the measurements for each type of fault. These formulae for the reactance are summarised in Table 5.2.

Type of fault	Reactance from substation to fault location
Three-phase	$X_{cable,1}=Im(U_{m,1} / I_1)$
Three-phase with earth	$X_{cable,1}=Im(U_{m,1} / I_1)$
Two-phase	$X_{cable,1}=Im((U_{m,1} - U_{m,1})/ (I_1-I_2))$
Two-phase with earth	$X_{cable,1}=Im((U_{m,1} - U_{m,1})/ (I_1-I_2))$
Single-phase (earthed networks)	$2*X_{cable,1}+ X_{cable,0}=Im((U_{m,1} + U_{m,2} +U_{m,0})/I_2)$
Single-phase (isolated neutral)	to be developed

Table 5.2 Impedances for the fault-loop [OIRS 001]

Good approximations can be obtained for all two- and three-phase faults in all network types, and for single-phase faults in earthed networks. In case of a single-phase fault in a network with isolated neutral, the fault current is largely induced by the overall network capacitance and not by the cable impedance from substation to fault location. In many cases these faults are not switched off, because the LV customers do not notice these kind of faults and the fault currents are relatively low. It could however be useful to derive an algorithm also for these faults, as it can help the operator to locate and isolate the fault before it develops in a multi-phase fault.

Additional information

From the registration of a fault, additional information can be obtained about the protection device that cleared the fault and about the network earthing.

When the fault is cleared by the circuit breaker in the substation, there will be no residual current in the feeder. When the fault is cleared by a circuit breaker or a fuse somewhere else in the network, there will still flow a current after clearing of the fault.

Notice about the earthing of the system is necessary for the network model used in the second stage of fault location. In case of an asymmetrical fault the impedance of the network earthing can be derived from the quotient of the zero-sequence voltage and current.

Both the absolute value and the phase angle of X strongly depend upon the earthing of the network. In earthed networks the impedance is characterised by a small inductive value, where in networks with isolated neutral the impedance is characterised by a large capacitive value.

Estimating the fault location using a network analysing program

In the second step of the fault location, the network analysis is performed. The actual network model is automatically opened and the loads in every feeder are adjusted, based on pre-fault current information. Then the short-circuit is simulated at equidistant points in the involved feeder. From the calculated voltage and current at the beginning of the feeder the impedance is calculated and compared with the value calculated in step 1. The results that match best are the most likely locations. These locations are shown on the computer screen. Relevant data are automatically printed.

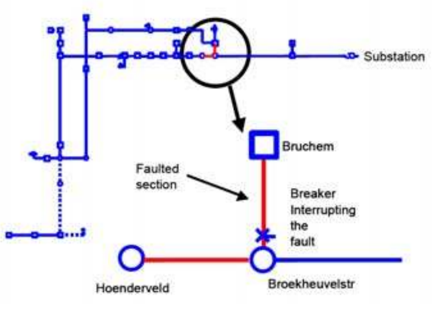


Figure 5.7 Identification of the faulted section in the network [PROV 001]

As an example, Figure 5.7 shows the results of the calculated location of the fault in a network [PROV 001]. The location module shows two possible locations (red colour):

- Between Broekheuvelstr and Hoenderveld.
- Between Broekheuvelstr and Bruchem.

The most possible location of these two can be obtained from the fault clearing time and the protection scheme. In this case the fault was not switched off in the substation, so the faulted section must be between Broekheuvelstr and Hoenderveld.

5.3.5 Practical experience

The experiences with fault location in MV networks within Alliander are described in Appendix K and are summarised here. The refurbishment of substation Zaltbommel was used to implement a pilot system based on information from protection devices [OIRS 001].

The positive experiences from this pilot system resulted in implementation of a fault location system in the substations that were equipped with the new SASensor equipment. Improvement of the SASensor system and the fault location software made it possible to correctly interpret the various registrations, and in case of a real fault, to pinpoint the location close to the real location [PROV 002].

Results

Table 5.3 shows the results for the period between October 2007 and December 2008.

Type of fault	Location			
	Recordings	OK	Adjacent	› 1 RMU
Three-phase	7	3	3	1
Two-phase	10	5	1	4
Single-phase (earthed networks)	4	2	0	2
Single-phase (isolated neutral)	5	3	2	0

Table 5.3 Accuracy of the fault location with SASensor

The first column shows the type of fault. The second column shows the number of occurrences of this type of fault. The next three columns show the accuracy of the fault location. Here “OK” means that the fault location was calculated in the same section as the real fault. “Adjacent” means, that the location was calculated in the section adjacent to the actual fault, which still is within the required accuracy. “› 1 RMU” means that the fault location was calculated more than one section away from the actual section. This result is often outside the required accuracy.

Although it is not valid to draw conclusions from this small amount of results, some remarks can be made:

- Most of the fault locations are calculated in the correct section or in the adjacent section.
- Only a few locations were calculated outside the required accuracy. This was due to two reasons. Some of the faults were far away from the substation, so specific assumptions regarding fault impedance were no longer valid. The other reason was the incorrectness of network models. For these cases, the accuracy of the results can be improved by improving the network model.
- It was expected that the location of single-phase faults would be less accurate than the location of multi-phase faults. However, this is not found in practice yet.
- It was expected, that all multi-phase faults could be located within the range of one section. This was not always the case.

- The applied algorithm for single-phase faults in networks with isolated neutral shows promising results. This algorithm is based on the same algorithm used for networks with impedance earthing.

Self-extinguishing and re-striking faults

In case of spontaneous single-phase faults, it may take some time before the fault has fully developed. Many recordings of single-phase faults show events that are self-extinguishing and re-striking, causing large transients in the current. Others show transients in the voltage that make clear that the fault is not stable. This can be noticed, not only in networks with isolated neutral, but also in networks that are earthed by means of an impedance.

In case of self-extinguishing and re-striking single-phase to earth faults, especially in repetitive sequences, the FFT will result in a smoothed registration, that looks similar to a single-phase to earth fault of different duration and different amplitude. As a consequence, the calculated values for current and voltage in these situations will result in a wrong impedance for the fault and thus in a wrong location. It is therefore necessary to add a criterion regarding self-extinguishing faults. As described in [PROV 002], such a test on self-extinguishing faults must be performed on the sampled data.

Two types of self-extinguishing and re-striking faults can be distinguished from practice:

- Faults for which the re-strike occurs more than a quarter cycle after the extinguishing.
- Faults for which the re-strike occurs within a quarter cycle after the extinguishing.

When a fault re-strikes more than a quarter period after extinction, the re-strike shows a transient current with high amplitude as described in chapter 3 and appendix F.

When a fault re-strikes less than a quarter period after extinction, the re-strike does not show a transient current with high amplitude. When zooming in on such an event, it can be observed that re-strike happens almost immediately after extinguishing. An example is shown in Figure 5.8 where the fault current (IFault) could be derived from the three measured phase currents. At t=470 ms, the fault current is zero and the fault extinguishes. From that moment the voltage in the faulted phase (UC) starts to rise. When (at t=472 ms) the voltage reaches a value near to 1.3 kV, the fault re-strikes. This can be seen in the rapid decreasing of the voltage and the sudden increase of both the fault current (IFault) and the current in the faulted feeder (IC). A same event happens at t=480 ms.

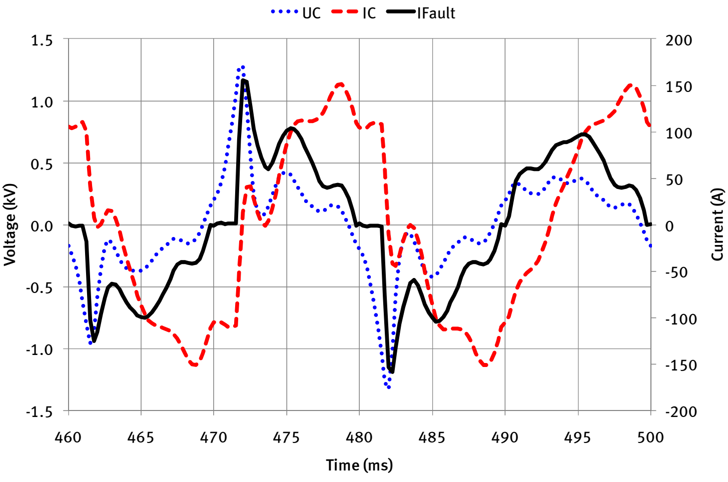


Figure 5.8 Detailed waveform of voltage and current during a stationary single-phase fault in a network with isolated neutral

It can be noticed that due to the short time between extinguishing and re-striking, the amplitude of the transient current is small. The FFT of such a signal will not result in the proper values for voltage and current. This may result in an error for the calculated corresponding impedance. Therefore this time frame is not suited for the fault location algorithm. An algorithm must find a time interval of at least one cycle, in which no extinction or re-strike of the fault occurs.

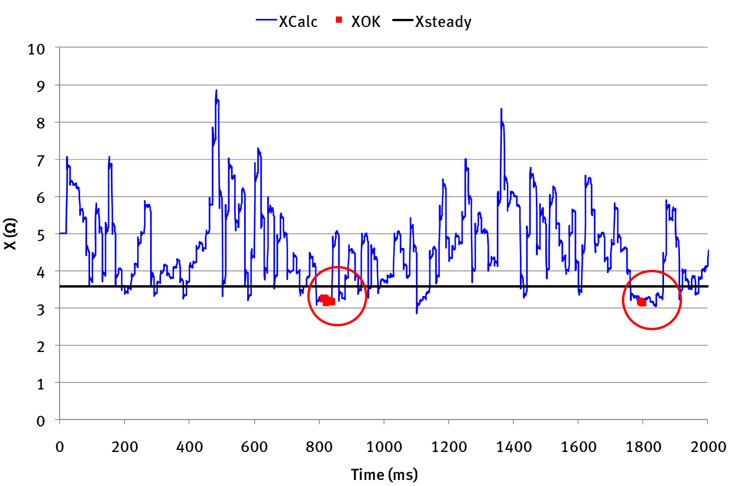


Figure 5.9 Deviations in the calculation of the fault impedance as a result of a non stable stationary single-phase fault in a network with isolated neutral.

Preliminary tests of such an algorithm show promising results, as is shown in Figure 5.9. Here the calculated impedance (XCalc) is compared with the calculated impedance of a registration at the moment the fault was stable (XSteady). The correction algorithm was able to identify two stable points for the correct calculation of the impedance to the fault location. These points (XOK) are circled in Figure 5.9.

Points of concern

A key factor for success of the implementation of software tools is a good communication between operators, developers and manufacturers. The modern software used for fault location has to be accepted for use in daily practice. It also may also involve extra training. The operators need to see the product as a useful assistance in their daily complex work and not as an extra workload. Therefore it is required that the software itself is straightforward and that its interaction with the operators is simple and clear. The amount of input data has to be minimised, the processes have to be automated and the results must be easy to interpret. For a good functioning of the programs, up to date network information is necessary. This implies special requirements for side processes like Geographical Information Systems (GIS) and the people involved.

The accuracy of the fault location method strongly depends on the correctness of the network model that is used for the short-circuit calculations. As MV networks are subject to changes, these network models must be updated on a regular basis, for instance in the geographic information system. This system is able then to generate the required network models. However, often additional data must be implemented manually, which is time consuming.

Although the fault location system is implemented as yet in 10 substations at Alliander, the number of recorded faults is not large. This means, that there are large time intervals between the operation of the fault location system, so not much experience has been gained. This may obstruct the acceptance of use in daily practice.

5.4 Conclusions

The protection of MV networks must be reconsidered, due to new developments on safety and power quality. Also distributed generation will influence the protection philosophy. It will be necessary to coordinate the protection of the network with the protection of the generators.

Besides protection there is an increasing need for more information processing and tools to manage and operate the distribution network. Two recent developments concerning substation automation and fault location are based on the research of this thesis work.

With the SASensor solution the introduction of substation automation will be straightforward, fast and economically feasible. With this system a sophisticated protection is possible. The open structure facilitates future extensions.

Secondly a new system for fault location in MV networks has been developed. This system is based on available data processing techniques. The system can pinpoint two and three-phase faults within 100 m. Single-phase faults in earthed networks can be located with an accuracy of about 500 m. The time between the actual fault happening and the calculation of the possible fault location is less than five minutes and mainly depends on the transmission time of the relevant data from the substation to the control centre. The accuracy of fault location mainly depends on the accuracy of the network model.

6 Distributed generation in underground cable distribution networks

Typical types of distributed generation like individual wind turbines, PV-systems and combined heat and power (CHP) units were implemented in the electricity networks during the last decades. In time these units grew both in size and in number. The first wind turbines had an output of 75 kW and could be connected on LV level. Nowadays wind turbines with a power of 6 MW are grouped in large wind farms and are directly connected to HV systems. Small-scale CHP units were installed in greenhouses. Also the size of these units is increasing and at the same time smaller-scale units (µCHP) are is applied at domestic customers.

The behaviour of the distributed generators depends mainly on the availability of primary sources like wind and sun and on the demand of heat. A relatively new phenomenon is that generators may be considered as a part of a virtual power plant that acts on market prices also. Therefore electricity generation by distributed generation often has quite an unpredictable nature.

Distributed generation has both positive and negative effects on the electricity system. This chapter describes the impact of the DG on a number of items regarding network performance and planning. The aim of this chapter is to describe the various issues and to find out in which cases they result in challenges for the optimal performance of a distribution network (both MV and LV), consisting of underground cables. Possible solutions have been described. It should be noted, that many of these items are inter-linked. A solution for one item may frustrate the benefits of other items. Therefore optimal solutions that minimise the negative impacts must be elaborated.

6.1 Impact of DG

Distribution systems were traditionally designed for a one way power flow from the substation towards the customers. Distributed generation changes this power flow. This can have both positive and negative consequences. The positive effects, the so called “system support benefits” [BARK 001] include:

- Loss reduction;
- Improved system reliability;
- Voltage support and improved power quality;
- Transmission and distribution capacity release;
- Deferments of new or upgraded T&D infrastructure.

In order to realize these benefits the DG units have to comply with several conditions like being reliable, controllable and being of proper size at the proper location.

Because most of the DG units are not owned by the grid operator and because their generation may depend on fluctuating energy sources like sun and wind, these conditions are not always met and this may even result in negative impacts. These negative impacts are described in many papers e.g. [HAIG 001] [HATZ 001] [LEES 001] [PEPE 001] [SAKI 001] [TRAN 001] [VU T 001] and affect:

- Voltage profile and voltage control;
- Power quality and reliability;
- Thermal limits of components;
- Balancing of loads and generation;
- Network planning and power flow management;
- Fault currents, protection, earthing and safety.

From a more practical point of view it is interesting to look at a Nordic survey [LAKE 001] which reflects attitudes towards DG by distribution system operators, as shown in Figure 6.1.

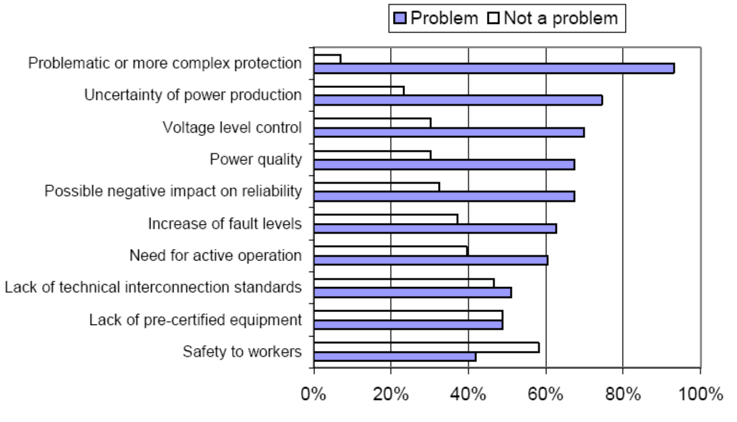


Figure 6.1 Challenges for distribution system operators (DG a problem or not) [LAKE 001]

Additional requirements for protection and uncertainties in power generation variations are found most difficult among that group of companies. Also voltage level control and other power quality issues are seen as possible problems.

In order to examine the consequences of DG more deeply, both the performance of the network during normal operation and with disturbances has to be regarded. Specific attention has to be given to power quality aspects, power flow management and to the losses and the stresses in the network. The influence of DG depends on the design and operation of the network and on aspects such as applied voltage level, types of cables and network topology.

6.1.1 Performance during normal operation

During normal operation distributed generation results in an increased variation of power flows. As a result, the voltage variations become larger, the transformer voltage control will act more frequently and the line drop compensation control is influenced.

Voltage profile

Most MV and LV networks are radially operated. The voltage profile in the network depends on the current in the network and the network impedances. In cable networks the voltage is mainly defined by the active current in the network and the resistance of the cable, as shown in chapter 3. As long as the local generation in a network is less than the normal load, there will be a power flow towards the end of the network and the voltage drops in this direction, resulting in a profile where the highest voltage occurs at the main busbar and the lowest voltage at the end of the network. However, the currents in the network and the voltage drop are less than in the situation without DG. This will result in an average improvement of the voltage profile. If the amount of generation is larger than the amount of load, the power flow reverses and the reverse flowing current in the network will increase in magnitude with more DG. This will result in a voltage rise in the network.

In general, the load and generation will not go up and down at the same time. There will be periods when the load is larger than the generation and periods in which the generation is larger than the loads. This will result in an increase of the so called slow voltage variations. These variations will be noticed most in LV networks.

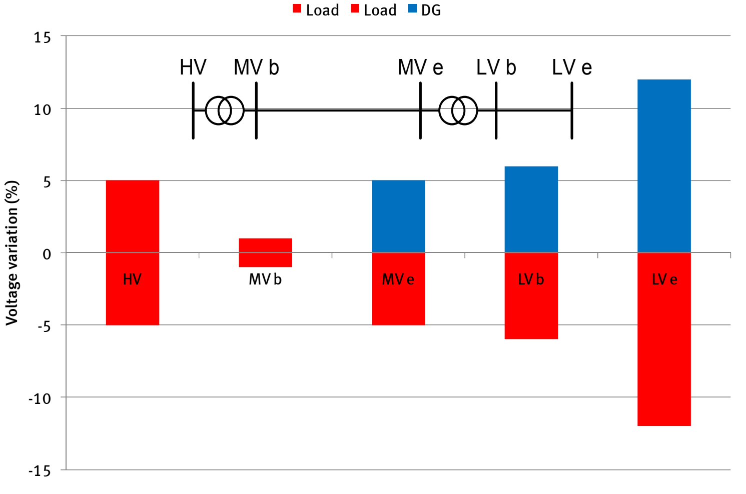


Figure 6.2 Typical voltage variations in radially operated MV/LV networks with DG

Figure 3.1 shows an example of the influence of distributed generation on the voltage variations. This figure is based on the assumptions used for figure 3.1 (in chapter 3) and on the thought that the influence of distributed generation is as large as the influence of the load. Some remarks are necessary.

The voltage variation depends on the coincidence of the presence of load and the generation of the various kinds of DG. In general, the lowest voltage will occur in a case of high load and low generation. The highest voltage will occur in case of high generation and low load. Normally there will always be some load during periods of high generation. In case of high load it is possible that there is no generation at all.

Also the simultaneous generation of various types of DG must be considered. DG units that can be expected in LV networks are solar panels and micro combined heat and power units. Maximum contribution of μCHP can be expected during the early morning and late afternoon, when many houses need to be warmed up simultaneously. During the rest of the day μCHP is either switched off or used to keep the houses on a moderate temperature. This reduces the possibility that all μCHP units are used simultaneously during this period. It can be expected, that the simultaneity of the generation between the various solar panels is large. Solar panels will produce most of the energy during the middle of the day. In countries like the Netherlands, most generation of solar energy can be expected during the summer, whereas most generation of μCHP can be expected during the winter. The possibility for simultaneous full power generation of all solar panels and all μCHP units is therefore not large.

Furthermore the amount of energy produced by DG in domestic areas is not large. This is either due to the output of generators or by limitations of the network. The output of a μCHP unit is based on the thermal need of a household and on the specific efficiency of the generator. For nowadays μCHP units the electrical output is about 1 kW. This equals the average power per household, when a large number of households is considered. Therefore in an LV network the maximum output of these μCHPs will never exceed the combined maximum load of the households. As a result the voltage rise due to μCHP will always be less than the voltage drop due to maximum domestic load. In the future other types of μCHP units may be expected. These units will be based on fuel cell technology and have a different efficiency for generating electricity. As a result the electrical output will be larger and more voltage rise may be expected.

The amount of solar energy is restricted by possible overloadings of cables and transformers. The maximum output of a solar panel is about 80 W per square meter. In principle it is possible to produce 4 kW per household, assuming 50 panels on a roof. If this is produced in all 250 households of a standard LV network, it will result in large overloading of a cable and the transformer.

In order to prevent overloading of a 150 mm^2 Al cable, the maximum amount of generation per feeder equals 170 kW (40 houses). In order to prevent overloading of a standard MV/LV distribution transformer, the maximum amount of generation in an LV network is limited to a value of around 400 kW (100 houses). Depending on the network impedance these amounts of power might result in too high voltages.

When calculating the influence of DG on the voltage level in LV networks it is necessary to also consider the influence of MV networks. Figure 6.3 shows an example of several voltage profiles in an LV feeder. This feeder has a length of 500 m and contains 60 domestic connections. It is subjected to a case of heavy load as well as to a case of large generation.

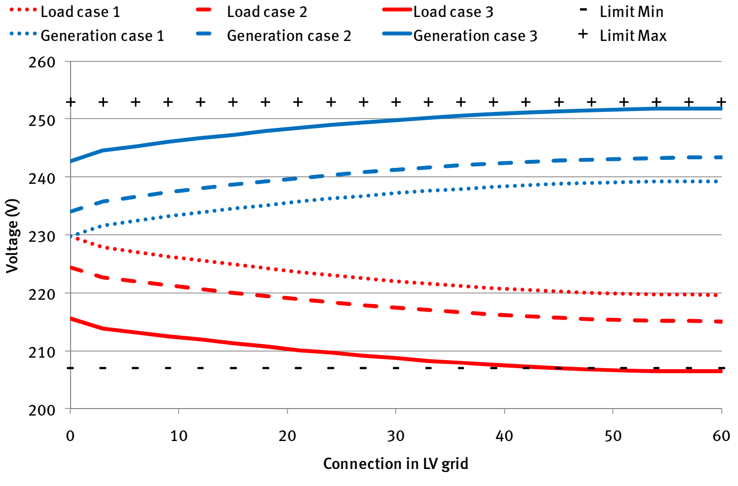


Figure 6.3 Example of voltage profiles in an LV network at high load situation and at high generation situation

This figure shows three cases:

- Case 1: the profile when the influence of the MV network and the MV/LV transformer has been neglected (dotted lines).
- Case 2: the profile when voltage drop over the MV/LV transformer is taken into account (dashed lines). This situation is representative for an LV network connected to the beginning of an MV feeder, close to the HV/MV substation.
- Case 3: the profile when also the voltage variations of the MV network are included (solid lines). This situation is representative for an LV network connected to the end of a 10 km long MV feeder, far from the HV/MV transformer.

In this example the influence of the MV network is about 5% in both directions and voltage variations up to 20% may be expected. When designing new networks, the tap changer of the MV/LV transformer should be set in a position that this variation fits in the full bandwidth of the voltage.

From this figure it becomes clear that there is a margin of about 10% for voltage variations in the LV network, when only the influence of the LV cables is considered. As a result, when LV networks are designed for a voltage drop of 6% during full load conditions, a voltage rise of 4% due to DG during low load conditions can be accepted. In networks that were designed without considering DG, the voltage drop due to high load might be chosen larger than 6% and therefore the space for DG is limited.

Voltage control

The influence of voltage control by transformers is important when line drop compensation (as described in chapter 3) is used. The local generation reduces or even reverses the power flow through the voltage regulating HV/MV transformer. Therefore the transformer notices a lower power demand. This will result in a lower set point for the voltage and thus in a lower voltage profile in the network. Especially in networks that contain a mixture of feeders with and without DG, too low voltages occur in the feeders without distributed generation. The impact depends on the compensation factor and the amount of generation. As long as the compensation factor is low and the penetration of DG is limited compared to the maximum load in the network, the influence can be neglected [PIGA 001]. In case of higher penetration of DG or higher compensation factors, the influence of the generation has to be included in the control [LEIT 001].

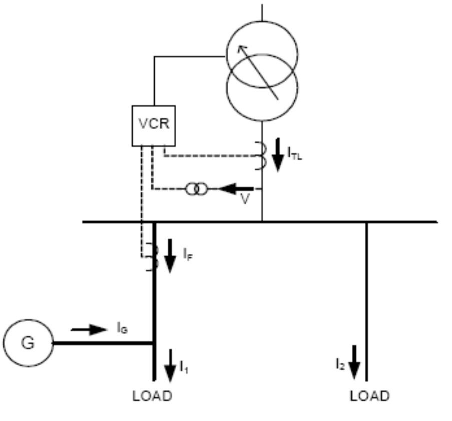


Figure 6.4 Line drop compensation where DG is taken into account [HISC 001]

An advanced line drop compensation method taking the contribution of the DG into account is described in [HISC 001]. According to this method (Figure 6.4), the transformer current I_{TL} is corrected with the current I_F in the feeder with a high concentration of DG. This method can be applied in networks that contain specific feeders with mainly generation and other feeders that contain mainly loads.

It is believed that distributed generation may improve the voltage profile, when generators with voltage control are used [FREI 001]. These units provide reactive power injection or consumption. As stated in chapter 3, to achieve this in a cable network a large amount of reactive power is required, resulting in an increase of the cable loadings and losses. Only close to a transformer this might have a positive impact. However, the reactive power increases the transformer current. In the case that the transformer is fully loaded due to active power, it is not possible to load the transformer with the extra current due to reactive power. Voltage control is most needed in cases of high load combined with low generation and in cases of high generation combined with low load. In both cases the transformer and cable loadings are high and there is little space for reactive power. As a consequence, there is limited margin for voltage control using reactive power, when voltage support is needed most.

6.1.2 Performance during disturbances

In case of a fault in the network the DG units will contribute to the fault current. This might result in improper operation of the protection. The protection of the generators in an LV network will not immediately notice faults in the MV network, resulting in unintentionally islanding. Also intentionally islanding is complicated with DG.

Increased fault currents

In case of a fault the DG units contribute to the short-circuit current. The amount of contribution and its duration depends on the type of generators [BARK 001].

- The short-circuit current contribution of synchronous generators depends on aspects like the pre-fault voltage, (sub)transient reactance and exciter characteristics. In the first periods the maximum contribution is about 5 to 10 times the rated current of the generators. The contribution decreases in time towards a value between 2 and 4 times the rated current.
- Induction generators can contribute to a fault current as long as they remain excited by any residual voltage. Their maximum contribution is between 5 and 10 times their rated current. This value decreases rapidly in time. When the fault is close to such a generator, the contribution can be neglected after about 10 cycles.

- For inverters the maximum contribution and duration of a fault current depends on manufacturer's design and controller settings. Often the maximum contribution is limited to the rated current of the inverter. The duration is set by the controller, in some circumstances this duration may be less than one period.

The increase of fault currents in a network may result in more thermal and dynamic stresses in various components like cables, circuit breakers and busbar systems. Especially in older substations, the dynamic stresses may be larger than the dynamic short-circuit withstand of the components.

In MV networks fault clearing is performed with circuit breakers. Therefore thermal stresses can be limited by proper protection settings. Dynamic stresses can only be limited by increasing the impedance between the generator and the fault. However, increasing the impedance has a negative influence on the voltage profile. Solutions for limiting the short-circuit current are described in paragraph 6.2.2.

In LV networks µCHP and solar panels are most applied. In general, the short-circuit current contribution of these DG units will be far less than the contribution of the feeding MV/LV transformer for several reasons:

- In case of a fault in the LV network the contribution of these appliances is limited due to the impedance of the in-house connections.
- Solar panels are connected with inverters, which normally limit their short-circuit contribution to a little (20%) above the rated current.
- The contribution of µCHP is limited to about 3 times the rated current.

Increased single-phase fault currents may also occur due to improper earthing of DG units. The earthing of DG units must comply with the earthing method of the network. Small generators are either connected directly to an LV network or by means of an LV/MV step-up transformer to the MV network. In both cases the star-point of the generator may be earthed, because the network to which it is connected is earthed by the star-point of the transformer. Nowadays larger generators (exceeding 2 MW) may be connected directly (without transformer) to the MV network. In these cases the generator may only be earthed if the network is earthed. If a generator in a network with isolated neutral is earthed, this earthing unintentionally would act as a network earthing. In case of an earth fault this will result in too large fault currents both in the network and in the generator, causing thermal and mechanical stresses in the components and unwanted protection activities.

Protection

Distributed generation influences protection items like:

- Blinding of protection;
- False tripping of network protection;
- Unnecessary tripping of generator protection.

Blinding of protection or "protection under-reach" occurs when DG in a faulted feeder reduces the fault current noticed by the network protection to a value below the pick-up current of that protection device. According to [COST 001] and [COST 002] this phenomenon is more probable in networks with overhead lines than in networks with underground cables.

False tripping of network protection occurs when the fault current contribution of DG in a healthy feeder exceeds the pick-up level of the protection for that feeder. This event, also known as "sympathetic tripping", can be prevented by changing the protection scheme or by using directional relays [COST 002].

Unnecessary tripping of generators occurs because present grid codes and standards [IEEE 001] prescribe that distributed generation should be disconnected when the voltage level is outside certain boundaries for a certain amount of time. These rules are tighter than the stability of many generator types requires. The current standard in the Netherlands is to disconnect the CHP-plants when the voltage in one of the phases drops to 70% of the nominal voltage for 200 ms [NMA 001]. Therefore the DG will switch off due to dips caused by almost all two- and three-phase faults in the network. An advantage for the grid operator is that, due to the fast switching off, the network protection does not need to be changed. A disadvantage is that a large amount of DG is switched off during disturbances, resulting in large changes of power flows and voltages.

To prevent unnecessary tripping, the protection of the network and the generators must be coordinated. The solution of this problem is outside the scope of this thesis. In [GELD 001] it is proven, that in an MV network the magnitude of the fault current can be used to distinguish between a fault in the own feeder and a fault in an adjacent feeder. In [COST 002] it is shown, that the critical clearing time for generators in case of faults in adjacent feeders is much larger than the currently used switching off times of the generators. In meshed operated networks however the protection coordination must be reconsidered. Without fast communication or other intelligent measures, the time-grading schemes would result in fault clearing times which are too large to work properly.

Fault location

Distributed generation has several influences on fault location methods (described in chapter 5). As DG contributes to the fault current, the fault current passage indicators “behind“ the fault might be affected by DG located between the fault and the end of the network. Also remote readable indicators may be falsely triggered. As a result, the restoration crew is not guided to the correct location. This issue can be solved by applying directional sensitive indicators. A drawback of these indicators is that they require current and voltage measurement devices, which makes them expensive.

When using intelligent fault location methods, the current recorded by the measuring devices is influenced by the distributed generation in the faulted feeder. This can influence the calculated impedance. The influence is only caused by generators between the measuring devices and the fault. In general the generation in the faulted feeder switches off faster than the network protection of the faulted feeder. When calculating the impedance for the remaining time between the disconnection of the generation and the disconnection of the feeder, there is no longer influence of the DG. However, as stated in chapter 5, it might be worthwhile to include an extra stage in the protection. This stage results in a fast disconnection of the feeder in case of faults close to the substation, in order to limit the effect of dips. In this case it is possible that the faulted feeder is switched off before the generation units switch off, influencing the impedance calculation. In this case the combination of a high short-circuit current and a short duration of the fault must be an indication for the fault location system that the fault must be close to the substation.

During a fault the DG may disconnect. As the calculation of the fault impedance is performed after this disconnection, the load of the feeder during the calculation of the fault impedance differs from the calculated pre-fault load. The calculation of the fault location is based on the expectation that there is no change in the load. As a result an error in the location can be expected. This pre-fault situation is especially important for a proper calculation of the location of single-phase faults. The fault location system must be extended with a procedure that is able to recognise the tripping of generators and to adjust the pre-fault load data.

Islanding and safety

Islanding occurs when a normal distribution network has been isolated due to a fault, while the generators in that network keep on running. In most cases this islanding is unwanted and unintentional. This is the case if the fault is outside the considered network or if the fault does not trip the protection of the generator. This may result in safety risks, because parts of the network still are carrying a voltage, when it is not expected by e.g. restoration crews.

A main cause for unintentional islanding is a single-phase fault in an MV cable network, that is not directly earthed. Due to the MV/LV transformer configuration, generators connected to LV networks will normally not notice such a fault and will not switch off. However, most events in the network cause these generators to switch off, as most of these generators are not equipped with controls for operating during islanding conditions. Most of the time there is no equilibrium between load and generation in such an island. This will result in an increase or decrease of the frequency or voltage, which is noticed by the DG protection resulting in a trip of the generator. Methods to detect unintentionally islanding are described in [BRUN 001] [GUIL 001] [OKAN 001].

Intentionally islanding can be performed by customers with DG who want to maintain continuous operation, even in cases of a disturbance in the rest of the network. In this case their DG units must be equipped with controls that can match the required power to the existing load. After network restoration the customer network has to be reconnected to the utility network. These networks are at that moment normally not synchronous in voltage magnitude, frequency and phase angle. Attention must be paid to synchronous reconnecting to the grid.

Intentionally islanding is also applied by the grid operator during specific activities regarding the MV/LV transformer, like replacement, maintenance or adjusting the off-load tap changer. In these cases the LV network will be fed by means of a (mobile) generation unit in order not to interrupt the supply to the LV customers. This unit is equipped with control that adjusts the generation to the load in the islanded network. This method can be used as long as the load in the islanded network is larger than the amount of generation by possible DG units in the network. When the LV network contains too much DG, situations may occur where the network generation exceeds the network load. In this case the mobile generator would have to draw energy from the grid, which is of course not possible.

6.1.3 Planning, operation and power quality

The uncertainty on the produced power by DG may result in problems with power flow prediction and network extensions planning. This uncertainty is not only due to natural variation of primary sources like sun and wind or due to heat requirement, but also due to the fact that specific groups of generators may act as large virtual power plants that produce power based on market prices.

Variable power flows will effect losses and the aging of components. Furthermore DG influences flicker, unbalance and harmonics in the system.

Network planning

Normal loads tended to grow smoothly with a specific factor every year. This growth is noticed over a large area. Planning procedures in electricity networks could therefore be performed by interpolation of maximum loads over a period of time. Nowadays, this methodology is being compromised by distributed generation in the network. DG tends to grow stepwise with specific amounts and is often concentrated in one specific area. Examples are wind farms and CHP plants in areas with a lot of greenhouses. The planning and operation of DG is influenced by economical and political aspects. Before the liberalisation of the electricity market, CHPs were used to reduce peak demands of local energy companies as kW prices at that moment were high. For the rest of the time the heat demand was determining the power output. Just after the liberalisation it was cheaper for the CHP owners to buy electricity from the market than to produce it with their own CHP, so the CHP units were less used. Nowadays groups of CHP owners act on the market and the generation follows the spot market prices. Many projects regarding sustainable DG profit from subsidies. Many plans are made to build new DG units and the network owner must take care of the network extensions. However, if subsidy plans change, the plans may be postponed or even cancelled, whereas the (expensive) network extensions already were made, without financial profits for the network owner.

Operation

The generation in a network influences the measured load data in the substation. This creates problems when monitoring the substation's annual maximum load. The measured load is the actual load reduced by the amount of distributed power being generated

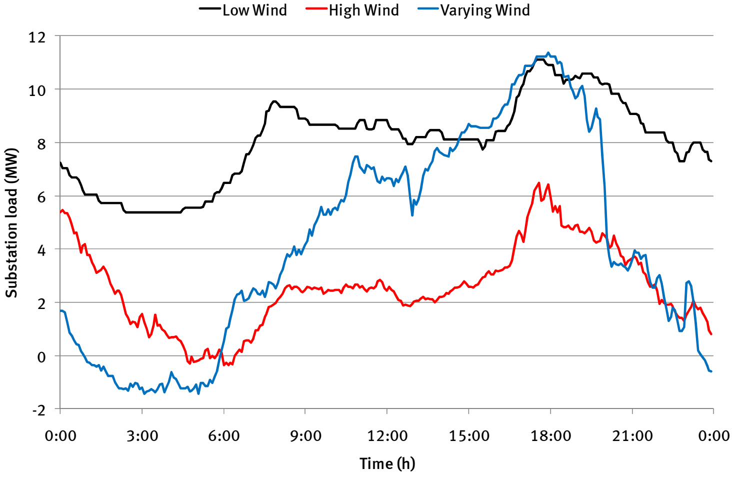


Figure 6.5 Influence of wind generation on a measured substation load profile

In Figure 6.5 the influence of wind power on the measured substation load profile is shown for various wind conditions. The actual maximum load might not be noticed at the substation during a very windy period at the time of the maximum load. This makes it difficult to track changes in load maxima or daily load profiles.

However, it is possible to separate the measured data in generation and load within certain error bounds [PROV 003]. The solution to the problem is relatively straightforward: if the generated power is considered to be a negative load, the profile of the generated power of that distributed source should be subtracted from the profile of the measured signal, and as a result the daily load profile is restored (6.1).

$$P_{Load,Actual} = P_{Load,Measured} - P_{Gen} \tag{6.1}$$

Historically only the amount of generated energy (kWh) was measured at the distributed source and not the generated instantaneous power (kW). In order to find the generation profile, a reference source signal is needed. This reference should then be scaled with a factor c_{Scale}, to match the amount of generation in the observed system (6.2).

$$P_{Load,Actual} = P_{Load,Measured} - c_{Scale} \cdot P_{Genref,Measured} \tag{6.2}$$

In [PROV 003] promising results have been obtained for a network containing solitary wind turbines, by regression methods using reference feeders containing only wind farms. Applying this method to detect the substation maximum load without generation showed a maximum more than 20% higher than the measured maximum (Figure 6.6).

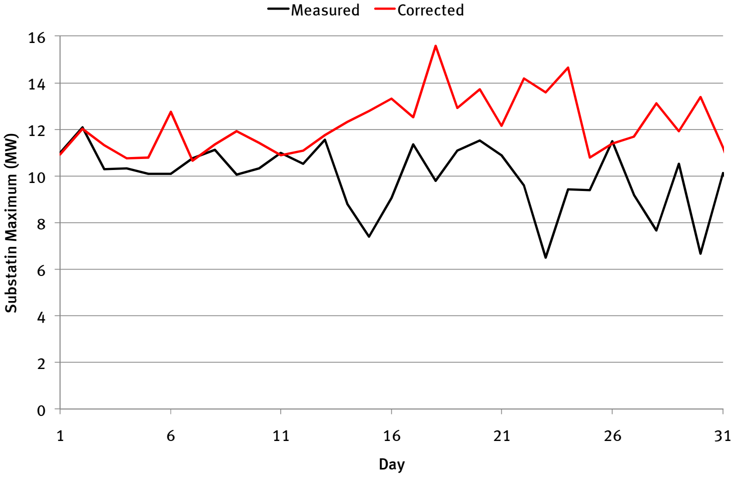


Figure 6.6 Measured and corrected substation maximum load data

The figure shows the measured daily maximum load of a specific substation (Measured) and the calculated maximum of the load without generation (Corrected). The measured data show a maximum on day 2 with a value of 12 MW. The maximum of the actual load without generation is calculated to occur on day 18 and has a value of 15.6 MW.

The most important part of the problem is to calculate the scaling factor c_{Scale}. This scaling factor can be obtained by minimising the correlation between the wind reference and the corrected data over the time of interest. The difficulty in this exercise is that the scaling factor is not a constant over a long period of time. This is because the scaling factor is influenced by:

- Maintenance on wind turbines causes the ratio with the reference wind park to change.
- Different types of wind turbines have different power curves as function of the wind speed.
- The number of wind turbines within a network may increase.

When more measurements are available the necessity for applying this method will reduce.

Power flow management

The uncertainty of power generation has consequences for the expected power exchange between a local network and its surrounding networks.

If no actions are taken, it will be hard to predict the power required by a certain network containing a large amount of DG. Also predictions of day-ahead load flows will be influenced. This affects decisions about operational activities like maintenance in networks, where security must be maintained.

On the other hand, when controllable generation and load is available in the MV network, the consequences of the uncertainty of power generation can be reduced by controlling the power of these generators with respect to the network requirements. Power flow management solutions can be obtained by a narrow cooperation of producers and consumers. The producers must have controllable generation. The consumers must have controllable loads. In this way an autonomous local market for such types of services can be created [JOKI 001]. The ability of the network can be further improved by the use of storage facilities.

As the power flow directly influences the voltages in the network and the loading of components, the power flow must be managed in order to prevent overloading and exceeding voltage limits. Various methods to manage the power flow such as meshed operation, controlling the output of DG and the use of power electronics and storage are described further on in this chapter. The use of intelligent nodes, containing storage and a power flow controller, will be discussed in chapter 7.

Losses and ageing

As long as the amount of actual generation in a network is less than twice the amount of actual load, it can be assumed that the resulting current in the network is less than the current would be in the case without DG. Therefore it can be stated that within certain limits the DG decreases the losses in the network compared to a situation without DG.

The behaviour of the current in networks with distributed generation may result in extra thermal stresses of components like transformers and cables. Contrary to normal loads, some kinds of distributed generation do not have typical daily profiles of high and low power. Wind turbine generators run at almost maximum power for several days. As a result network components might operate in the vicinity of their ageing point due to the full load for several days. Therefore a power derating of these components is often advised [DECL 001].

The fluctuating behaviour of the generation will result in more variations of the power flow through the transformers with voltage regulating possibilities. This results in more tap changer actions, which will reduce the life time of the tap changers.

For cables the duration of high loading is too short to expect drying out of the soil. In case of PILC cables, the heating due to continuous load may result in a too high temperature of the insulation material, which will result in extra ageing of the cable. When PILC cables are used, they always must be designed for the maximum expected current, but XLPE cables may be designed for a lower current. In case of fluctuating generation, heating and cooling result in additional thermal and mechanical stresses. As stated in chapter 3 this causes voids in the paper insulation, thus increasing the risk of cable damage when PILC cables are applied. XLPE cables are less vulnerable for temporary overloading and varying loads.

Flicker, unbalance and harmonics

Apart from the slow voltage variations described earlier, DG influences also other PQ aspects like flicker, unbalance and harmonics. Flicker is caused by the starting and stopping of a generating unit. In general, the µCHP units at households will not result in flicker problems, as their output is about 1 kW, which is less than the power consumption of many household appliances like washing machines, micro wave ovens and vacuum cleaners. Flicker problems might occur when a large amount of DG is started or stopped simultaneously. This however will hardly occur and when it happens (may be because of market signals) it will not be in a repetitive way.

Unbalance occurs because of the fact that many domestic generators are connected single phase. However, in proper designed LV networks single-phase customers are distributed in such a way that a near symmetrical situation is obtained and asymmetry will hardly be noticed.

Harmonics may be introduced by power electronic inverters. Most of them use pulse width modulation (PWM) operating at high switching frequencies. The contribution to the most severe harmonics in general is small. However, the capacitances in the inverters create a resonance circuit with the network impedance. In cases where large amounts of inverters are used, the resonance frequency becomes lower than the 25^{th} harmonic [ENSL 001], [DYSK 001]. This may result in high harmonic voltages and currents. The design of the inverter must take care of this harmonic distortion.

Rotating generators have relatively low impedance for harmonics. Therefore they might absorb harmonic currents. This reduces the harmonic voltage in the network, but the harmonic currents increase the thermal losses in the generator.

The real influence of distributed generation on power quality aspects is hard to predict. It is therefore recommended to perform regular measurements which have to be compared to a reference measurement from a moment where no DG is implemented or active.

Ripple control signal

As rotating machines have a relatively low impedance for harmonics, they will not only absorb harmonic currents, but also ripple control signals [VERM 001]. This may reduce the level of this signal to a value below the pick-up value of the relays that use these signals. There are cases where the start/stop sequence of distributed generators is controlled by means of a ripple control signal. It is possible that the signal for switching off the generator will be too low and the generator continues to produce power.

This has been noticed in the 1990’s, when CHP units were used to reduce peak power consumption. Ripple control signals were used to automatically switch on when a peak value was expected and to switch off these units when the situation of peak load was over. However, often the level of the control signal for switching off was too low and the generators kept running. Most of these generators operated on LV level. The impedance of the generator and the impedance of the MV/LV transformer act as a voltage divider for the ripple control signal. The influence of the generator on the ripple control signal on MV level is limited. A solution for the problem was to replace the receivers from the LV level to the voltage transformers used for revenue metering on MV level.

Disturbance of the ripple control signal may also be caused by the capacitors for reactive power compensation in asynchronous generators like wind turbines. These capacitors create a resonance circuit with the network impedance. If the resonance frequency is close to the frequency of the ripple control signal, the signal will be absorbed. This results in a too low signal in a large area affecting a large amount of customers.

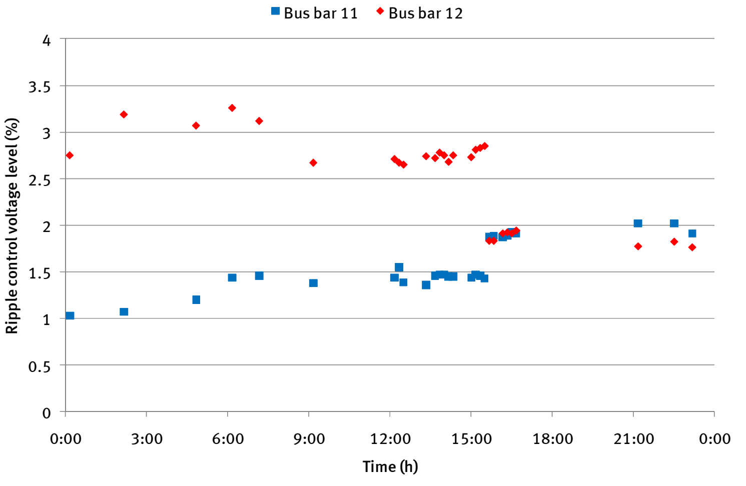


Figure 6.7 Effect of a wind farm on the ripple control level
(measurements performed on substation Marnezijl on june 26 2007)

Figure 6.7 shows this effect caused by a wind farm connected to the MV side of an HV/MV substation. The wind farm can be connected to two different busbars (busbar 11 and busbar 12), that can also be operated in parallel. In the beginning of the day the wind farm is connected to busbar 11. The ripple control level of that busbar is much lower than the level on busbar 12. A little after 15:00 the two busbars are connected. The ripple control levels are equal. However, the signal on busbar 12 halved, compared to the situation before. At 21:00 the busbars are separated with the wind farm connected to busbar 12. Now the signal on busbar 12 is lower than on busbar 11. Such impacts of DG on ripple control functioning can be limited by applying a blocking filter or by rescheduling loads and generation over the various busbars.

6.2 Solutions for network performance

From the previous paragraphs it became clear that under several conditions the performance of the network is negatively influenced by distributed generation. It is also clear that measures that limit negative influence on voltage may increase the negative influence on (fault) currents. It is therefore important to find solutions that will not deteriorate other measures. Some solutions can be implemented in the network without changing the basic design and operation, but sometimes solutions are needed that involve reconsideration of the basic design and operation. In these cases the use of new technologies like power electronics and storage may be required.

6.2.1 Common practice solutions in the network

Common practice solutions that can be applied in the network are: dedicated connection to the network, limiting the network impedances, advanced voltage control of transformers, active management of generation and loads, and the use of power electronic interfaces. The benefits of these solutions must be compared to the economical and the technical efforts to obtain them.

Dedicated connection of DG to the network

The best way to limit the negative impact of DG is to connect it to a separate MV/LV distribution network, connected to the HV network by a separate transformer. However, this is not always a practical and economical solution. Grid operators normally follow a general approach which has been proven feasible. An example of a Dutch grid operator is:

- Domestic appliances and generators smaller than 50 kW will be connected in the LV network.
- Generators smaller than 160 kW are connected with a separate LV cable to the LV side of an MV/LV transformer.
- Generators smaller than 2 MW are connected in the MV network.
- Generators and small wind farms with a power less than 10 MW get a separate connection to the MV busbar of the HV/MV substation.
- Larger wind farms or groups of CHP units are connected by a separate HV/MV transformer.

Limiting the network impedances

When DG is connected according to the guidelines of the previous section, the negative impact on the voltage profile can be further decreased by limiting the impedance of the network. This can be obtained by the choice for large cable diameters and relatively short networks. This also reduces harmonics and losses. When applied on LV networks it improves safety when TN earthing is applied.

A drawback of limiting the network resistance is the increase of the fault current contribution. This is most relevant in MV networks because, as stated earlier, in LV networks the increase of fault currents from DG is hardly noticed. Also the economical impact must be considered. Increasing cable diameters implies increasing cable costs. Decreasing network lengths on one voltage level implies an increase of transformers to another voltage level.

Advanced voltage control of transformers

In order to reduce voltage variations in the LV network, it might be advantageous to introduce more possibilities for voltage control like on-load tap changers in the MV/LV transformer. When these tap changers are operated mechanically, this will result in a lot of switching actions, reducing the lifetime of these devices. As an alternative this switching might be performed with power electronics. An example of such a transformer is the so called “Smart Trafo” [HAAN 001]. Such a device however is larger than a normal distribution transformer and therefore it does not fit in standard compact distribution ring main units. Also the price of such a unit is higher than the price of a standard transformer.

Active management of generation and load

Severe situations like exceeding voltage limits or too high currents generally occur just a few moments per year. The costs for network reinforcement to cope with these extreme situations may be high. It can be advantageous for grid operators, to make financial deals with producers and consumers to adjust generation and to shift consumption in order to prevent security problems in existing networks. The costs for these measures must be compared with the costs for network extension.

In the case where limits tend to be exceeded due to too much generation, limitations can be set on the amount of generated power by the units. This limitation is known as curtailing. In domestic appliances like solar panels and µCHP the curtailing function is provided by built-in over-voltage protection. For larger DG units specific curtailment signals can be provided by means of communication [PFAJ 001]. These curtailing actions may consist of either switching off or decreasing the delivered power. Curtailing requirements can be set on most DG units.

In the case where limits tend to be exceeded due to too much load, generators can be asked to produce energy. This can be performed only if the prime mover of the generator can be controlled, as is the case for CHP. In heavy load situations it can also be considered to apply fast load shedding when the lower voltage limit is reached. This is in general not accepted by society. On the other hand it is possible to influence the behaviour of the customer by means of a variable tariff. This may shift specific power extensive activities towards a time interval where more generation or less load is expected.

In this way also the impact of DG can be reduced. The standard variations in tariff based on night, day and weekend might not be sufficient. For continuous adaptations, domestic appliances like washing machines and refrigerators and in future chargers for electrical cars can be applied with smart controls, acting on a variable tariff. This is one of the ideas behind the introduction of “smart meters”.

Power electronic interfaces

Since many DG units are coupled to the network with power electronic (PE) equipment, it can be advantageous to add additional functionalities in the control of these devices, which may improve the performance of the network. In [MORR 001] several examples are given:

- Contributions to voltage control. The contribution to active voltage control with reactive power is limited in cable networks. However, certain control activities can be developed regarding curtailment.
- Fault ride-through support. When DG units stay connected during faults, they can support the grid during and after a voltage dip. This results in a temporary overloading of the converter, which in general is allowed due to the short duration of the dip. Generally, DG coupled with PE can stay connected to the grid during voltage dips.
- Frequency control. The contribution depends on the type of DG. Inertial response can be used with DG units that have kinetic energy available like wind turbines and (μ)CHP units. The primary frequency control can be performed by DG units that have a controllable primary source, such as fuel cells and micro turbines.
- Damping of harmonics. By implementing an additional control loop, it is possible to give the output impedance of the converter a specific behaviour for a wide frequency range. In this way harmonics can be mitigated.

Limitations of common practice solutions

All these common practice solutions have their limitations. These limitations can have technical, financial or practical reasons:

- Cable diameters cannot be increased infinitely.
- Replacing existing cables with cables having larger conductor diameters is often too expensive.
- Advanced line drop compensation is complicated when feeders containing a mixture of load and generation are concerned.
- Active control of generation and load depends on the willingness of producers and consumers to change their habits based on financial profits.
- Power electronic interfaces hardly influence the voltage profile.

In general it can be stated that as long as the voltage rise between the beginning of an LV feeder and a house connection at the end of that feeder during maximum generation and minimum load is less than 4% no voltage problems will occur in distribution networks that are designed with the following criteria:

- The MV network consists of 240 Al XLPE cable with a maximum feeder length of 10 km feeding a load which is limited to half of the loading capacity of the MV cable.
- The LV network consists of 150 Al cable with a maximum feeder length of 450 m and the voltage difference between the beginning of an LV feeder and a house connection at the end of that feeder during the maximum load is less than 6%.

In cases where these common practice solutions will not be sufficient, other measures must be taken, as is described in the next paragraph.

6.2.2 Future solutions

In cable networks voltage and short-circuit current problems can be seen as being most important. Voltage control with reactive power compensation in these networks is limited because of the lack of reactance in the network. Advanced voltage control with MV/LV transformers is limited due to required space. As the voltage problems are caused by increased flows of active power, future solutions may therefore be based on reducing and influencing these active power flows. The solutions for voltage control may result in an increase of short circuit currents. Therefore specific measures that reduce these short-circuit currents must be considered.

Meshed network operation
Meshed network operation may result in a reduction of voltage variations. This reduction is noticed most in networks where high load in one feeder and high generation in the other feeder occur simultaneously.

Figure 6.8 shows the voltage profile for two MV feeders where one feeder has mainly load and the other mainly generation. The feeders have a length of 10 km with MV/LV connections every 500 m. The solid lines show the voltage profile in the radial situation for the load feeder (Load R) and generation feeder (Gen R). The dashed lines show the voltage profiles in case of a meshed situation for the load feeder (Load M) and generation feeder (Gen M). In the meshed situation, the load at the far end of the load feeder will be fed by the generation on the end of the generation feeder. This decreases the current in the beginning of the feeders and reverses the power flows at the end of the feeders. As a result, the variations in the voltage profile over both networks reduce. The influence of meshed operation on the voltage profile reduces when the difference in load and generation between the feeders is less.

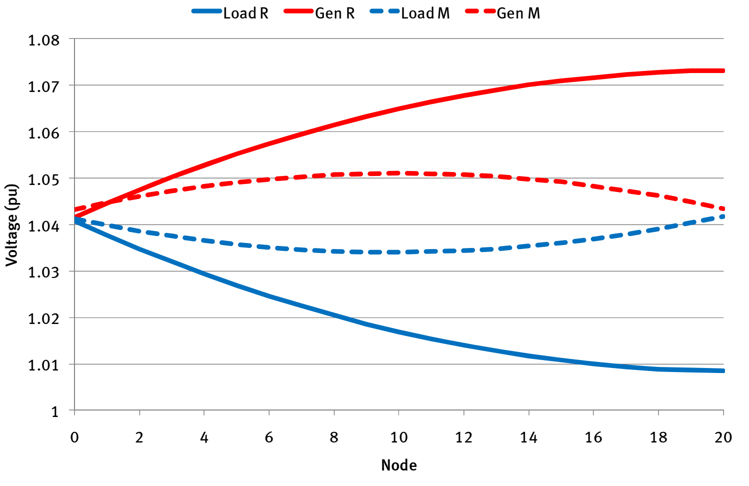


Figure 6.8 Calculated voltage profile in a radial network (solid lines) and a meshed network (dashed)

As stated in paragraph 3.2.1, meshed generation benefits from the diversity of load and generation in all feeders. Therefore it can be attractive to extend the meshed operation with extra measures to influence the active power flows [UEMU 001], which will be discussed further in chapter 7.

During a disturbance, meshed operation results in an increase of short-circuit currents and requires a more complex protection scheme compared to radial operation.

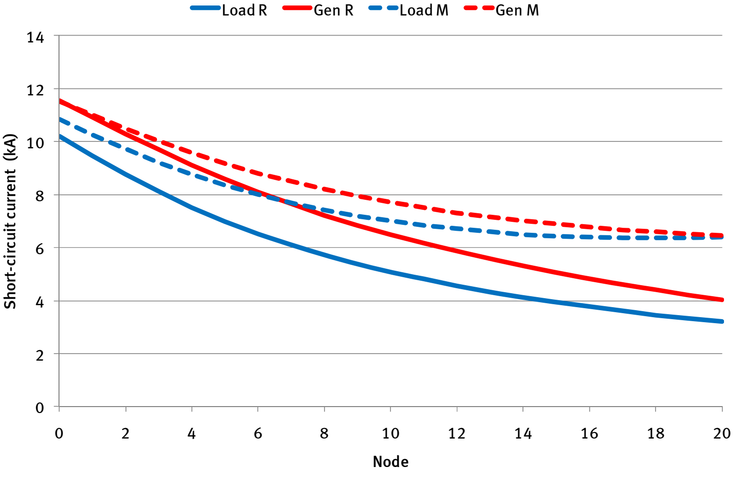


Figure 6.9 Calculated short-circuit currents in a radial MV network (solid lines) and a meshed network (dashed)

Figure 6.9 shows the short-circuit currents in the same network and for the same cases as shown for Figure 6.8. From the difference in the solid lines, it becomes clear that in this case DG contributes about 20% to the short-circuit current. From the dashed lines it can be seen, that the short-circuit currents in both feeders increase in case of meshed operation.

Meshed operation alone is therefore not an adequate solution for the power flow. Measures to cope with the short-circuit currents and possibilities to control the active power flow are necessary.

Short-circuit current limiting devices

Short-circuit current limiting (SCCL) devices can be used to limit the short-circuit contribution of generators and the network. However, these devices always introduce additional impedances in the network, which will have a negative impact on the voltage profile. In general, reactors will be used as short-circuit current limiter [PAAP 001], but in order to have a noticeable impact on MV level, their size is large. In order to reduce the short-circuit contribution by 50%, the size of such a reactor must be equal to the short-circuit impedance of the generator (X_d”).

A 10 kV generator with a nominal rating of 3 MVA and an sub-transient reactance of 0.15 pu has an impedance of 5 Ω. This value is much larger than the value of 0.3 Ω for the reactors that are connected often at the beginning of an MV cable feeder to limit the short-circuit contribution of the feeding HV network and HV/MV transformer.

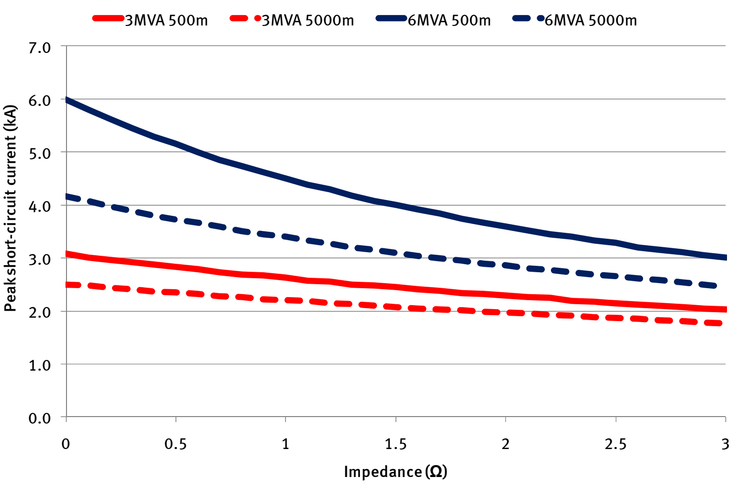


Figure 6.10 Calculated limitation of the peak short-circuit contribution by an SCCL for different generators on various distances from the substation

Figure 6.10 shows an example of the influence of the impedance of an SCCL on the peak short-circuit contribution of two types of generators (3 MVA and 6 MVA) in a 10 kV network, located on 500 or 5000 m from the substation. Often the peak short-circuit contribution of the generators is limited to a value of around 1 kA/MW. From the picture it becomes clear, that large inductances are necessary to fulfil this requirement.

In order to limit the influence of this impedance on the network performance during normal operation, this impedance should only be operated in case of a short-circuit. Various concepts for this are known. One example is to apply power electronics that can be used to bridge the large inductance in case of normal operation. As soon as a short-circuit is noticed, the power electronics stop to conduct the current and the current is transferred towards the inductance. A disadvantage of this system is that the current through the power electronics results in extra losses.

Also super-conducting short-circuit current limiters (SC-SCCL) are seen as promising [FISC 001]. During normal operation the device has (almost) no impedance and will therefore not influence the network performance. Due to the natural properties of these devices the super-conductivity disappears above a certain current density. This will increase the impedance and reduce the short-circuit current. The extra heat produced by the short-circuit current must be cooled away before super-conductivity is established again.

New super-conducting materials integrate fault current limiting in the cables (FCL HTS cable). In these cables superconductivity is re-established immediately after the short-circuit is over [GESC 001].

A relatively new development is based on the saturation of a reactor core. During normal operation the core is forced into saturation, resulting in a low impedance. Due to the short-circuit current the core comes out of saturation resulting in a high impedance. As some of the aspects regarding this system will be patented, no reference papers are available yet.

Storage and power electronic interfaces

Devices for storing electrical energy can be used to improve network performance. A combination of slow and fast storage devices is necessary to mitigate all kinds of disturbances and to deal with balancing and congestion management during normal operation.

In Figure 6.11 an overview is given on various applications for storage of electrical energy. Fast operating storage devices like flywheels and super capacitors often have limited capacity. They can be used to mitigate voltage dips and to bridge the relatively short period between loss of power and starting emergency generators in case of a local black out.

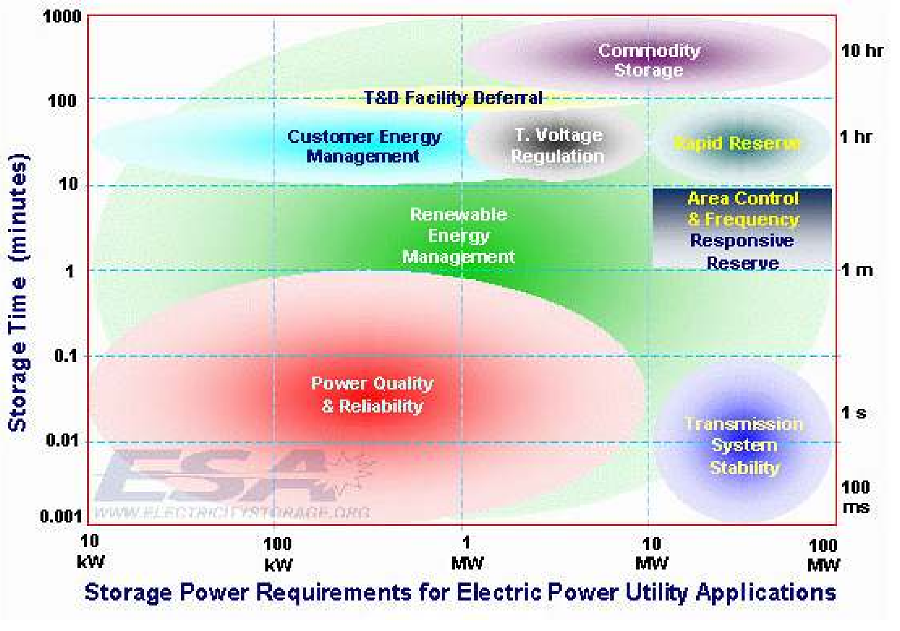


Figure 6.11 Overview of various applications for storage devices [ESA 001]

Slow operating storage devices mostly have larger capacity and can therefore be used to limit effects of variations in generation and load. During high generation, energy can be stored, and used in periods of high load.

When using storage devices to improve voltage profiles, a proper location and size of the storage devices is necessary. From a technical point of view the best solution is to install as many storage devices in the network as possible. From operational and economical point of view it is often more practical to use a few larger devices, than many small ones. These few devices must be located on points in the network where they can really influence the power flows. A large storage device at the beginning of a radial feeder will not solve the voltage problems in that feeder, as the power flows in that feeder remain unchanged.

Power electronic devices can be used to control the transfer of energy from one feeder to an adjacent feeder [BUCH 001]. The control systems of these devices can limit the magnitude and duration of short-circuit currents. As a consequence, these devices can be used in a system with controlled meshed operation.

Combining meshed operation with storage and power electronics may be a perfect way to reduce the impact of load and generation on the voltage profile, without increasing the impact on short-circuit currents. The influence of DG on short-circuit current contributions can be further reduced by advanced SSCL devices. The idea of voltage control in networks with storage and power electronic equipment will be described in chapter 7.

6.3 Conclusions

In this chapter the impact of DG on MV/LV cable systems has been described. Also possible solutions to limit the negative impact have been proposed.

In normal operation the DG causes more spread in the voltage profile, which may cause extra problems when the feeding HV/MV transformer is equipped with a voltage controller based on line drop compensation.

In case of a short-circuit, all DG units will contribute to it. As a result, the short-circuit currents may be higher than expected and a possible reverse current direction can disturb the proper functioning of the protection. Considered are blinding, false tripping and unnecessary tripping of the protection. Blinding of protection is not expected in cable networks and false tripping can be prevented by applying directional relays. Unnecessary tripping can be prevented by a better coordination of protection settings for the network and the DG. Another problem in case of a short-circuit is that fault location methods may fail if the generated power is not compensated. Finally, unintentional islanding may occur after isolating a fault, causing safety risks.

In order to limit the negative impact of large amounts of DG, some common practice solutions have been described, like separating load and generation flows, limiting network impedances, use of advanced transformer voltage control, actively managing generation and load and use of power electronics to connect DG. Also some future solutions have been proposed, like meshed operation, use of short-circuit limiting devices and use of power electronics and storage.

Meshed operation of a network reduces the negative impact on voltage profiles, but measures must be taken to limit the increased short-circuit currents. Also the protection schemes for meshed operation are considered to be quite complex.

Large generation units on MV level may result in too large short-circuit contributions, especially in substations that were not designed with DG in mind. These short-circuit contributions can be limited by a short-circuit current limiter (SCCL), the pros and cons of which have been discussed.

A combination of meshed operation with a controlled power flow by using power electronics and storage can be an interesting option. This will be discussed in detail in chapter 7.

7 Voltage control in autonomously controlled networks

This chapter is related to techniques and control strategies as a solution for operating problems in future distribution networks. From the previous chapters it became clear that distributed generation influences the performance of MV and LV networks. In case of large amounts of DG these problems cannot simply be solved by standard network solutions. On the other hand it can be assumed, that a combination of meshed operation and controlled power flow, using power electronics and storage can be an interesting option. Such a network can be transformed into an autonomously controlled network which is described in chapter 2.

The focus in this chapter is on the control strategy to obtain an optimal voltage for all customers under all combinations of load and generation. A suggested solution for the network design is to replace the normally open point between the MV feeders by a so called “intelligent node”. This node is able to improve the voltage profile by controlling the power flow in several feeders with the help of power electronics and electricity storage. The voltage profile can be improved even further by adding intelligence to the voltage control on the HV/MV transformer feeding the distribution network. Because of the autonomous behaviour of the control systems, their operation must be based on local measurements.

The simulation studies described in this chapter have been performed on a realistic model of a typical Dutch MV/LV distribution system containing underground cables.

The study shows the theoretical possibilities of the control methods. The results of the calculations can be used for the design of the components, which is outside the scope of this thesis.

7.1 Problem definition

Chapter 3 made clear that, in distribution networks with cables, the main challenge during normal operation is to keep the voltage within the limits. The challenges during disturbances are to keep the short-circuit currents within specified limits and to define a proper protection coordination. These challenges increase when distributed generation is involved. It is stated in chapter 6, that in cable networks voltage problems occur when the amount of distributed generation equals the amount of maximum load. The voltage control problems increase if some feeders in the network contain load, while the other feeders contain a combination of DG and load. Furthermore it must be considered, that a solution for a voltage problem may have a negative influence on the short-circuit currents and the protection coordination and vice versa.

As the solution is faced towards networks in the future, it is assumed that several items stated in earlier chapters will be further developed and will be feasible for operation in these networks. As a result, it is assumed, that:

- Sufficient storage facilities are available.
- Power electronic devices can be used to transfer power from one feeder to one or more other feeders.
- The number of distributed generators is not limited by their short-circuit contribution. If necessary a dedicated short-circuit current limiter (SCCL) can be applied.
- The information and communication means for measurement and control systems are sufficient for the applied method.

It might be advantageous to transfer parts of the network that contain a mixture of load and generation into autonomously controlled power networks (ACN) as described in paragraph 2.5. As a result, the future distribution network consists of several ACNs, containing load and generation, and a number of feeders that contain only load (load feeders).

Chapter 6 stated that controlling the voltage profile by influencing the power flows with storage, power electronics and controlled meshed operation is an interesting option. Such an option can be applied in the ACN. The voltage profile in the remaining feeders (containing only load) must be controlled by the HV/MV transformer. However, this transformer also influences the voltage in the ACNs, so an optimal control strategy for this transformer must be developed. Several constraints are set on the final solution:

- Loads and generation outputs are not controlled, so curtailment of generation or load shifting in time is not considered.
- In order to minimise complexity, the number of controls must be limited. Therefore the controls must operate on MV level. Controlled tap changers on MV/LV transformers are not considered.
- The communication between the controls is limited. Controls (especially in the ACN) must work with local information that might be extended by limited information from other controls.

As described in earlier chapters, the MV and LV networks in the Netherlands contain only underground cables and have a high reliability. Therefore the main focus of this study on controls in the ACN is on the behaviour of the network during normal operation. The required controls however should not have a negative impact on the behaviour during disturbances. The layout and operation of the network and the controls must result in an optimal voltage profile for all possible combinations of generation and load. They also must benefit the limiting of short-circuit currents and a proper protection philosophy. The optimal voltage profile is based on the minimisation of the voltage deviations from a specific reference voltage and will be described further on in this chapter.

7.2 Applied method

The study must result in a control strategy, enabling optimal network performance by using local measurements. This means that control units must act on signals obtained from their own terminals like voltage, current, active and reactive power. The network performance however is a global figure based on measurements and observations of signals like voltage and current at many points in the network. This optimal performance must be obtained for all expected combinations of load and generation. Relationships between the parameters used for the control must not depend much on load and generation in the network. However, they might be influenced by changes in network topology and must be adapted when network topology changes. Before going into more detail, a simple example is given.

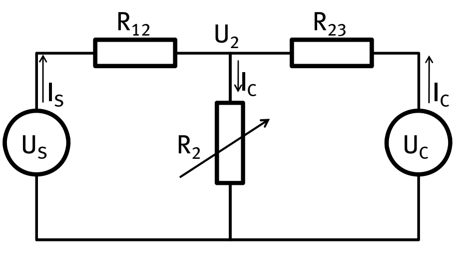


Figure 7.1 An example network needed to explain the various steps in the applied method.

Consider the network in Figure 7.1. The network consists of a voltage source U_S, a controlled voltage source U_C, two fixed resistors R_{12} and R_{23}, and a variable resistor R_2. The goal for the controlled voltage source is to keep the voltage U_2 at a defined value for a large number of values of R_2. The controlled source may only use a relationship between its output voltage U_C and its current I_C. Although this relationship is already visible from the figure, it is also possible to perform calculations for various values of R_2 and to adjust U_C in order to obtain the required value of U_2. This is shown in Table.2.1 assuming U_S=1, R_{12}=1, R_{23}=1 and $U_{2,ref}$=0.95 (per unit values).

From this result it is possible to find a relationship between U_C and I_C:

$$U_C = 0.95 - 1 \cdot I_C \tag{7.1}$$

Which of course equals:

$$U_C = U_{2,ref} - R_{23} \cdot I_C \tag{7.2}$$

This relationship is independent of R_2, U_S and R_{12}.

R_2	I_2	I_S	I_C	U_C
1	0.950	0.05	-1.000	1.950
2	0.475	0.05	-0.525	1.475
3	0.317	0.05	-0.367	1.317
4	0.238	0.05	-0.288	1.238
5	0.190	0.05	-0.240	1.190
6	0.158	0.05	-0.208	1.158
7	0.136	0.05	-0.186	1.136
8	0.119	0.05	-0.169	1.119
9	0.106	0.05	-0.156	1.106
10	0.095	0.05	-0.145	1.095

Table.7.1: Calculated control voltage for various values of R2

The relationship between the local control signals is in this case obtained from calculations in the whole network using all relevant network data. A similar strategy will be followed for the controls in the rest of this chapter, where the relationships between the local parameters will be given for one specific network topology.

In order to find these relationships, several steps must be performed, as is shown in Figure 7.2. In this figure the various steps are linked with a thin arrow. The outputs and inputs of the various steps are given with a thick arrow.

The steps are as follows:

- Calculation of the optimal performance of the network. The optimal performance can be obtained by performing network calculations and applying optimisation routines for various combinations of load and generation. The optimisation routines make use of all available information in the network in order to find the optimal settings for the control units. This will be described in paragraph 7.4.2. The results of this calculation must be stored and analysed, which is described in paragraph 7.4.3.
- Find relations between local signals. The output of the control equipment must be based on local measurements, so relationships between the outputs and possible inputs must be investigated. The results of the calculations performed in the first step must be analysed in order to find possible relationships in signals that can be measured or calculated by the controls. If acceptable relationships cannot be found, it is necessary to investigate what other information is needed. This is described in paragraph 7.4.4.
- Translate relations into control functions that only make use of local information. This is also described in paragraph 7.4.4.

- Calculate performance with control functions using local information. New calculations must be performed for the same combinations of load and generation as used in the first step. During these calculations, the operation of the controls must be based on their local measurements. This is described in paragraph 7.4.5.
- Compare results. The results regarding performance of the former step must be compared with the results regarding performance of the first step. When these results differ, the impact of these differences must be investigated. If necessary, other relationships must be found. This will also be described in paragraph 7.4.5.

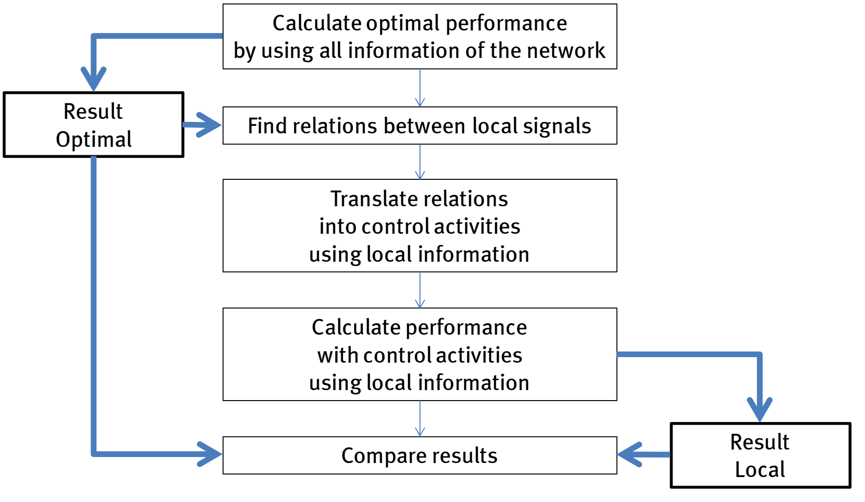


Figure 7.2 The various steps in the applied method

The results of the calculations will show the theoretical possibilities of the control actions and the applied components and can be used for the design of the components.

7.2.1 Methods to control the voltage

Occasional voltage problems are noticed most at the terminals on low voltage level. Several possibilities to improve the network voltage are:

- Distributed storage;
- Sophisticated transformer control;
- Forced power flow.

Distributed storage

Installing storage facilities at (all) LV terminals results in local energy management systems. Such systems could also use the storage facilities of electric cars if available. These systems are not only based on the local needs, but will react also on market prices. Since this item is not a typical network solution it will not be discussed further.

Sophisticated transformer control

The possibilities and shortcomings of transformer control are described in chapter 6 and are summarised here:

- Introduction of on-line tap changers on the MV/LV distribution transformers eventually based on power electronics. A drawback of this method is that a large number of these devices is necessary. Furthermore these devices often do not fit in standard compact MV/LV distribution stations.
- Sophisticated control for HV/MV transformers. Standard transformer control techniques such as fixed ratio or line drop compensation are not sufficient. The control must be able to distinguish typical load feeders from feeders that contain distributed generation.

It must be observed, that the needed control actions may result in an increase of tap changer operations, which if practiced with standard techniques would decrease the lifetime of the tap changer.

Forced power flow

The voltage profile can also be controlled by managing the active power flow in the MV or LV network. A (theoretically) simple way to do this is to connect a storage device at the end of a feeder. In cases of high generation a certain amount of the generated power is stored in the device. This decreases the amount of power towards the beginning of the feeder, resulting in an overall decrease of the voltage level compared to the normal situation of high generation. If the amount of power that is used for storage is large enough, it is possible to obtain a voltage at the end of the feeder that is lower than the voltage at the beginning of the feeder. In case of high load the storage device feeds the loads at the end of the feeder, resulting in an increased voltage level compared to the normal situation of high load. As a result the voltage variations are reduced. If the power is large enough, it is possible to obtain a voltage at the end of the feeder that is larger than at the beginning of the feeder [PROV 005]. The effect of obtaining a high voltage during periods of high load and a low voltage during periods of high generation can be seen as a kind of line drop compensation.

When more feeders are to be controlled (as normally is the case in an ACN) each feeder must be equipped with its own storage device. In the case that two controlled feeders are connected to the same normally open point, it can be advantageous to apply a different solution. This is to transform the NOP between these feeders into an intelligent node [PROV 005]. The principle configuration of the intelligent node is described in chapter 2. The intelligent node in this special case (Figure 7.3) contains a storage device and a power flow controller (PFC).

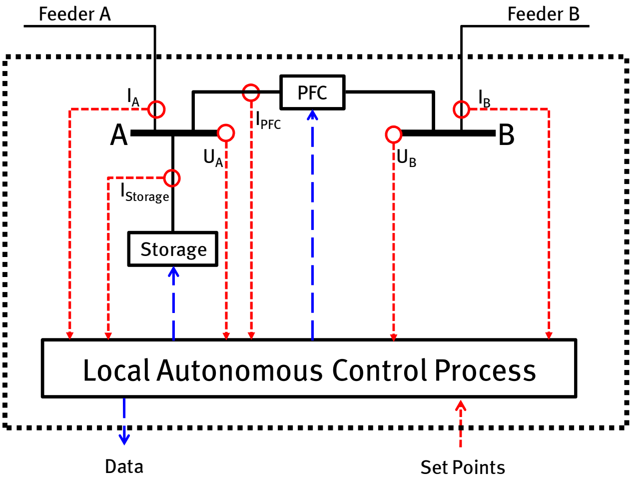


Figure 7.3 Example of the application of an intelligent node connecting two feeders and controlling the voltage profile with storage and a power flow controller (PFC)

The red lines show the inputs for the local autonomous control process. These inputs are the various local parameters like currents and voltages and some set-points received from other controls. From these data it controls the PFC and the storage device and if necessary it sends data to other controls (blue lines).

The currents in the two feeders towards the intelligent node can be described by:

$$I_A = I_{Storage} + I_{PFC} \tag{7.3}$$

$$I_B = -I_{PFC} \tag{7.4}$$

The exchange between the intelligent node and feeder B is controlled by the PFC. The exchange between the intelligent node and feeder A is controlled by both the PFC and the storage device. In this way the exchange between the two feeders and the intelligent node can be controlled independently from each other, as is the case when two separate storage devices were used. As a result, the intelligent node is able to control the voltages at each side independently from each other.

The local autonomous control process of the intelligent node measures the actual voltages and calculates the amount of power to be transferred by the PFC and to be stored by the storage device.

Closing the network with an intelligent node establishes a controlled meshed operation of the network. This solution results in a better voltage profile during normal operation without increasing fault current levels. The power electronic equipment in the PFC minimises the transfer of short-circuit currents from one feeder to the other. The concept also supports a radial network protection philosophy still to be applied. Since voltage and current at both terminals of the intelligent node are known, it is possible to develop an algorithm that is able to detect faults in a feeder towards the intelligent node and if necessary to supply a signal towards circuit breakers to switch off this feeder at the intelligent node. And the control system can receive remote signals for switching in the circuit breakers in order to restore the network. This will help to simplify the protection and restoration philosophy of meshed operated networks.

In case of a malfunctioning, two main contingencies can be distinguished:

- Malfunctioning of the PFC.
- Malfunctioning of the storage device.

In case of a disturbance of the PFC, this device can be by-passed. As a result the power flows in the connected feeders cannot be controlled independently of each other and the short-circuit contributions from one feeder to the other cannot be controlled. However, the storage device controls the power flows in the two feeders simultaneously. In case of a disturbance in the storage device, the PFC takes care of a controlled exchange of power between the two feeders.

The solution of using the intelligent node can be applied on LV level as well as on MV level. The benefit of introduction on LV level is, that the solution is located close to the source of trouble. A possible drawback is that many devices are required. When introducing the system on MV level, only a limited number of devices is necessary.

7.2.2 Proposed control

In this paragraph a control system is proposed that is based on two kinds of voltage control devices:

- Forced power flow by using an intelligent node on MV level that contains a storage device and a PFC.
- A sophisticated HV/MV transformer tap changer control.

The maximum number of voltage control devices is limited to just a few locations in the network (Figure 7.4), namely in the HV/MV substation and at specific normal open points.

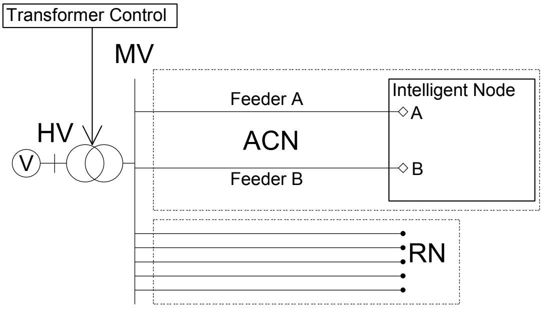


Figure 7.4 The layout of the voltage control

The sophisticated transformer control is located in the HV/MV substation. The tap changer of this transformer and its operation time are similar to a standard HV/MV transformer. The sophistication is based on intelligent signal processing which is discussed further on in this chapter.

Forced power flow control using an intelligent node is located at a strategically chosen NOP between two MV feeders of the ACN. The operation time of this control is fast compared to the transformer control.

In [PROV 006] it is shown that simple control actions of the intelligent node already significantly improves the voltage profile at LV customers in the ACN. This control was based on applying a high voltage at the terminals of the intelligent node in case of high load, and a low voltage in case of high generation. The influence of the intelligent node is best noticed by customers connected close to the intelligent node.

The influence of a sophisticated transformer control is described in [PROV 012]. This control was based on line drop compensation. During cases of high load and low generation this control was based on the load in feeders containing only load. During periods of high generation and low load the control had to be based on the loading of the feeders in the ACN. Such a control has benefits for both the customers in the rest of the MV network (RN) and for the customers in the ACN close to the transformer. A first investigation of the proposed method that combines these controls is described in [PROV 013]. It can be expected that both the voltage profile in the ACN and in the RN will be improved.

7.2.3 Optimal voltage profile

The main task for the controls is to obtain an optimal voltage at every considered customer's connection point. A proposed method for quantifying the voltage quality for a specific moment is the deviation from a reference voltage (U_{ref}) for all these customers:

$$Dev = \sqrt{\sum_i \left(U_i - U_{ref}\right)^2} \qquad (7.5)$$

This reference voltage can be a constant value over the time (e.g. 230 V for LV networks) but may also vary based on load and generation in the network. The reference voltage however always is within the limits stated in norms and standards. The differences are squared, in order to have the same effect for a positive as for a negative voltage difference. Squaring the differences instead of using absolute values, results in a better functioning of optimisation routines.

The optimal voltage profile is then found by minimising this deviation, the so called MinDev method [PROV 006]:

$$MinDev = min \sqrt{\sum_i \left(U_i - U_{ref}\right)^2} \tag{7.6}$$

This means that the controls have to work in such a way that the sum of all absolute deviations from the reference voltage is minimised.

7.3 Modelling

7.3.1 Network configuration

The network used for calculations is a representation of a typical Dutch MV/LV distribution network with underground cables. A part of this network containing several feeders with both load and generation is considered as an ACN. Several measures to limit the influence on the voltage which are described in chapter 3 and 6 already have been taken. The main characteristics of this network are:

- The MV network has a meshed structure but is operated radially. The maximum feeder length is 10 km. All cables are of the type 240 Al XLPE. Between the MV busbar of the HV substation and the first cable of each feeder a reactor is connected in order to limit the short-circuit contribution of the HV network.
- The LV network has a radial structure. Each feeder consists of a 150 Al cable and has a length of 450 m, which is the typical maximum for TN-earthed LV networks.
- The maximum load in an LV feeder results in a voltage difference of 6% between the beginning of that feeder and the end of that feeder.
- The maximum load in an LV network will not overload the MV/LV transformer
- The maximum load of all LV networks connected to an MV feeder will result in a loading of 50% for the first cable section of that MV feeder. This is necessary, because, for redundancy reasons, in case of a disturbance the load of one feeder must be taken over by an other feeder.
- The total load in the network is close to the maximum rating of one feeding HV/MV transformer.
- In the LV networks that are part of the ACN, distributed generation is connected. The simultaneously produced maximum power of this DG will not result in overloading of cables and transformers.
- In MV rings that are part of the ACN, the NOP is replaced by an intelligent node as described earlier in this chapter.

7.3.2 Network model

The network described above is reduced in order to obtain a model to be used for the calculations. This reduction is necessary to speed up the calculations. However, these reductions may not result in loss of accuracy.

The network model used is shown in Figure 7.5. Three MV feeders are modelled in detail (Figure 7.5 left). Two feeders (mixed feeder A and mixed feeder B) contain both load and generation. Together with the intelligent node these two feeders represent the ACN. The third feeder (load feeder) contains only load and represents a typical feeder of the RN. The rest of the load of the RN is modelled on the MV busbar of the substation.

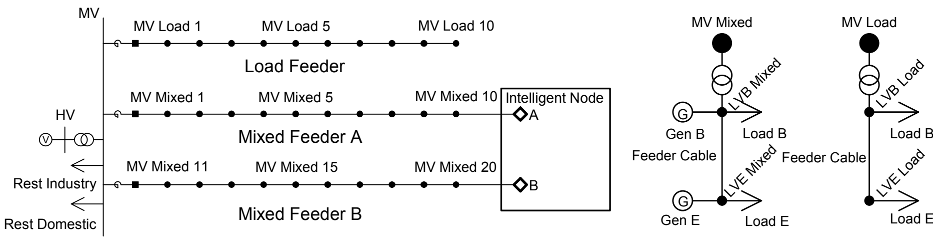


Figure 7.5 Model of the MV network (left) and LV network (right)

The number of LV networks connected to an MV feeder is limited to 10. As a result, the distance between each MV/LV transformer is 1 km. In reality more LV networks might be connected with less difference in distance. However, as the total load of these networks is limited to the 50% loading of the first MV cable, the only difference is the maximum load in each network. When regarding the voltage profile over the MV cable, there is hardly any difference if the total load is divided equally over 10 or over 20 connections.

Each LV network model (Figure 7.5 right) consists of an MV/LV transformer, one feeder cable, two loads and in case of the mixed feeder two generators. The length of each LV feeder cable is 450 meters. The distributed loads and generation of the actual LV network (containing more feeders) are concentrated on two locations in the model, the end and the beginning of the feeder cable. The loads ($Load_e$) and generation (Gen_e) at the end of that feeder cable cause the voltage drop/rise in the feeder cable. The loads and generation ($Load_b$, Gen_b) at the beginning of the feeder cable represent together with $Load_e$ and Gen_e the total load / generation in the LV network.

The maximum value for $Load_e$ can be calculated from the maximum allowed voltage drop. As connection cables towards houses are not modelled, the combination of maximum value for $Load_e$ and zero value for Gen_e must result in a 6% voltage drop over the LV cable to simulate the worst case. As a result, the value of $Load_e$ is 100 kW. The maximum value for $Load_b$ can be obtained from the 50% load of the first MV cable and the already calculated value of $Load_e$. This results in a value of 270 kW. The sum of these loads equals 370 kW. In order to prevent overloading of the MV/LV transformer, it is rated 630 kVA. As a result there is a lot of margin for distributed generation.

It must be noted that when 20 LV networks were modelled on one MV feeder, the value for $Load_e$ would still be 100 kW and the value for $Load_b$ would reduce to 85 kW. As a result a 400 kVA transformer can be used, which is more common.

In order to differentiate for various types of load, two specific load behaviours are defined. The loads in one feeder of the ACN and the loads in the RN are given a domestic load behaviour. The loads in the other feeder of the ACN are given an industrial load behaviour. Also two loads are modelled on the MV busbar, one having an industrial and the other a domestic behaviour. These loads represent the rest of the feeders and have a total value of 45 MW.

The values for Gen_e and Gen_b must be based on the applied scenario of generation. The ratio between Gen_e and Gen_b will be equal to the ratio between $Load_e$ and $Load_b$. Each feeder has a different behaviour of the generation.

As the analysis is based on loadflow calculations, the intelligent node can be modelled as two separate storage systems. For load-flow calculations each storage system can be represented as a single load or generator. The energy stored in the system can be calculated by simple ‘bookkeeping’ of power to the load and duration of that power. When the storage system is charged it can be seen as a normal load. When the system is discharged it can be seen as a negative load.

7.4 Analysis

A pre-condition for the control systems is that they must work with local measurements, and only if necessary with information obtained from other control systems. Therefore the study has to be split in several stages, as was explained in paragraph 7.2:

- Calculate the optimal voltage profile for the network.
- Analyse the results.
- Investigate how to approach the control behaviour.
- Calculate the voltage profile based on this control.

For these calculations, the model is subjected to a scenario of various amounts of generation and load. For each combination of load and generation, a number of load-flow calculations must be performed in order to find the proper settings of the control equipment. The amount of calculations depends on the specific requirement (optimisation or control actions) and on the number of iterations needed for the convergence of the applied methods.

7.4.1 Scenario for load and generation

In principle the number of scenarios to apply to the network is infinite. However, the main purpose is to prove that the concept is functioning under various combinations of load and generation. The scenario sets requirements to the components and possible other controls that have to manage the system. During the initial state of developing the ACN concept it was thought that in such networks a near equilibrium of generation and load was established. Based on this assumption, a scenario is developed in which the amount of energy consumed by the loads equals the amount of energy produced by the distributed generation. This scenario is based on a 1-week measurement (5-minutes average) of load and generation in specific MV feeders in a Dutch network and shown in Figure 7.6. The load data are obtained from two feeders containing either domestic (L_{dom}) or industrial (L_{ind}) loads. The value of 1 pu is based on the maximum load.

The generation data (G_1 and G_2) are obtained from measurements of two different feeders containing generation. The measured generation data are scaled in such a way that the produced energy in that week equals the consumed energy by the loads. The figure shows that generation is low at the beginning and high at the end of the week. This is not necessarily representative for distributed generation, but is acceptable for this experiment.

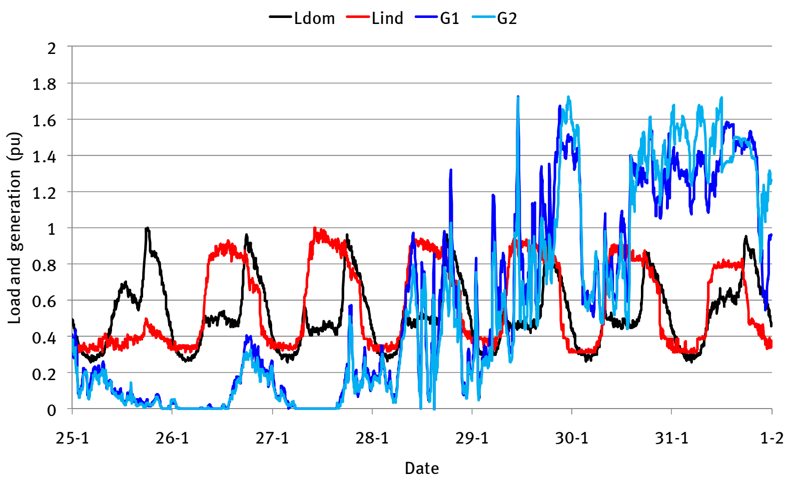


Figure 7.6 Load and generation data

Figure 7.7 shows a rough estimation of the net load in each feeder of the network model. From this figure three different periods can be distinguished for the mixed feeders:

- A period where the load is larger than the generation (25-1 until 27-1).
- A period where the load is almost equal to the generation (28-1 and 29-1).
- A period where the generation is larger than the load (30-1 until 31-1).

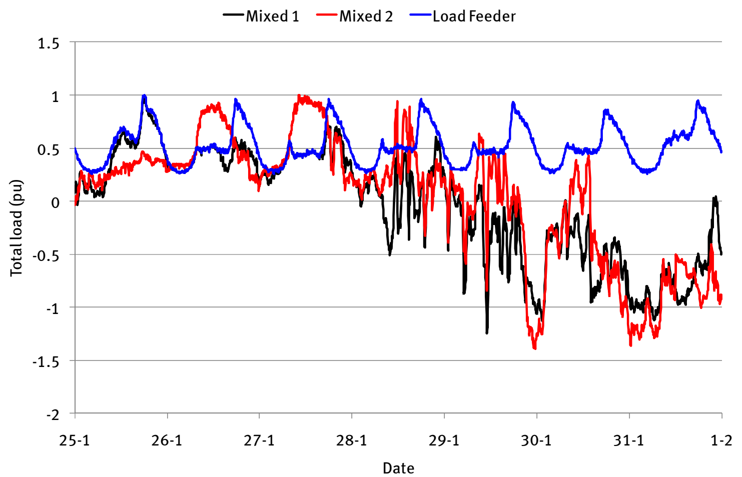


Figure 7.7 Estimation of the net load in each feeder

Without control measures low voltage levels can be expected in both mixed feeders as well as in the load feeder, in the period when the load is larger than the generation. During the days where the generation in the mixed feeders is larger than the loads, the absolute value of the net load in these feeders exceeds a value of 1 pu. Without control measures high voltage levels can be expected in both mixed feeders whereas low voltage levels can be expected in the load feeder.

7.4.2 Control strategies using global information

Based on the profiles for load and generation as described before, calculations must be performed on the network model. For each specific time point the process of Figure 7.8 is followed.

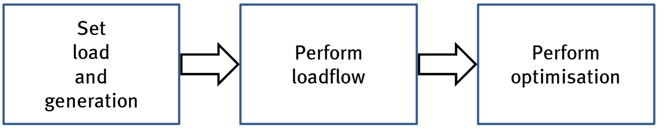


Figure 7.8 Process during optimisation

First the load and generation in the model are set, corresponding to the measured values for the specific time point. Then a load-flow calculation is performed. This load-flow results in a specific voltage profile in the network. Then the optimisation routine will adjust the parameters of the control equipment, in order to obtain an optimum voltage profile. The number of parameters that can be changed and the definition of optimal voltage will be described next.

Control parameters

In order to know which cases have to be analysed, it is necessary to know which parameters influence the voltage deviation. The voltage deviation in the load feeder depends on the load in the feeder and the voltage at the MV busbar of the substation. The only way to influence the voltage deviation in the load feeder at a certain load is the tap changer of the HV/MV transformer. The voltage deviation in the mixed feeders depends on the actual load and generation, the voltage at the MV busbar and the power exchange with the intelligent node. The parameters to influence the voltage deviation are the power exchange with the intelligent node and the voltage on the MV busbar. As a result, three parameters influencing the voltage control can be defined:

- The power exchange between the intelligent node and feeder A, basically only influencing the voltage profile in feeder A.
- The power exchange between the intelligent node and feeder B, basically only influencing the voltage profile in feeder B.

- The tap changer position of the HV/MV transformer, influencing the voltage profile in all feeders.

Possibilities for optimal voltage profile

The optimal voltage profile can be obtained for either only the ACN or for the whole network. The optimal voltage for the ACN alone can be obtained by control activities from both the intelligent node and the transformer. However, the control actions of the transformer might have a negative influence on the rest of the network. Therefore the following steps must be followed:

- First the influence of the intelligent node on the ACN must be investigated.
- The next step is to find out whether further improvement is possible by using the transformer control and what the impact of this control is on the RN.
- The final step is to investigate the possibility of obtaining an optimal voltage profile in both the RN and the ACN and to what amount these profiles differ from the earlier obtained optimal profiles.

As a result, four control actions have to be examined in detail:

- BASE. This is the standard case, to which the other control actions have to be compared. The intelligent node is not working. The tap changer of the HV/MV transformer controls the MV busbar voltage at a value of 1.05 pu with a margin of + /- 0.01 pu.
- OPT2. The tap changer of the transformer controls the MV busbar voltage at 1.05 pu, while the intelligent node is used to obtain a minimum voltage deviation in the ACN.
- OPT3. Both the tap changer of the transformer and the intelligent node are used to obtain a minimum voltage deviation in the ACN.
- OPT4. The tap changer of the transformer and the intelligent node are used to obtain a minimum voltage deviation in the whole network (both the ACN and the RN).

Optimisation method

The optimisation method must be based on the following aspects:

- The active power used by the intelligent node to control the voltage can be varied continuously.
- The transformer tap can only be varied in discrete steps.
- The transformer tap can only be changed one position up or down during each time interval.

For a certain value of the transformer tap position the MinDev value (described in paragraph 7.2.3) is calculated by a minimisation routine based on the "steepest descent method". Parameters to be used in practice are the power transfer by the PFC and the power towards/from the storage device. When the transformer control is involved, this minimisation routine must be performed on three tap settings (actual tap, actual tap -1, actual tap +1). The optimal tap is the one resulting in the lowest value of MinDev.

Since the aim of the study is to prove the possibilities and to show the consequences for the control equipment, the only limitations set are on the power towards the intelligent node:

- The maximum power exchange between the intelligent node and the connected feeders may not result in exceeding thermal limits of components and cables.
- The storage device in the intelligent node may only be charged in the case where the generation exceeds the load in the ACN.
- The storage device in the intelligent node may only be discharged in the case where the load exceeds the generation in the ACN.

7.4.3 Results of the calculations

Several results of the calculations are described here. First the consequences of the applied methods for the LV network are shown, followed by the consequences for the voltages at the transformer and at the intelligent node. Next is explained how the control actions are influencing the voltage deviation in the network. Finally the impact of the actions on the storage device are discussed

Influence on voltages in the LV network

The influences of the various control actions on the voltages in the LV network are shown by visualising the extreme voltages in these networks. Figure 7.9 (for feeder A) and Figure 7.10 (for feeder B) show the maximum and minimum voltages in the LV networks of the ACN for the various control actions. Although an extreme scenario of distributed generation is used, only during a very short period of time the limit for the maximum voltage (1.1 pu) is exceeded in the BASE-case. The effect of the control actions are characterised by:

- Voltage limits will not be exceeded anymore.
- The extreme values of the voltage can be reduced by at least 3%.
- The curves for the maximum and minimum voltage show symmetry around the value of 1 pu.
- All control actions result in an increased margin towards the voltage limits and therefore result in an improved voltage profile.

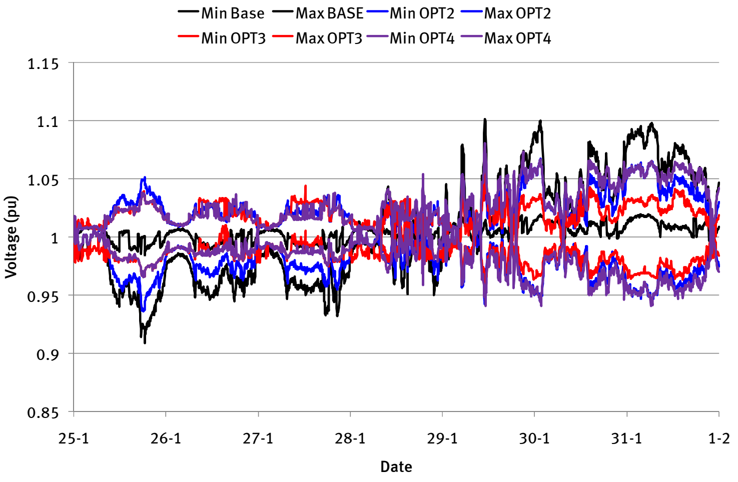


Figure 7.9 Maximum and minimum voltages in the LV networks connected to feeder A of the ACN as a result of the various control actions

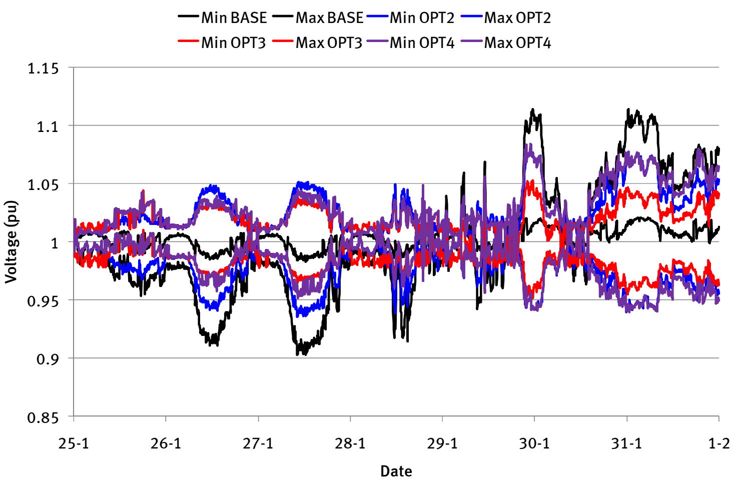


Figure 7.10 Maximum and minimum voltages in the LV networks connected to feeder B of the ACN as a result of the various control actions

Figure 7.11 shows the influence of the various control actions on the minimum and maximum voltages in the RN. Control method OPT2 has no influence compared to the BASE case. The control action OPT3 results in too low values (<0.9 pu) in case of a period with heavy generation combined with heavy load.

This is due to the fact, that this method reduces the voltage on the MV busbar in cases of high generation. As a result, the voltage drop due to the load will result in exceeding the lower limit for the voltage level.

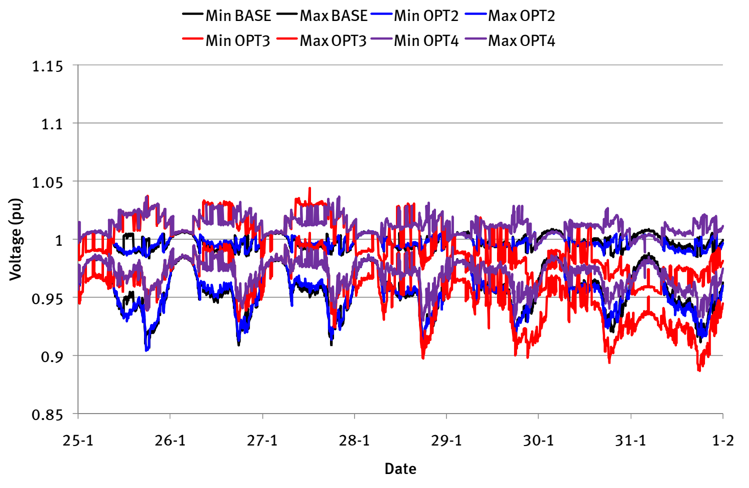


Figure 7.11 Maximum and minimum voltages in the LV networks connected to the RN as a result of the various control actions

Impact on the transformer voltage

The voltages on the MV side of the HV/MV transformer are shown in Figure 7.12. The influence of the method OPT2 is minimal. Sometimes the voltage differs 0.02 per unit from the BASE-case. This is caused by the power exchange with the intelligent node, which influences the power flow through the transformer. In some cases this would result in a voltage outside the limits set for the voltage control of the transformer, so the transformer step is adjusted.

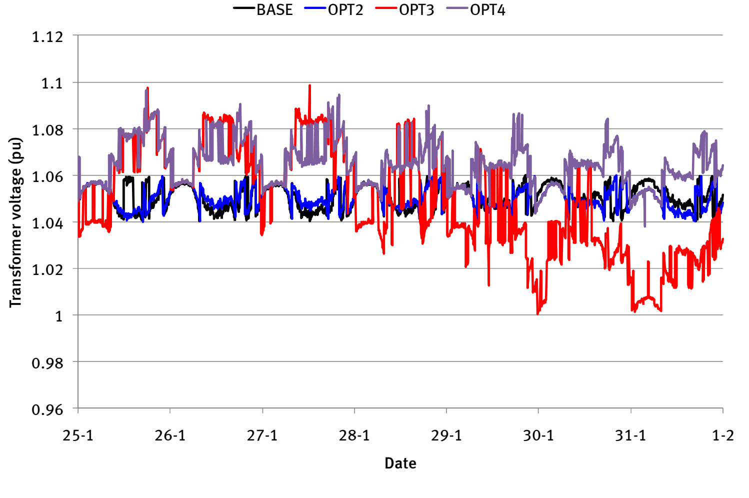


Figure 7.12 Voltage at the MV side of the transformer as a result of the various control actions

The methods OPT3 and OPT4 show that during periods of high load, the voltage is raised compared with the BASE case. This effect can be regarded as line drop compensation. During the periods of high generation, the method OPT3 results in a voltage that is generally lower than in the BASE case. This is because this method reduces the voltage increase in the ACN due to the generation. During this period, the method OPT4 differs from OPT3. In situations where the load is low, the results of method OPT4 follows the same curve as the results for OPT2 and BASE. In the case of high load the voltage obtained by the method OPT4 is higher than that obtained by the methods OPT2 and BASE. During these periods, the voltage drop or rise in the ACN is limited, because load and generation are almost equal. Therefore, the method OPT4 can reduce the voltage drop due to the load in the RN, by increasing the MV voltage.

Impact on the voltage of the intelligent node

The voltages on the terminals of the intelligent node are shown in Figure 7.13 for the terminal connected to feeder A and in Figure 7.14 for the terminal connected to feeder B.

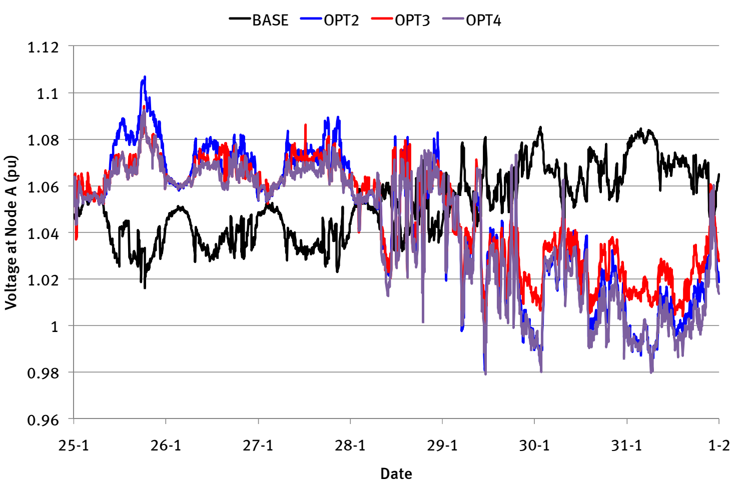


Figure 7.13 Voltage at the terminal of the intelligent node connected to feeder A as a result of the various control actions

The figures make clear, that all methods try to reduce the voltage deviation by applying a high voltage at times when the voltage in the BASE case is low and by applying a low voltage when the voltage in the BASE case is high. The amount of compensation differs for the various actions and depends on the influence of the HV/MV transformer.

During the case of little generation in the first days, the voltage profile in the ACN is positively influenced by the transformer control used by the methods OPT3 and OPT4.

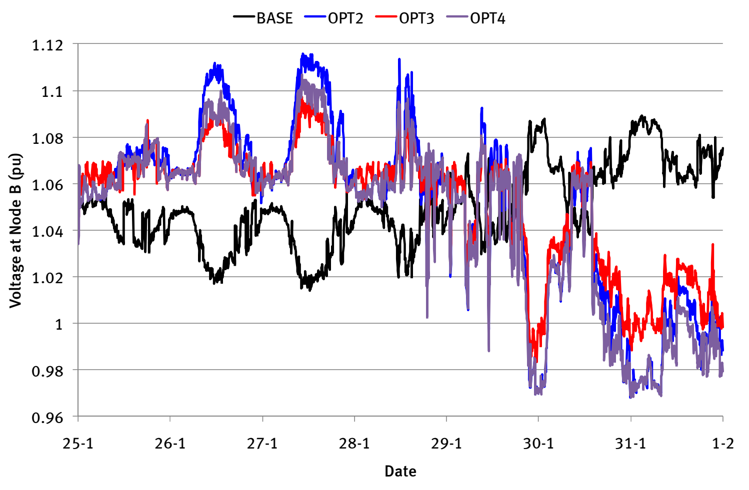


Figure 7.14 Voltage at the terminal of the intelligent node connected to feeder B as a result of the various control actions

Therefore the methods OPT3 and OPT4 need less support from the intelligent node than OPT2. In the period of high generation, the method OPT3 positively influences the voltage profile in the ACN by reducing the voltage on the MV busbar. Therefore, less support is necessary than with OPT2 and OPT4.

Voltage deviation

The voltage deviation (formula 7.3) is a measure for quantifying the voltage quality on the various nodes in the network. As described in paragraph 7.3.2, the voltage deviation can be calculated from the differences between the various node voltages and a reference value. For the calculations in this chapter a value of 230 V is used as reference voltage. The voltage deviation is calculated for four situations:

- DevA, the voltage deviation for the LV nodes connected to mixed feeder A.
- DevB, the voltage deviation for the LV nodes connected to mixed feeder B.
- DevRN, the voltage deviation for the LV nodes connected to the load feeder.
- DevTot, the voltage deviation for all LV nodes in the network.

Figure 7.15 shows the voltage deviations for the various feeders in the BASE case. When this figure is compared with the Figure 7.6 (on page 193) showing the load and generation, it is clear that for the ACN, the voltage variation is largest during periods of high load and no generation and during periods of high generation and low load.

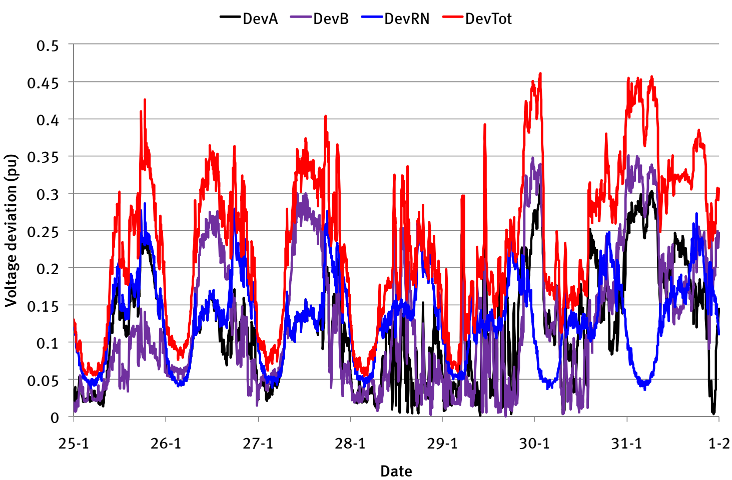
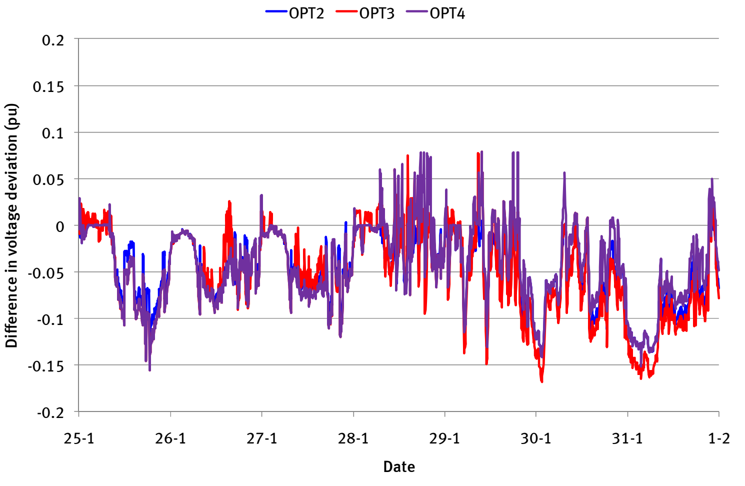


Figure 7.15 The voltage deviation for the various feeders in the BASE case

For the RN the voltage variation is largest during periods of high load. As the voltage deviation in the total network depends on the voltage deviation in the ACN and the voltage deviation of the RN, large voltage deviations can be observed in both cases of high load and of high generation.

The effect of the various control actions on the voltage deviation is shown in Figure 7.16 for both feeders of the ACN, in Figure 7.17 for the RN and in Figure 7.18 for the total network. In these figures the difference with the BASE case is given. Here a negative value means that the control action has reduced the deviation, meaning an improvement. A positive value means that the voltage deviation is larger than without control action.

As can be seen from Figure 7.16, the various control actions all reduce the voltage deviation in the ACN. During periods of high load and low generation the methods OPT3 and OPT4 show a better performance than OPT2. During periods of high generation the method OPT3 performs better than OPT2, where the performance of OPT4 hardly differs from OPT2.



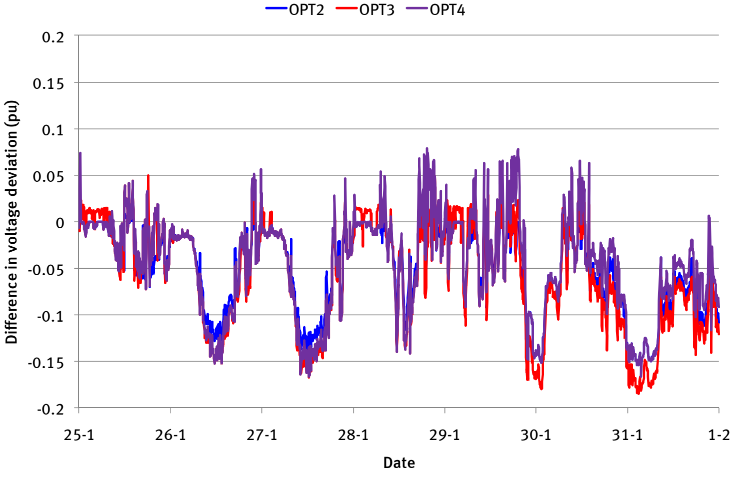


Figure 7.16 Comparison of the influence on voltage deviation in feeder A (top) and feeder B (bottom) of the ACN as a result of the control actions

As can be seen from Figure 7.17, the voltage deviation in the RN is influenced by both OPT 3 and OPT4 and not by OPT2. The method OPT2 sometimes shows a small influence (both negative and positive), due to the power exchange with the storage in the intelligent node. This exchange influences the current in the HV/MV transformer, which can change the transformer tap compared to the BASE case, resulting in a change of 0.05 pu in the voltage deviation. When comparing the influence of OPT3 and OPT4, it can be seen, that in the beginning of the examined period, when generation is low, both methods reduce the voltage deviation. However, at the end of the examined period, when generation is high, the method OPT4 still reduces the voltage deviations, where OPT3 increases it.

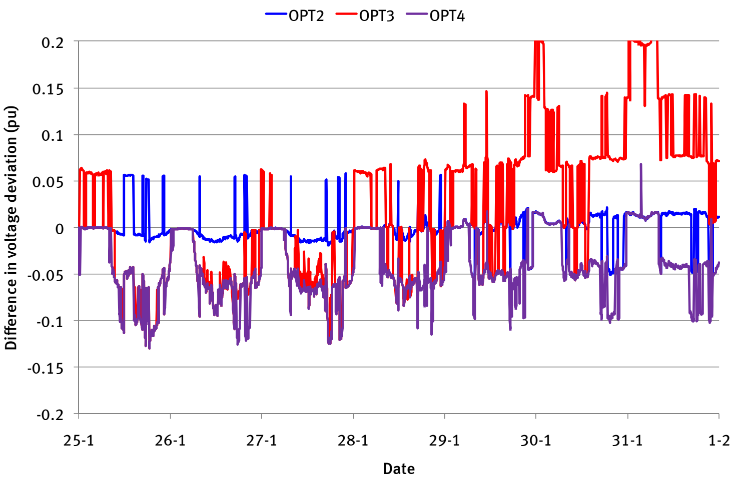


Figure 7.17 Comparison of the influence on voltage deviation in the RN as a result of the control actions

As expected, it can be seen from Figure 7.18 that for the total network the method OPT4 has the best reduction of the voltage deviation. When comparing OPT4 with OPT2 it can be seen that OPT4 performs better in periods with low generation (the first part of the examined period). In cases with high generation however, both OPT2 and OPT4 have the same performance.

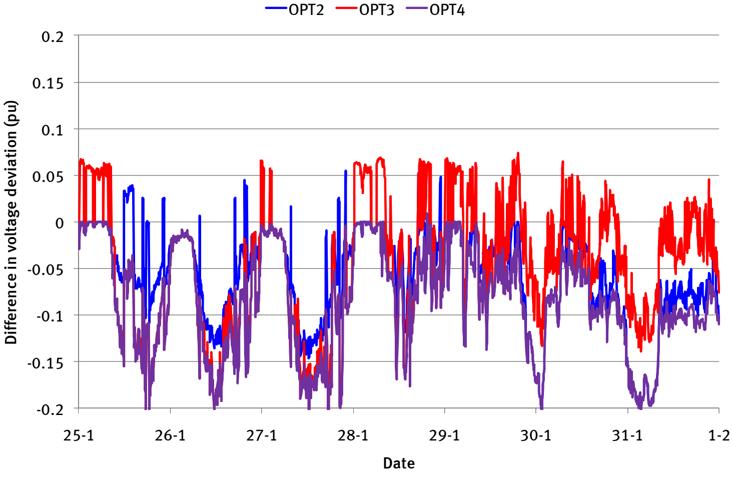


Figure 7.18 Comparison of the influence on voltage deviation in the total network as a result of the control actions

Classification

The results can also be shown according to the power quality classification method as introduced in [COBB 001] and described in Appendix E. From the values over the examined period the mean value and the standard deviation of the voltage for each node can be calculated. These data can be visualised in a graph showing the standard deviation as a function of the mean value. In this graph specific areas are defined showing the quality graduated from A (very good) to F (very poor). The line between classification area C and D is based on the limits stated in EN 50160 regarding slow voltage variations. Figure 7.19 shows this classification for each individual point in the LV network.

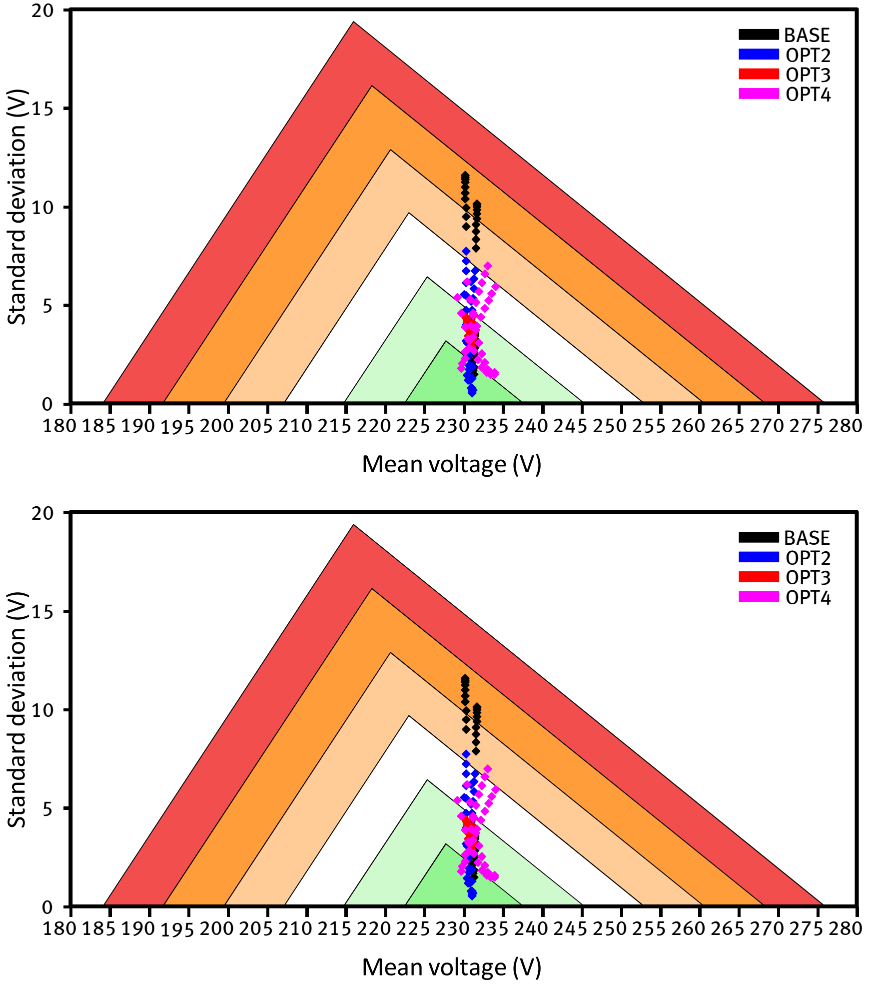


Figure 7.19 Classification of the results for the various control actions in the ACN (upper plot) and RN (lower plot)

The upper plot shows the results for the LV nodes in the ACN, the lower plot shows the results for the LV nodes connected to the load feeder (RN). In the base case many points of the ACN lay outside classification zone C, which is not acceptable. As a result of all three control actions most points lay within classification zone C or better. For the RN many points lay close to each other. For every control action two groups of points can be distinguished. One group is formed by the points close to the MV/LV transformer, the other group is formed by the points at the end of the LV cables. For the RN the method OPT2 has the same results as the base case. Most points have classification A or B. The method OPT3 results in a larger standard deviation and a slightly lower mean value. As a result half of the points are moved towards classification C. As a result of method OPT4 all point are either in or close to classification A.

Influence on storage

The feasibility of the proposed control actions depends on the capacity of the storage equipment. The example used in this study case is based on a period in which the produced energy of the DG in the ACN equals the consumed energy by the loads. In such a case the storage device can act as a temporary buffer and the energy contents at the end of the observed period should equal the energy amount at the beginning of the period, if no conversion losses are taken into account. However, this is not the case for the various methods.

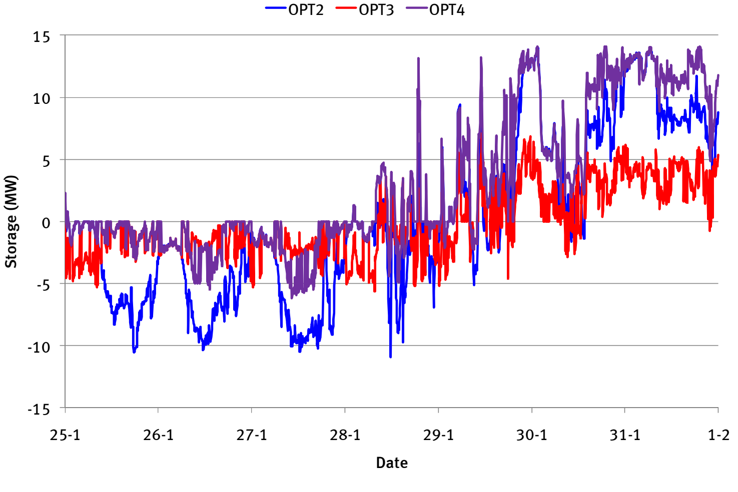


Figure 7.20 Power exchange of the storage device (positive values mean storing energy)

Figure 7.20 shows the power exchange of the storage device for the various control actions. A positive value means that energy is stored. In the first part of the examined period, when the load is larger than the generation, the power is negative and energy is delivered by the storage device.

The methods OPT3 and OPT4 require less power from the storage device, because the voltage is also improved by the HV/MV transformer. In the second part, when generation is larger than the load, the power is positive and energy is stored. The methods OPT2 and OPT4 require more power to be transferred to the storage device than OPT3. This is due to the fact, that OPT3 can also use the HV/MV transformer to control the voltage. In this period the transformer control used by OPT4 is limited, because it has negative impact on the voltage in the load feeders and therefore this method requires about the same amount of storage as OPT2.

The consequences for the energy content of the storage device are shown in Figure 7.21. In this figure, showing the result for a lossless conversion, it is assumed that the energy available at the start of the analysis is large enough to cope with the discharging needs of the first days.

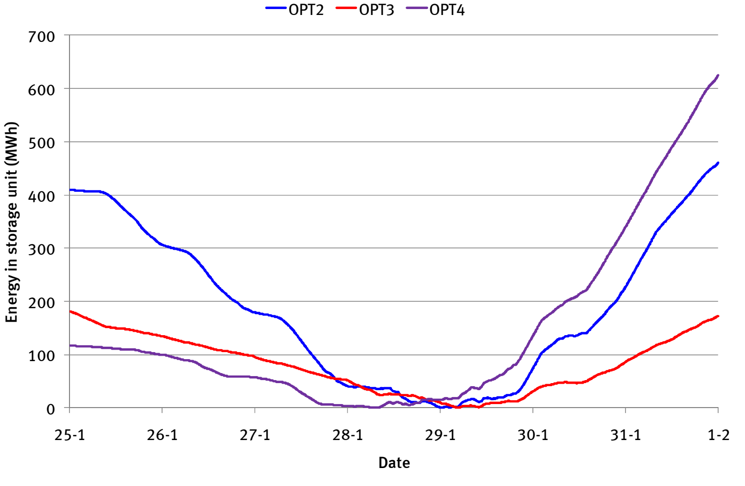


Figure 7.21 Energy content of the storage device for the various methods

Both methods OPT2 and OPT3 are almost energy neutral. The energy content at the end of the considered period equals the energy at the beginning of that period. Method OPT4 will result in a larger energy content at the end of the considered period than at the start. When losses are included, both methods OPT2 and OPT3 will result in a negative energy balance, where more energy is required from the storage device than is stored. Even in this situation method OPT4 will result in a positive energy balance, where more energy is stored than extracted.

The required power and energy content of the storage device is beyond nowadays technology. Storage devices of this size are not available for this voltage level yet. It is questionable whether this will be in the near future. However, the aim of this study is to show the possibilities of the controls and the challenges for the components.

Some further remarks are necessary when judging the size of the proposed storage device:

- The applied scenario of load and generation is just an example for a network with distributed generation. If other scenarios of load and generation are considered, other results for the storage system will be obtained. In cases where the amount of generation is less, there is less need for storing energy and method OPT4 will become more feasible.
- The applied scenarios for load and generation in the feeders connected to the intelligent node look very similar. During periods of high load/generation in one feeder there is also a high load/generation in the other feeder. As a result, there is little profit from the meshed operation. Most of the voltage control is performed by the storage device. It is advisable to connect the intelligent node between two feeders with different profiles, for example a mixed feeder and a load feeder. This will reduce the amount of storage needed.
- The optimal voltage profile based on the MinDev method forces all voltages in the LV network round the applied reference voltage of 1 pu. As a result, there is a large difference between the extreme voltages and the limits set by nowadays norms. Varying the reference voltage based on load and generation conditions may decrease the forced power flows and energy storage.
- Even in this worst case scenario, the voltage limits are hardly exceeded when no control actions are taken. Control is actually only needed in case of high generation and low load.
- In order to cope with the differences in stored and required energy a supervising energy management system is needed. This system must optimise the energy content of the storage system for the expected developments in load and generation. When a period of heavy load is expected, the system must be fully charged, when a period of high generation is expected, the system must be fully discharged. These charging and discharging actions can be performed in periods of low load and low generation, because in those periods the voltage in the network shows low deviations from the reference voltage. Discharging of the system can also be applied with charging of electric vehicles.

7.4.4 Consequences for the controls

The above described control actions use information of all LV customers in the network in order to obtain an optimal voltage profile. It should be investigated whether the control could use only local measurements or will need further information from other controls to obtain the same results. Therefore, relations between the various signals must be found. Regarding the intelligent node there is a relation between the active power and the voltage at the connections of this node. Regarding the transformer control there is a relation between the voltage on the MV busbar and the active power required by the loads in the network.

Intelligent node

The calculations using global signals show that there is a relation between the active power towards a connection of the intelligent node and the voltage on that node.

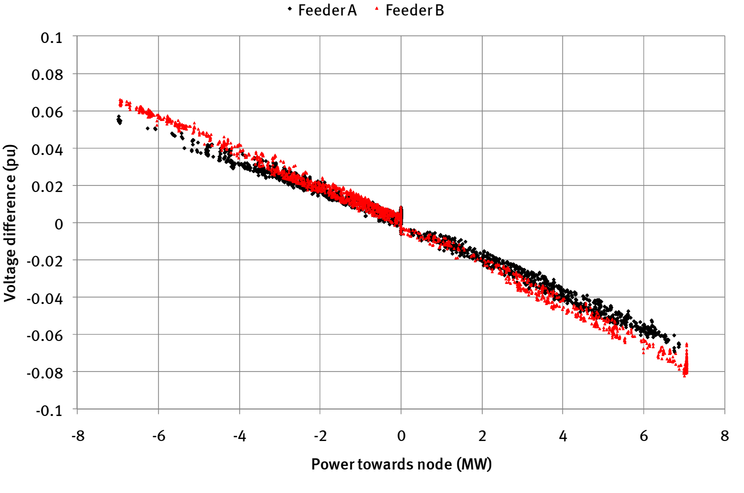


Figure 7.22 Voltage difference at the terminals of the intelligent node as function of the power towards that node for method OPT2

Figure 7.22 shows the voltage difference from a reference value of 1.05 pu for both terminals of the intelligent node as a function of the power towards that node for method OPT2. At both terminals, this voltage difference almost linearly depends on the power towards the terminal. The slopes of the curves differ. This is due to a difference in cable length of the different feeders. Around the zero value a number of data points is outside the expected line. This is due to the restriction that storing energy is only allowed when there is more generation than load. The results for feeder B show some data points outside the expected line for maximum power. This is due to the fact that the amount of power towards the intelligent load is limited by the maximum current rating of the cables.

For the methods OPT3 and OPT4 the voltage at the MV busbar of the HV/MV transformer has to be used as reference voltage instead of a fixed value of 1.05 pu.

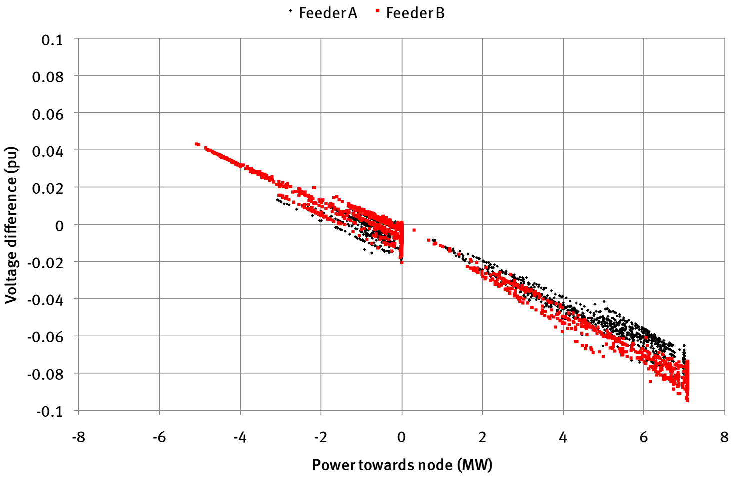


Figure 7.23 Voltage difference at the terminals of the intelligent node as function of the power towards that node for method OPT4

Figure 7.23 shows the voltage difference from the voltage of the MV busbar and both terminals of the intelligent node as a function of the power towards that node for method OPT4. Also here linearity can be observed. However the data points show a larger deviation from a straight line than in the case for OPT2. When the power flow is away from the intelligent node (negative values) the largest deviations occur around P=0. Here the intelligent node wants to store energy, but this is not allowed because the actual load in the controlled feeder is larger than the generation. In the case where the power flow is towards the intelligent node, the deviations tend to increase with increasing power.The control actions of the intelligent node need therefore to be defined by two lines showing the desired voltage as function of the power towards the intelligent node. One line is used for the case where the power is negative and one is used for the case where the power is positive.

Transformer control

The voltage of the MV busbar as function of the load in the network is shown in Figure 7.24 for OPT3 (upper plot) and for OPT 4 (lower plot). The points show the calculated voltage versus the load in the network. These dots can be grouped in parallel lines (for several transformer tap changer positions) each showing a decrease of the voltage as a result of an increase of the load. The average voltage of each line increases when the load increases.

This is shown with the straight line. This behaviour is typical when line drop compensation is used. The slope of the dashed line is a measure for the compensation factor.

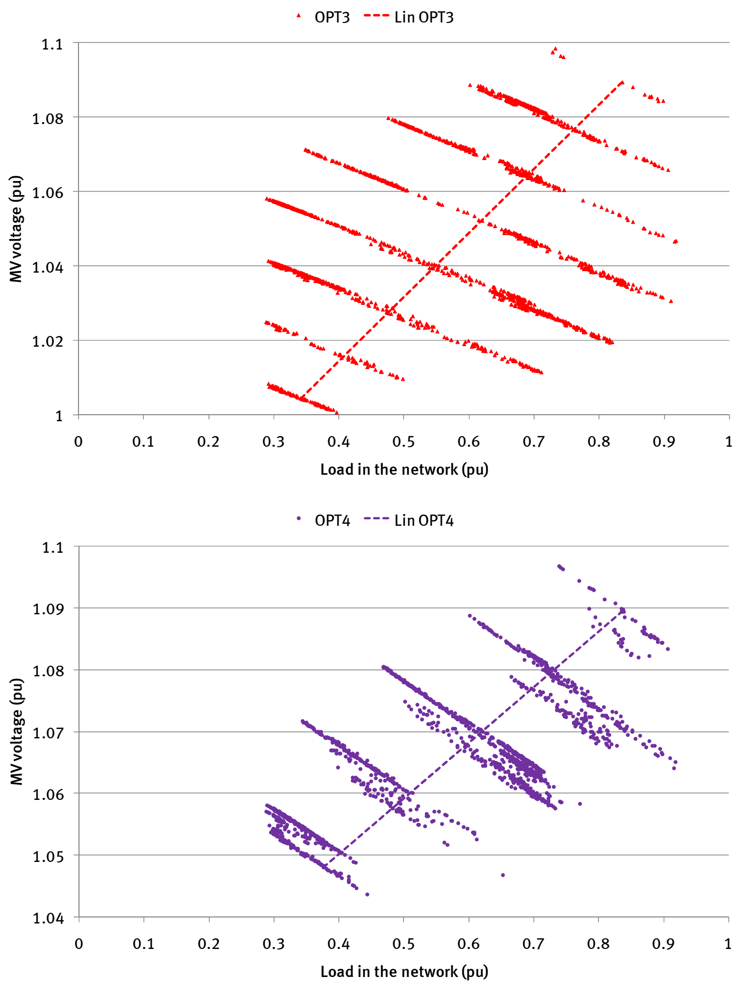


Figure 7.24 Transformer voltage as function of load in the network when applying method OPT3 (upper) and method OPT4 (lower)

The two plots show some differences. The slope of the dashed line differs and the lowest voltage as a result of OPT3 is less than the lowest voltage as a result of OPT4. These low voltages as a result of method OPT3 have a negative impact on the voltages in the load feeders. This is avoided by method OPT4. As a result, the group of data points around the value of 1.05 pu for the method OPT4 consists of almost one third of all data points.

In Figure 7.25 the results of method OPT4 have been split for the cases where the load in the ACN is larger than the generation (Load) and the cases where the generation in the ACN is larger than the load (Gen).

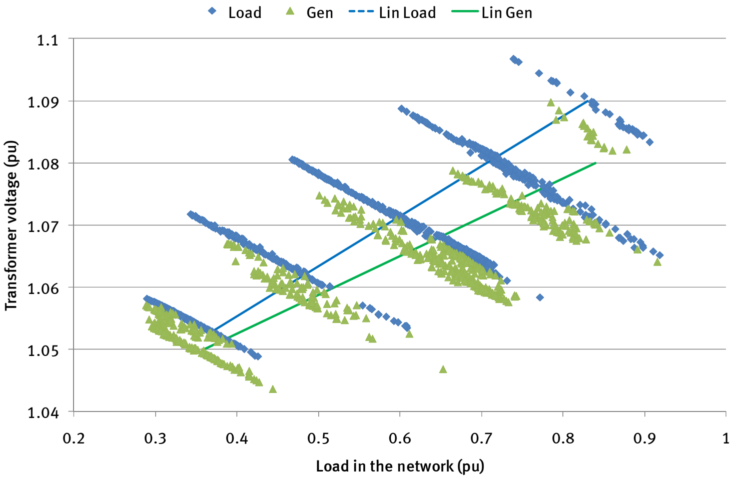


Figure 7.25 Transformer voltage as function of load in the network when applying method OPT4

This figure shows that the points belonging to the cases where the generation is larger than the load in general have lower values than the points belonging to the cases where the load is larger than the generation. Also the straight lines representing the compensation factor for line drop compensation differ. Therefore OPT4 must be considered for load conditions and generation conditions separately.

The method OPT3 can be applied with line drop compensation over the full range of load. For method OPT4 it is advisable to split the transformer control:

- During conditions where the load in the ACN is larger than the generation, line drop compensation based on the line Lin Load must be applied.
- During conditions where the generation in the ACN is larger than the load, line drop compensation based on the line Lin Gen must be applied.

In all cases this line drop compensation must use the value of the actual load in the network. However, the transformer notices a combination of this load, the actual generation in the network and the storage by the intelligent node. Therefore, the transformer must be equipped with an intelligent line drop compensation method, that is able to distinguish generation from load.

When measuring all feeders separately (Figure 7.26), typical load feeders can be recognised, because these loads have a high predictability. In the other (mixed) feeders the generation can be seen as a difference between the expected load and the measured feeder loading.

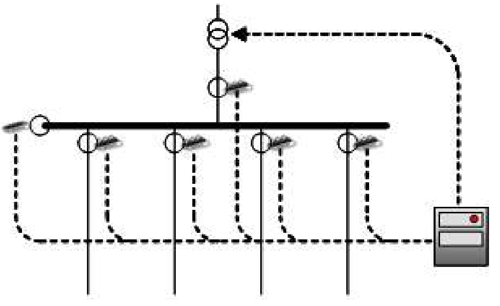


Figure 7.26 The transformer control needs information from all feeders

As most load profiles are highly predictable every day, the deviation from this profile must be due to generation. This method can be improved when measurements of specific generation is available [PROV 003] as described in chapter 6.

7.4.5 Control strategies using local information

Based on the profiles for load and generation as described earlier, new calculations must be performed on the network model. For each specific time point, the process of Figure 7.27 is as follows.

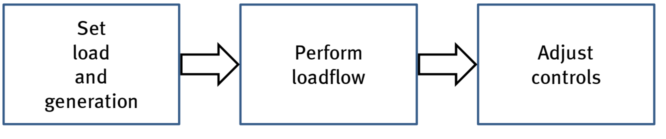


Figure 7.27 Process during control actions based on local control

First the load and generation in the model are set according to the measured values for the specific time point. Then a load-flow calculation is performed. This loadflow results in a specific voltage profile in the network. Then the control routine will adjust the parameters of the control equipment according to the control strategies. This is an iterative process based on actual and required voltages and powers.

Control strategies

Based on the findings in the previous paragraph several control actions based on local measurements were examined:

- LOC2. This method is based on OPT2. The tap of the transformer controls the voltage on a value of 1.05 pu. The intelligent node controls its voltage as a function of the power at its terminals as shown in Figure 7.22.
- LOC4. This method is based on OPT4. The tap of the transformer uses two different modes of line drop compensation, based on the actual load in the network, according to Figure 7.25. Differentiation is made between periods where the load in the ACN is larger than the generation and periods where the generation is larger than the load. The intelligent node controls its voltage as function of the power at its terminals, as shown in Figure 7.23.

Results

The difference for the voltage deviations between method OPT2 and LOC2 is given in Figure 7.28 for both feeders of the ACN. Here a positive value means that LOC2 is worse than OPT2.

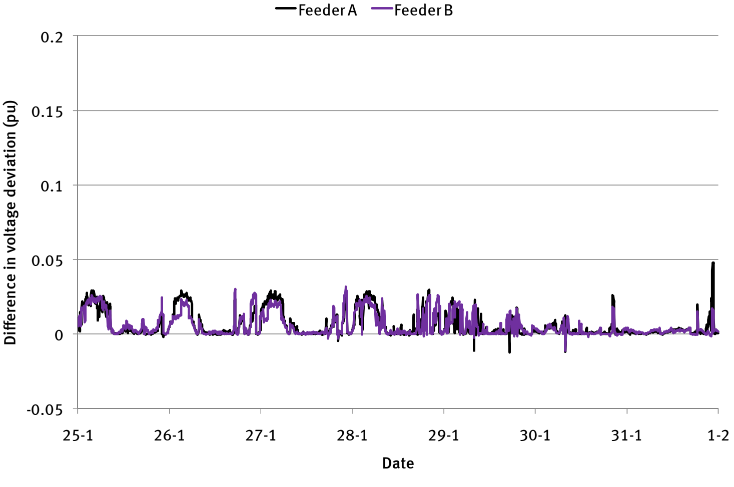


Figure 7.28 Differences between method OPT2 and LOC2

The figure shows that a good similarity is obtained. Differences mainly occur when the deviation is small in both methods.

The difference for the voltage deviations between method OPT4 and LOC4 is shown in Figure 7.29 for both feeders of the ACN and for the total network. Here a positive value means that LOC4 is worse than OPT4.

Good similarity is obtained during the period of high generation and during periods of low load. However, during the periods of high load noticeable differences are visible. This is due to the fact that the transformer control does not act as expected, resulting in a different tap changer position and as a result in a difference in the voltage. The intelligent node uses this voltage as a reference voltage and therefore almost the same differences in deviation for the ACN and the total network are visible.

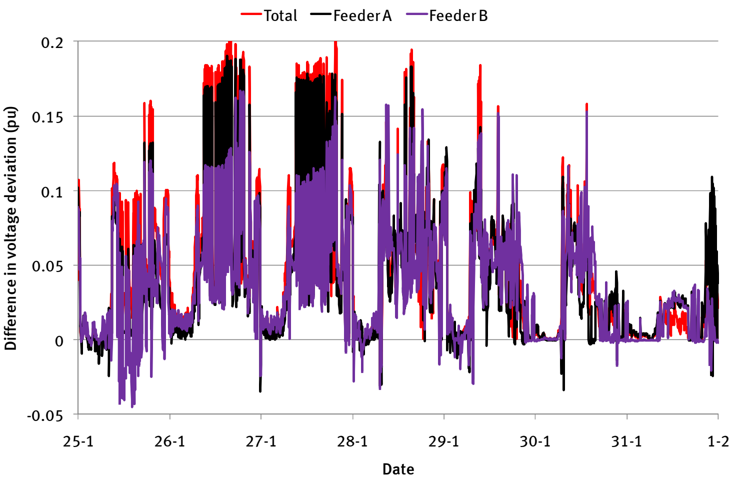


Figure 7.29 Differences between method OPT4 and LOC4

As was shown in Figure 7.25, various tap changer positions can be applied for the same load, especially during situations where the load is larger than the generation. In order to obtain a good representation of the method OPT4, the transformer control needs to differentiate between more combinations of load and generation, resulting in a more complex control scheme. This differentiation is not investigated in this study.

It can be concluded that the results of optimisation method LOC2 can be implemented by using only local measurements at the intelligent node. Method LOC4 requires a complex control both for the intelligent node and for the transformer. The intelligent node needs local measurements of the voltage and power and additional information of the voltage at the MV busbar of the substation. The transformer control must distinguish various combinations of actual load and generation in order to obtain correct settings of the voltage control.

7.4.6 Simple actions

From the previous paragraphs it becomes clear that in principle it is possible to obtain an optimal voltage profile in the network, which means that the deviations from 230 V are minimised. These control actions however require a lot of storage activities in the intelligent node, as the voltage at the terminals of the intelligent node must be high in case of high load and low generation whereas the voltage must be low in case of low load and high generation. Some of these controls also require complex control schemes.

Therefore also a simple control mode (C105) is investigated. This method keeps the voltage at the terminals of the intelligent node on a constant voltage level of 1.05 pu, which is the same as the voltage at the MV busbar of the HV/MV substation.

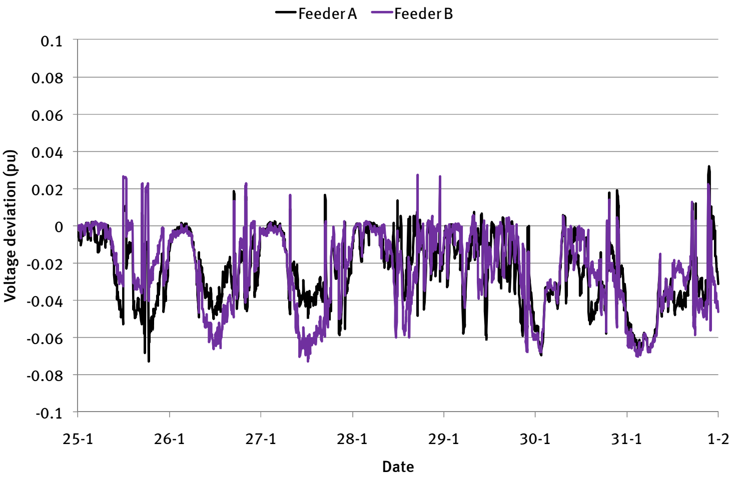


Figure 7.30 Differences in voltage deviations between method BASE and C105

Figure 7.30 shows the difference of the deviations in feeder A and feeder B for this method and the BASE case. A negative value means that method C105 performs better than the BASE case. This method decreases the voltage deviation especially in the cases where the BASE case shows large values.

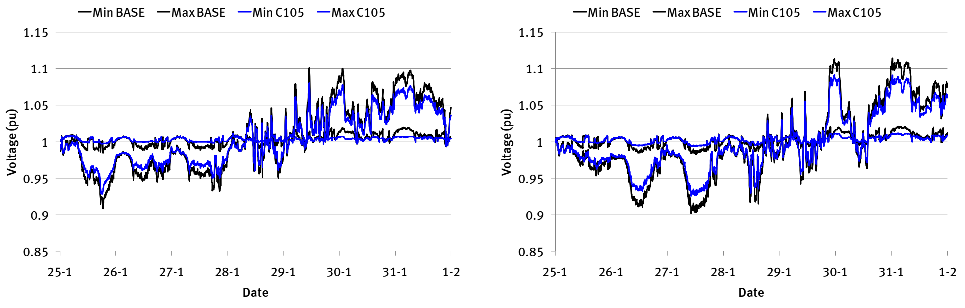


Figure 7.31 Differences in extreme voltages between method BASE and C105 for mixed feeder A (left) and mixed feeder B (right)

As a result the extreme values of the voltage are reduced when compared with the BASE case, as shown in Figure 7.31.Also the amount of energy required in the storage device is limited, as is shown in Figure 7.32.

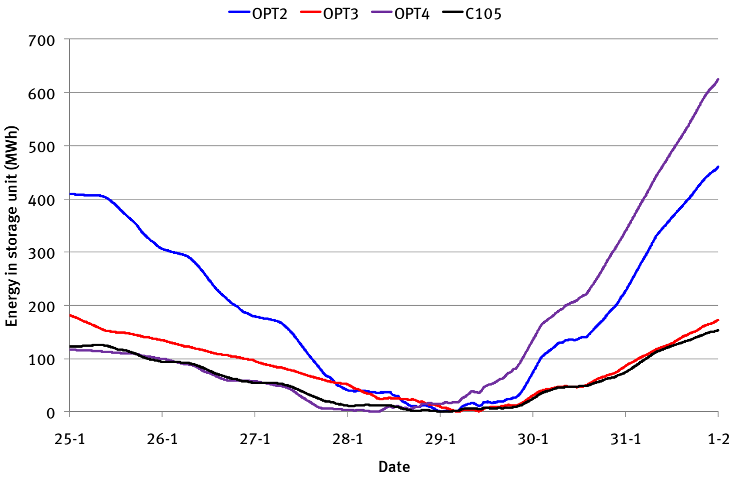


Figure 7.32 Energy contents of the storage device for the various methods

During the first part of the observed period, the amount of stored energy is similar to method OPT4, during the last part it is the same as OPT3.

This method, requiring simple control actions, is able to limit the effects on the voltage in cases where it is needed most. Although the voltage profile is far from optimal, no voltage limits are exceeded and the required storage capacity is limited. This performance is sufficient for practical operation of the network.

7.5 Conclusions

A future distribution network control concept has been developed. It is based on the transformation of parts of the network that contain a mixture of load and generation, into autonomously controlled networks (ACN). This results in a distribution network containing several ACNs and a number of feeders that contain only load. The concept of the ACN establishes controlled meshed operation, which enables performance within all limits regarding voltage, current en protection for both normal and disturbed operation even in the case of large amounts of DG. In the ACN the normally open point (NOP) is replaced by a so called "Intelligent Node". This node contains a power flow controller and a storage system. This concept of the intelligent node enables voltage control by controlled power flow. The intelligent node also minimises the short-circuit contribution from one feeder to another feeder and supports the radial network protection philosophy to be applied in meshed operated networks.

Control strategies were developed in order to obtain an optimal voltage profile, using the intelligent node and an intelligent voltage control on the HV/MV transformer.

The optimal control of the intelligent node is a voltage control, based on the linear dependence of the voltage and the power flow to the intelligent node. The voltage needs to be compared with a reference voltage. This reference voltage is either a fixed value or the voltage at the MV busbar.

The HV/MV transformer control must distinguish between situations where the load in the ACN is larger than the generation and situations where the generation in the network is larger than the load. In both cases the control of the transformer uses line drop compensation. However, the set-points for the voltage and the compensation factor differ. In cases where the load is larger than the generation, several combinations of load and generation must be distinguished in order to obtain the correct set-points. This requires information and knowledge on the amount and behaviour of the load and generation in the network.

Especially during worst cases (high load combined with low generation or high generation with low load), large amounts of power must be exchanged with the storage device. This sets requirements to the storage devices which problem cannot be solved with today's technology.

A voltage control based on a fixed value at both the terminals of the intelligent node and the MV busbar of the HV/MV substation will not result in the optimal voltage profile, but will however guarantee a good voltage quality and might therefore be a good alternative.

8 Conclusions, contribution and future research

New developments in distribution networks, like the increasing penetration of distributed generation and the introduction of new sensitive equipment, lead to more stringent requirements for nowadays and future networks. In order to study the impact of these developments, various aspects regarding design and operation of these networks were investigated:

- MV and LV network design;
- Coordination of voltage and current;
- Evaluating and analysing tools and methods;
- Protection, substation automation and fault location;
- Impact of distributed generation.

Finally an example is given of how to control the voltage in a network with a high penetration of DG with the help of power electronics and storage based on the concept of autonomously controlled networks.

In this chapter the main conclusions are summarised, the thesis contributions are highlighted and some recommendations for future research are given.

8.1 Conclusions

MV and LV network design
Modern MV networks combine the benefits of symmetrical loading, typical for European systems, with the multi-earthing concept, typical for North American systems.

Because distribution networks in the Netherlands are mainly constructed with underground cables, the reliability of these networks is rather good compared to the networks in the rest of the world.

One of the solutions is to develop an autonomously controlled network concept, based on intelligent nodes. Most of the innovative techniques are already developed but must be adapted for the distribution voltage level and must meet the requirements of network operators and the customers connected to these networks.

Coordination of voltage and current
Managing current and voltage both in normal and in disturbed operation requires a good network design and a good earthing concept.

Regarding the normal operation of a distribution network, keeping the voltage within the specified limits is of major concern. This may be achieved by choosing the right combination of network components and controlling mechanisms. Over-sizing network components may be a technical solution, but it will not always be the most economical solution.

In MV and LV networks, cables have a better performance than overhead lines. The relatively small margin in costs makes it possible to choose cables with larger diameters. By choosing larger diameters and reasonable cable lengths, problems with voltage and other power quality items can be reduced.

Disturbances in network parts of one voltage level may have impact on the own voltage level, but also on network parts of lower voltage levels. The impact on voltages and currents has been listed. Short-circuits have their impact on over-currents, transient currents and voltages, dips, swells, increased negative-sequence voltages, and have their impact on the safety of people and apparatus. In LV networks the loss of a neutral may cause voltage problems in customers' installations.

Regarding the earthing of underground cable distribution networks it is recommended to use impedance earthing in the MV network combined with a TN earthing in the LV network. Using impedance earthing for an MV cable network reduces the risk of multi-phase faults causing large fault currents and dips. It also reduces the risk on transient over-voltages due to re-striking of cable faults.

A TN system for the LV network reduces the risk of damaged apparatus and maintains safety for people. However, care must be taken for the earthing of other service providers.

Evaluating and analysing tools and methods

Calculating methods originally were developed for the use in HV network studies. Gradually these methods migrated to advanced tools for MV and LV network models. Distribution systems have a totally different scope of study than transmission systems. For example, stability problems seldom occur in distribution systems but power quality problems are of growing importance.

Modern applications are based on the traditional load-flow and short-circuit calculating methods. They combine available data and extended network models in selectively repeated calculations. Their output is tuned to the questions for network analysis, design and operation. New applications have been developed for protection coordination, dips evaluation, fault location, network restoration, closing normally open points and MV network state-estimation.

There are characteristic differences between the power systems of HV, MV and LV levels. These differences are the cause of specific calculating tool requirements for each voltage level. One of these requirements for LV calculations, concerning the large diversity of loads, led to the development of a stochastic load-flow. Also economical optimisation is special at LV and MV.

The concern of safety for customers and the combination with public lighting led to the development of a new extended cable model. One of the main items was the complexity of understanding the return path in a system with multiple contacts to earth.

In LV and MV network calculations the accuracy of the models and the availability of data are the main obstacles.

Protection, substation automation and fault location

The protection of MV networks must be reconsidered, due to new developments on safety and power quality. Also distributed generation will influence the protection philosophy. It will be necessary to coordinate the protection of the network with the protection of the generators.

Besides protection there is an increasing need for more information processing and tools to manage and operate the distribution network. Two recent developments concerning substation automation and fault location are based on the research of this thesis work.

With the so called SASensor solution the introduction of substation automation will be straightforward, fast and economically feasible. With this system a sophisticated protection is possible. The open structure facilitates future extensions.

Secondly, a new system for fault location in MV networks has been developed. This system is based on available data processing techniques. The system can pinpoint two- and three-phase faults within 100 m. Single-phase faults in earthed networks can be located with an accuracy of about 500 m. The time between the actual fault happening and the calculation of the possible fault location is less than five minutes and mainly depends on the transmission time of the relevant data from the substation to the control centre. The accuracy of fault location mainly depends on the accuracy of the network model.

Influence of distributed generation

In normal operation DG causes more spread in the voltage profile. The control of the voltage by the feeding HV/MV transformer is affected when this transformer is equipped with a voltage controller based on line drop compensation.

In case of a short-circuit, all DG units will contribute to it. As a result the short-circuit currents may be higher than expected and a possible reverse current direction can disturb proper functioning of the protection, which leads to blinding, false tripping and unnecessary tripping of the protection. However, blinding of protection is not expected in cable networks with limited length as applied in the Netherlands. False tripping can be prevented by applying directional relays. Unnecessary tripping can be prevented by a better coordination of protection settings for the network and the DG.

Another problem in the case of a short-circuit is that fault location methods may fail if the generated power is not estimated correctly. Finally, unintentional islanding may occur after isolating a fault, causing safety risks.

In order to limit the negative impact of large amounts of DG, some common practice solutions can be considered, like separating load and generation flows, limiting network impedances, the use of advanced transformer voltage control, actively managing generation and load and the use of power electronics to connect DG.

In general it can be stated that for distribution networks designed with the following criteria, no voltage problems will occur:

- The MV network consists of 240 Al XLPE cable with a maximum feeder length of 10 km feeding a load that is limited to half of the loading capacity of the MV cable.
- The LV network consists of 150 Al cable with a maximum feeder length of 450 m and the voltage difference between the beginning of an LV feeder and a customer connection at the end of that feeder during the maximum load and minimum generation is less than 6%.

In cases where these common practice solutions will not be sufficient, other measures must be taken, like meshed operation, use of short-circuit limiting devices and use of power electronics and storage.

Meshed operation of a network reduces the negative impact on voltage, but measures must be taken to limit the increased short-circuit currents. Also the protection schemes for meshed operation will be more complex.

Autonomously controlled networks

A future network design and operation method has been developed. The design is based on the idea of considering parts of the network that contain a mixture of load and generation as autonomously controlled networks (ACN). This results in a distribution network containing several ACNs and a number of feeders that contain only load. The concept of the ACN establishes a controlled operation, which enables performance within all limits regarding voltage, current and protection for both normal and disturbed operation even in the case of large amounts of DG. In the ACN the normally open point (NOP) is replaced by a so called “Intelligent Node”. This node contains a power flow controller and optionally a storage system. This concept of the intelligent node enables voltage control by controlling the power flow. The intelligent node also minimises the short-circuit contribution from one feeder to another feeder and supports the radial network protection philosophy to be applied in meshed operated networks.

Control strategies were developed for obtaining an optimal voltage profile, using the intelligent node and an intelligent voltage control of the HV/MV transformer.

The optimal control of the intelligent node is a voltage control, based on the linear dependence of the voltage and the power flow towards the intelligent node. The voltage needs to be compared with a reference voltage. This reference voltage is either a fixed value or the voltage at the MV busbar

The HV/MV transformer control must distinguish between situations where the load in the ACN is larger than the generation and situations where the generation in the network is larger than the load. In both cases, the control of the transformer uses line drop compensation. However, the set-point for the voltage and the compensation factor differs. In cases where the load is larger than the generation several combinations of load and generation must be distinguished in order to obtain the correct set-points. The line drop compensation to be used must be based on the load situation instead of the measured exchange signal. This requires information and knowledge on the amount and behaviour of the load and generation in the network.

Especially during worst cases (high load combined with low generation or high generation with low load), large amounts of power must be exchanged with the storage device to obtain a perfect voltage profile. This sets requirements to the storage devices which is not yet feasible.

A voltage control based on a fixed value at both the terminals of the intelligent node and at the MV busbar of the HV/MV substation will not result in the optimal voltage profile, but will however guarantee a good voltage quality and might therefore be a good alternative.

8.2 Thesis contribution

The research performed during this thesis project has led to numerous contributions in the field of design, operation and analysis of MV and LV distribution networks. Some of them are already in use. In general, a better insight of the performance of networks consisting of buried cables is obtained. This helped network developers in making better choices regarding optimal network size and cable dimensions. The better insight regarding voltage behaviour ensures a better power quality. Also, based on results of actual studies, new earthing methods have been proposed, ensuring the safety for clients and workers.

The gained insight and experience initiated new network analysing tools and contributed to the development of existing network analysing programs. The experience with the earthing methods and safety for the LV customers lead to the tool called OPTI, for the calculation of the optimal LV feeder length and cable types, with respect to voltage quality, short-circuit behaviour and safety in a TN-CS earthed system. This experience of LV network design, combined with the research on the diversity of LV loads and the idea of stochastic load-flow contributed to the development of the widely used computer program Gaia *LV Network design*. The gained insight in the MV distribution networks behaviour and the research on the dispersed generation contributed to developments in another widespread computer program, Vision *Network analysis*.

The research on the voltage behaviour in MV distribution networks lead to the development of a new state-estimation technique in MV distribution networks, where the lack of measurement data is compensated by knowledge of the network and its load behaviours.

The necessity for including power quality items like voltage dips into the protection philosophy is made clear based on measurement results. The basic ideas concerning economically feasible automation in MV networks were developed, leading to the introduction of the SASensor techniques, nowadays applied in several HV/MV substations.

The research on reliability aspects in the MV distribution networks initiated the development of a new fault location technique, resulting in a practical application, which helps reducing the time to locate a short-circuit location in practice. Monitoring the fault events has led to new insights concerning earth faults. Some of these faults are self-healing faults and re-striking faults, causing transient voltages of unwanted proportions. These phenomena should be investigated further in another research project, where methods could be developed to reduce the effects.

The growing penetration of distributed generation in distribution networks, challenges the network designers. In this research the limits for the amount of distributed generation in a cabled distribution network have been investigated. As a result, design criteria have been described, reducing the negative influence on the power quality.

During the research, the intelligent node has been proposed. Its major properties and functionalities have been described in this thesis. The concept of an autonomously controlled network containing such intelligent nodes is a promising way to manage the expected challenges regarding future network operation and performance. The control strategy for networks containing large amounts of distributed generation by using intelligent nodes has been investigated in this research. Further research will enable a cost-effective practical implementation of the intelligent node. Especially when electricity storage facilities can be incorporated and when electric vehicles can play a role, the benefits of the intelligent node will become clear.

8.3 Recommendations and future research

Nowadays measurement systems in substations, in the network and at customers (smart meters) create large amounts of data. It is necessary to analyse and combine these datasets in order to obtain better accuracy of the calculation models, resulting in an improved design of LV and MV networks.

Nowadays planning of distribution networks is based on expected extreme values for voltages and currents. When more knowledge is obtained about the stochastic behaviour of loads and local generation, the evaluation can be performed with a probabilistic load-flow giving the risk that certain levels might be exceeded.

Spontaneous faults in MV networks sometimes start with a sequence of self-extinguishing faults before they develop into a real fault. An algorithm must be developed which can locate the fault from the measured voltage and current signals due to the self-extinguishing faults. In this way the weak cable can be located and repaired before the real fault occurs. In this way the number of faults resulting in customer minutes lost will reduce and the reliability of the network will increase.

The proposed topology and control in chapter 7 have several possibilities for further research. This research must focus on technical, economical and environmental subjects. Technical research items are the control activities, development of a storage management system, optimal location of the control systems and evaluation of the losses in the network, use of power electronic components and the storage system. The applied scenario in chapter 7 is based on extreme values for load and generation, which has a large impact on the amount of storage. The influences of other, less extreme, scenarios on the storage system must be investigated and must result in an adequate storage management system. This management system can be extended to electric vehicles and other storage devices.

The proposed controls in this thesis should work with an estimation of load profiles and with local measurements of current and voltage. The main objective for future studies on this subject is to distinguish load and generation at the off-going feeders of the MV busbar and to estimate the amount of load and generation in the feeders connected to the intelligent node.

As communication becomes cheaper and faster, it can be advantageous to use more external signals for the activation of the controls. The information of smart meters at the customers can be used for estimating loads and generation.

The proposed location of the intelligent node as well as the number of feeders connected to it might not be an optimal solution. In networks that contain a mixture of load feeders and mixed feeders, it can be advantageous to use the intelligent node to interconnect a load feeder with a mixed feeder.

In case of high generation, a part of this energy can be transferred from the mixed feeder to the load feeder. It can also be advantageous to connect more feeders to the intelligent node. This reduces the need for storage.

Further technological research can be performed on the storage and power electronic devices. It must be investigated which developments are necessary before these devices can be suitable for the proposed network structure.

Economical research must be performed on the costs, lifetime and availability of the proposed solution, which has to be compared with other solutions like higher cable capacities and reducing the LV network lengths combined with an increase of the number of MV/LV transformers.

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[ZIPS 002] Zipse, D.W., 'Earthing - Grounding Methods: a Primer', Industrial and Commerical Power Systems Technical Conference, 2002. 2002 IEEE, 8-8 May 2002, Page(s):158 - 177

A Earthing

To prevent undesired situations like electric shocks or malfunctioning of equipment a proper earthing system is necessary. Various earthing methods can be applied. Each way of earthing has specific consequences for the voltages and the currents during disturbances as well as for protection settings. In the past, separate earthing principles were applied for each voltage level. The introduction of sensitive electronic devices and installations requires an integrated earthing philosophy. This integration even expands towards other networks like telephone and cable television connections entering at customer's installations. There are various types of earthing methods that can be applied to networks and installations. Each of these types has its specific advantages and drawbacks. These are described in many papers [ANGE 001] [FOLL 001] [ZIPS 001] [ZIPS 002] [SAKI 003] [PROV 009] [WAES 001].

A.1 Earthing a network

Earthing of a network can be performed in several ways as shown in Figure A.1.

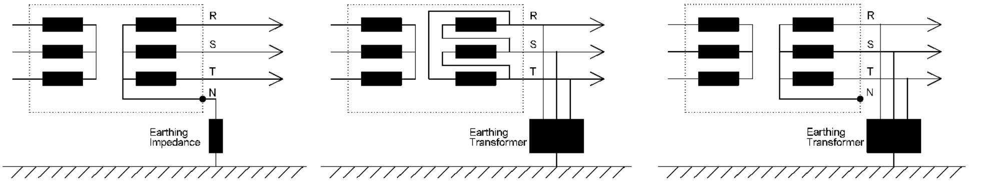


Figure A.1 Different ways of earthing a network

In networks where the secondary windings of a transformer are connected in Y an impedance towards earth can be connected directly to a neutral point (see Figure A.1 left). In this case the zero-sequence impedance of the earthing circuit consists of the series connection of the extra impedance and the zero impedance of the transformer.

In the case where the secondary windings of the transformer are connected in Δ an artificial star-point can be created by a so called earthing transformer (Figure A.1 middle). In this case the zero-sequence impedance of the earthing circuit is equal to the zero-impedance of the earthing transformer. This method can also be applied to be independent of any possible star-point (see Figure A.1 right).

Earthing transformer

The earthing transformer (see Figure A.2), sometimes also known as interconnected star compensator, is described in [PHIL 001]. It can be constructed either in a zig-zag way (left) or as a conventional Y-Δ transformer (right). In both cases the star-point of the transformer is directly connected to the local earth.

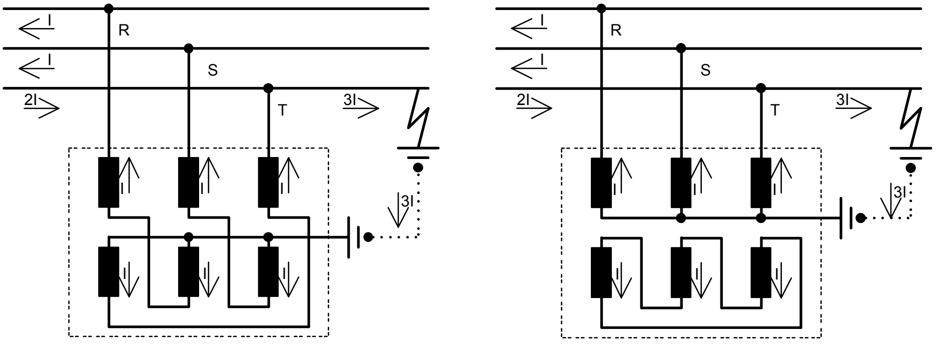


Figure A.2 Two types of earthing transformer zig-zag (left) and Y-Δ (right) [PHIL 001]

In the case of the zig-zag construction, the currents in the primary windings have the same magnitude and phase angle because:

- The current in the secondary winding of phase R is forced into the primary winding of phase T.
- The current in the secondary winding of phase T is forced into the primary winding of phase S.
- The current in the secondary winding of phase S is forced into the primary winding of phase R.

In the case of the Y-Δ configuration, the secondary currents are equal because of the Δ connection of the windings. Therefore also the currents in the primary windings of the transformer must be equal (both in amplitude and in phase).

In case of a phase to earth fault a current of 3I is flowing over the faulted phase towards the location of the fault in the network. This current returns into the neutral point of the earthing transformer. This will result in a current I towards the network in all three phases on the primary side of the transformer. As a result a current with a value I will flow in the healthy phases from the connection of the earthing transformer towards the network transformer and a current of 2I is flowing from the network transformer towards the earthing transformer in the faulted phase. As the sum of the currents from the network transformer towards the earthing transformer equals zero, there is no zero-sequence current noticed in that part of the network.

Global earthing

In earthing the network also the amount of earthing points can differ, which results in:

- Non-distributed earthing;
- Distributed (global) earthing.

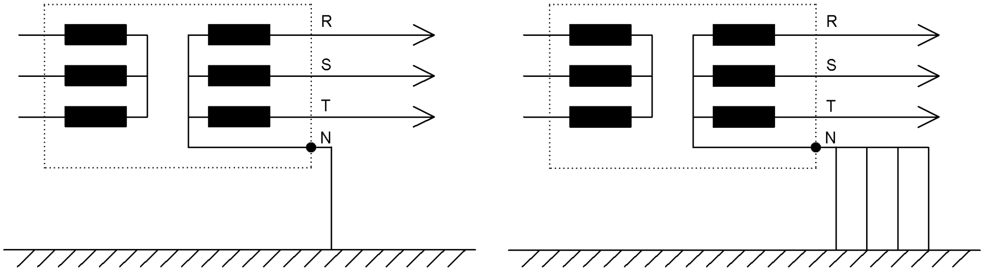


Figure A.3 Network with non-distributed (left) and distributed/global earthing (right)

In networks with a non-distributed earthing (see Figure A.3 left) there is only one single point where the network is earthed. This is often the case in three-phase European type overhead MV networks without neutral and in LV networks that are fed by this type of MV networks. The earth potential rise (EPR) due to earth faults depends solely on this earthing. The fault current due to these faults has to return through the earth and can therefore be low for large distances.

In networks with a distributed earthing (see Figure A.3 right) many points of the network have an earthing point. This type of earthing is applied in North American type networks and in MV cable networks, where the cable sheaths are connected to the star-point of the MV/LV transformer. The earth current has more paths to return. Therefore it will generally be larger than in non-distributed networks in case of earth faults. The current divides itself over the metallic path and earth. At the fault point the fault current has several return paths. This reduces the EPR. Distributed earthing is also known as global earthing.

In cable type networks the LV networks are mostly earthed at the star-point of the secondary of the MV/LV transformer. The sheaths of the MV cables are connected to that earthing point. In case of PILC cables the continuous earth contact of the lead sheath acts like an extra local impedance to earth [BUSE 001] reducing the local earthing resistance of the earthing point. In case of XLPE cables the copper sheaths create a low resistance path between the various earthing points [ERP 001] [POPO 001] which results in a multi-connected earthing system with many return possibilities and an overall low earthing impedance.

A.2 Earthing concepts

Several earthing concepts can be distinguished:

- Neutral point isolated;
- Direct earthing;
- High impedance earthing;
- Low impedance earthing;
- Resonance impedance earthing.

Neutral point isolated

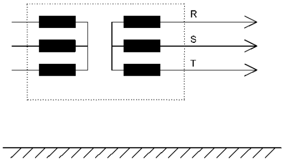


Figure A.4 Networks with isolated neutral

In networks where the neutral is isolated (see Figure A.4) there is no specific path for the return of the current through the earth. The current can only return through the capacitances between the phase conductors and earth and is therefore of low value. The steady state voltages of the healthy phases during such a fault are increased to the phase to phase voltages. The phase to phase voltages will hardly be influenced by a single-phase to earth fault. In this way loads connected phase to phase (directly or by a Y-Δ transformer) will not be affected. In overhead networks the low value of the current often results in self-clearing of the (temporary) fault without disturbing customer loads. In cable networks the fault current is often too low to cause a continuous fault. This can result in a series of self-clearing and re-striking faults resulting in high and steep transient over-voltages. This is treated in further detail in chapter 3 and appendix F.

Direct earthing

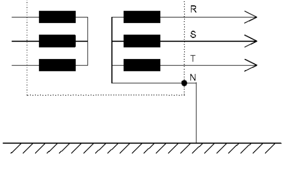


Figure A.5 Direct earthing

In directly earthed networks (see Figure A.5) the neutral point of the transformer is directly connected to earth. This results in a very low impedance path for the return of an earth current, which may cause high fault currents and dips at customer loads. The fault current, however, is rather good to detect and can be switched off by the protection. In case of an earth fault, the voltages of the healthy phases remain almost equal to the voltage in undisturbed situations; however, a large earth potential rise may be expected at the location of the fault.

High impedance earthing

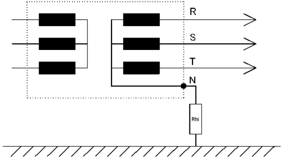


Figure A.6 High impedance earthing

In networks with high impedance earthing (see Figure A.6) there is a high impedance path for the return of an earth fault current. The current has therefore a low value. The steady state voltages of the healthy phases during such a fault are increased to the phase to phase voltages. This type of earthing is often applied in (small) industrial networks.

Low impedance earthing

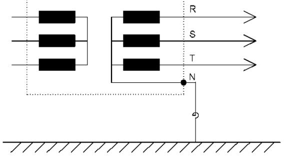


Figure A.7 Low impedance earthing

In networks with low impedance earthing (see Figure A.7) the single-phase to earth current is to a certain extent limited by the impedance. Compared to direct earthing the fault current is lower, which limits the dips and earth potential rise. Compared to isolated or high impedance earthed networks the fault current is larger and can easier be detected by the protection devices. Close to the fault the voltages of the healthy phases are increased to the phase to phase voltage. These values decrease towards the transformer. Compared to networks with isolated neutral, the impedance of the earthing device results in smaller transients and therefore in a reduction of voltage stresses on the insulation during single-phase to earth faults.

Resonance earthing

The value of the earthing impedance could be chosen in such a way that it compensates the capacitive single-phase to earth current. In this way, the single-phase to earth fault current is almost zero. Such compensation coils are known as Petersen coils. The coils are adjustable (see Figure A.8). Therefore they can be tuned to various network reconfigurations and extensions. The steady state voltages of the healthy phases during a phase to earth fault are increased to the phase to phase voltages.

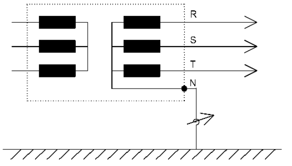


Figure A.8 Resonance earthing

Compensation with Petersen Coils is popular in overhead networks. In this case self-restoring single-phase faults (wind, lightning, trees) will not result in the interruption of the power supply. In networks containing a mixture of overhead lines and underground cables problems occur as faults in the cable are not self-restoring. The fault extinguishes but will return. This can cause high over-voltages eventually resulting in a multi-phase fault.

A.3 Connecting the LV customer network to the public network

When connecting the network of the customer to the public network care must be taken to the earthing of both systems. In the LV grid the earthing systems of the various networks have consequences for consumer electronic appliances like computers, video and television. A well-engineered earthing concept is needed to reduce disturbances and to keep the EMC requirements towards apparatus within an acceptable level. In the past the lead water tubes and the armours of PILC cables had a significant contribution towards electrical safety due to their good contact with the soil over a large distance. Nowadays the water tubes are replaced by plastic ones and PILC cables are more and more substituted by XLPE or PVC isolated cables. The influence on safety aspects can no longer be neglected and therefore the LV earthing philosophy has to be reconsidered. Domestic earthing systems must prevent users and apparatus from hazardous shocks during short-circuits within the building. During such a disturbance the earthed apparatus will carry a voltage relative to local earth. This voltage depends on the impedances of the network components and the earthing system. When a person touches an earthed apparatus during a disturbance his touch voltage will be a part of that voltage.

This will result in a current through the body. In order to prevent dangerous shocks this current should not be too high and not last too long, so the fault has to be switched-off in time. Switching-off the fault is done by the protection device. In most households this is a fuse or a circuit breaker. To switch-off in time, the circuit resistance needs to be low. The circuit resistance is mainly determined by the impedance of the return path.

A.3.1 Earthing arrangement

In the international standard IEC 60634 three different types of earthing arrangements are distinguished. These arrangements use a two letter code (TT, TN and IT). The first letter indicates the connection between earth and the power supply network. Here T stands for earthed (French word Terre) and I for isolated. The second letter stands for the way the equipment is earthed. Here T stands for direct connection with earth and N stands for earthing via the supply network.

Mostly the LV networks are earthed at the star-point of the MV/LV transformer (T). The earthing at the customer is either by an own earthing electrode (TT earthing) or by the public supply network (TN earthing). From EMC point of view TN earthing is favourable. However, this has consequences for the protection and the length of the network. Also attention has to be paid to the touch- and step voltages in the LV network due to faults in the MV network. These consequences are described in chapter 3.

Figure A.9 shows the most common earthing principles applied nowadays, which are described below.

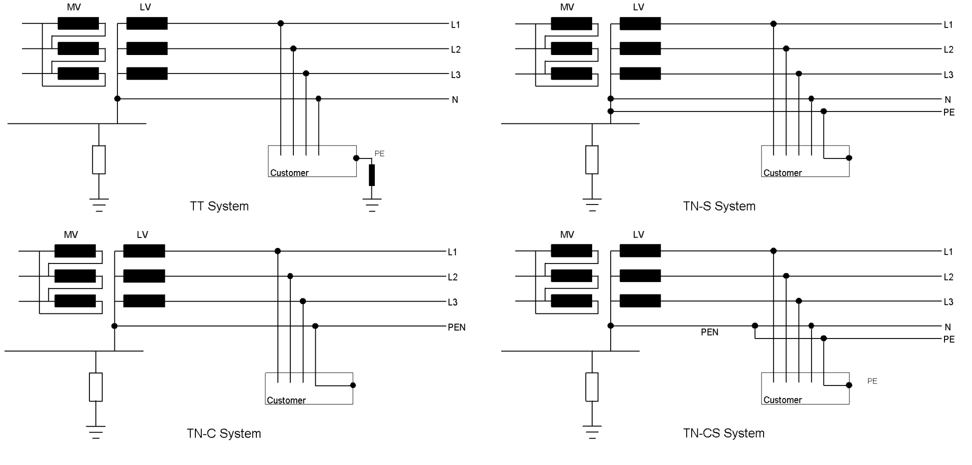


Figure A.9 Various types of connecting LV earthing of the customer

TT earthing system

In a TT (Terre Terre) earthing system (see Figure A.9 upper left), the protective earth (PE) of the customer is separated from the earthing of the public network. The customer is responsible for the maintenance and proper functioning of his own earthing system. The return path consists of the earthing circuit at the customer, the earthing impedance of the MV/LV transformer and the resistance of the earth between customer and transformer. The value of the circuit resistance (R_c) must be low. A rule of thumb when fuses are used is: $R_c < 30/I_n$, with I_n being the rated current of the fuse. In the past, the circuit resistance was kept within a safe region because of low values of I_n, the metal water tubes and the PILC cables. Replacement of the water tubes and the cable insulation by plastics form a threat for safety. In areas with a high earth resistance a safe value for the circuit resistance can no longer be obtained. In this case residual current devices (RCD) must be used. Hower, these devices (especially the 30 mA RCD) show failure rates between 5 and 10% [BIEG 001]. Larger customers can never reach a safe value for their circuit resistance, due to the high values of the rated current of the fuses. Customers with a TT earthing system are not vulnerable for voltage rises due to short-circuits in the public network. Lightning strokes however can result in large voltage differences between both the active parts and between active parts and earthing systems, which can result in damage of equipment. Especially apparatus like radio, television, video and IT equipment, is vulnerable for this kind of disturbances, since it is also connected to networks of other suppliers with other earthing concepts.

TN earthing system

In a TN (Terre Neutral) earthing system the public network provides a safe earthing of the customer by means of a low resistant connection with the earthing of the MV/LV transformer. This system always guarantees sufficient low impedance of the return circuit. Also safety at lightning strokes is increased strongly, due to the considerable reduction of over-voltages between neutral and earth. Extra (small) electrodes in the LV network take care of a good distribution of externally induced (lightning) currents. The connection of customer earthing to the network earthing makes the customer vulnerable for faults in the public network. This will not be limited to faults in the LV system, but regards also faults in systems on higher voltage levels. These types of faults (further described in chapter 3) have to be taken into account and additional measures might be required.

TN systems exist in several configurations. In a TN-S system (see Figure A.9 upper right) the neutral and earth conductor are separated. From EMC point of view this is the best solution both for 50 Hz and higher frequencies, especially with shielded cables where the shield is used as earthing conductor.

A disadvantage of a TN-S system is that it requires 5 conductors. Another disadvantage is that a break of the neutral results in undefined voltages in apparatus and that a break in the PE conductor leads to safety risks. In a TN-C system (Figure A.9 lower left) neutral and earth are combined into one (PEN) conductor. The advantage of this system is that it only requires 4 conductors instead of 5. This reduces cable costs and is therefore often applied in industrial networks. There are two main disadvantages. First the safety and voltage problems that occur when the PEN conductor is interrupted as already described for the TN-S system. The second problem is caused by the stray currents, which are a result of return currents (due to asymmetry but also multiples of the third harmonic) that not only flow through the PEN conductor but also through metal parts connected to these conductors. These stray currents induce magnetic fields, which can influence the control of processes. Small magnetic fields of 1μT are able to distort the image on the screens of CRT tubes. Magnetic fields over 100 μT can be dangerous for human bodies. The TN-CS system (see Figure A.9 lower right) is a combination of TN-S and TN-C. The public supply network is a TN-C system and the customer network is a TN-S system.

A.4 Examples of network earthing in MV and LV grids

Network earthing is related to the type of network. Three types of distribution networks can be distinguished as was explained in Chapter 2:

- American type overhead networks (distributed earthing).
- European type overhead networks (non-distributed earthing).
- European cable type networks (various earthing methods).

American type overhead networks

American type overhead networks consist of a four conductor MV network and a three conductor LV network. The star-point of the secondary of the HV/MV transformer is directly earthed in the substation. The fourth MV conductor is connected to that point and earthed on all the connections to the MV/LV transformers and on the poles. The neutral of both the primary and the secondary of the MV/LV transformer are earthed. In this way a multi-earthed earthing system is obtained.

European type overhead networks

The European type overhead network lacks a fourth conductor in the MV system. The earthing of the MV and LV networks is separated. The LV network is directly earthed at the star-point on the secondary side of the MV/LV transformer. The MV network is often earthed by means of Petersen coils.

European type cable networks

The earthing philosophy for cable networks depends on the size of the network and the currents that can be expected during single-phase to earth faults. In a network with isolated neutral the fault current due to a single-phase to earth fault is determined by the zero-sequence capacitance of the network. In a 10 kV cable network this current is approximately 1 A/km. A part of the fault current returns through the sheath. The sheaths of most of the cables are constructed in such a way that they can carry this current continuously as long as the fault current is less than 300 A. Fault currents of 300 A are in the range of normal operating currents and cannot be detected as faults by simple over-current protection relays.

However, there is enough time to (manually) detect the location of the fault. The phase to phase voltages will hardly be influenced by a single-phase to earth fault. In this way loads connected phase to phase (directly or by a Δ Y transformer) will not be affected by this fault. The low fault current will not result in thermal damage of cables and isolation. As a result, in small networks containing less than 300 km of cable the neutral is often isolated.

Fault currents larger than 300 A may damage cable sheaths and have to be switched off. In networks that contain so much cable length, that the single-phase to earth fault current exceeds 500 A, this fault current can simply be detected by the over-current relay. The magnitude of the current is so large that the risk of self-extinguishing is limited. So also in these networks operation with isolated neutral can be applied. Switching capacitive currents, especially when they are small, is a problem for circuit breakers. Tests on generally used circuit breakers showed, however, that these breakers were able to switch these currents [KEMA 001].

Networks where the single-phase to earth fault would be between 300 and 500 A, must be earthed in order to obtain reasonable inductive single-phase fault currents. When direct earthing of the transformer star-point is applied in MV networks, the single-phase to earth fault current can reach values of 8 kA and will result in a noticeable voltage dip. When low impedance earthing is applied, the fault current can be limited to 2 kA.

Compensation by means of Petersen coils in cable networks is applied in case of a short number of long feeders with small cable diameters. In this type of networks an earth fault at the end of the feeder will not result in a noticeable fault current even if the network is earthed. In the Netherlands this type of earthing is only applied on specific locations (Zeeland).

Low impedance earthing is becoming more common in cable networks. This is due to a better performance during single-phase to earth faults:

- When a single-phase fault is not switched off and not located in due time, it may develop in a multi-phase fault. These multi-phase fault currents give severe damage to equipment and cause dips in the network. Spontaneous single-phase faults in networks with isolated neutral will develop in 2- or 3 phase faults after a certain amount of occurrences (5-30). In these networks single-phase faults due to digging will develop into a multi-phase fault at the moment the digging device damages the second conductor.
- The transients are limited compared with isolated neutral operation. This results in a reduction of voltage stresses on the insulation material.
- Fault currents and accompanying voltage dips are reduced compared with direct earthing.

Network earthing in LV grids is done either according to a TT system or to a TN system. In case of TN earthing the TN-CS configuration is commonly used. The power supply network is a TN-C system and the customer network is a TN-S system. In cases where the LV network contains both a neutral and a protective earth (PE) conductor the TN-C system is created by regularly interconnecting these conductors.

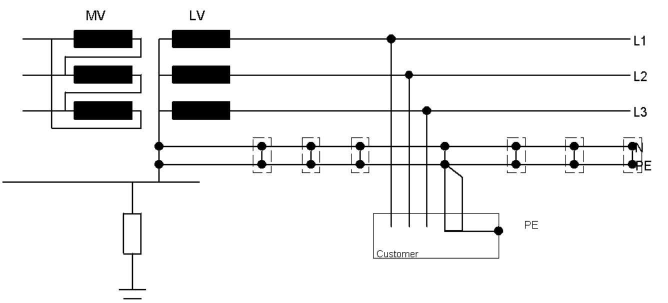


Figure A.10 An LV cable grid with TN

This interconnection can, for example, be established when the cable system network consists of a 4 conductor cable with copper sheath of sufficient equivalent cross-section. In that case, the neutral and the sheath are interconnected at all joints and at all the customers' installation (see Figure A.10). This ensures a safe current return path even if the neutral conductor is broken. The risk of simultaneous broken neutral and broken shield can be neglected. In this way the system combines the advantages of TN-S and TN-C. The paralleling of neutral and PE also reduces the return impedance for asymmetric currents and in this way the effect of dips due to switching large single-phase loads. In the Netherlands most of the newly build LV networks are based on this concept.

A.5 Earthing and safety

When a person touches a voltage carrying object, the body of that person is becoming a possible return path for the current. This can result in a dangerous situation. Important parameters regarding safety are the magnitude, duration and frequency of the current. An AC current is more dangerous than DC. International standards like IEC 479-1 and IEEE Std 80 describe the relationship between the magnitude of the current through the body and the maximum permissible duration of this current (see Figure A.11). Differences between these standards are described in [LEE 001].

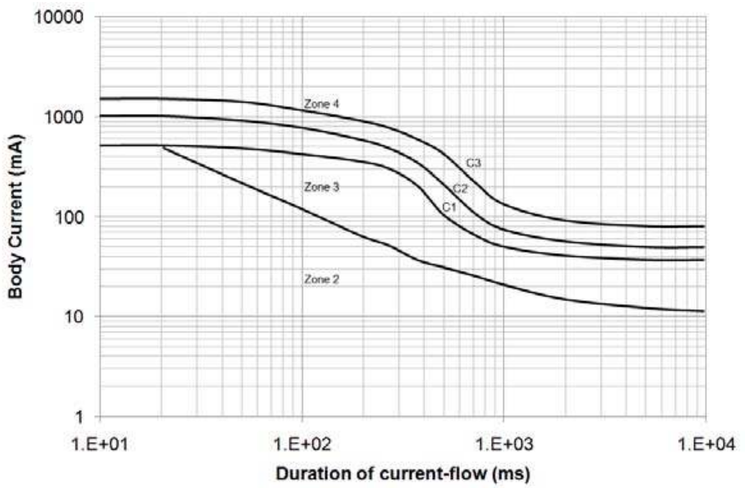


Figure A.11 Permissible duration of body current according to IEC 479-1

In general people will not touch a connected network, because they are aware of the danger. However, there are situations where a potential difference between the protective earth and the local earth can occur. In customers and industrial installations this may occur when a life wire makes contact with the protective earth of an apparatus (motors, washing machines etc.). This must be detected by a protective device (fuse or RCD) that takes care for switching off.

Also faults in networks can result in dangerous situations. In case of a single-phase fault to earth in a TN earthed network, the current through the PE conductor causes a voltage rise over that conductor and also on the customers earthing system (see Figure A.12 left). Someone who at that moment would touch an earthed appliance will experience a part of that voltage. Such effects can also be caused by single-phase faults in the MV grid (Figure A.12 right).

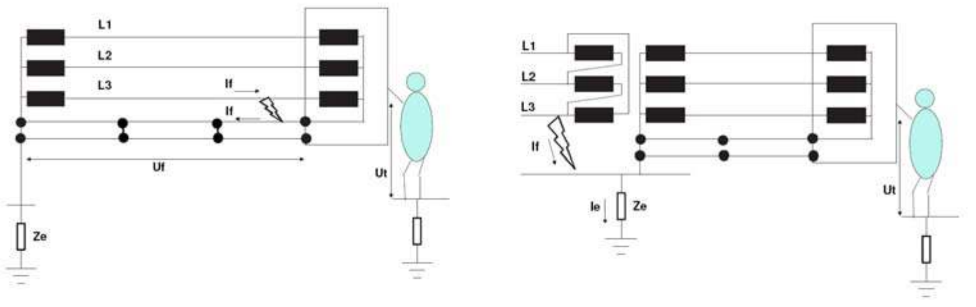


Figure A.12 Dangerous situation due to a fault in the LV (left) and MV (right) network [PROV 009]

The relationship between the fault voltage U_f and the touch voltage U_t depends on aspects like the resistance of the human body, shoes and earth. The impedance of the human body depends on the magnitude of the voltage and on the way the person makes contact: with one or two hands, with one or two feet. Managing these fault currents and voltages is treated in chapter 3.

A.6 Earthing philosophy of Alliander

The earthing system is important in order to limit the impacts of faults on voltage and current. The best approach depends on the type of network. For networks containing overhead lines, earthing with Petersen coils has proven to be a good solution. In this way the effect of the self-healing of single-phase to earth faults can be fully achieved. In cable networks, however, other phenomena play a role. This paragraph describes the earthing philosophy for cable distribution networks developed within Alliander (a Dutch network operator [ALLI 001]) that consists of:

- A TN system in the LV grid
- Impedance earthing in the MV grid

A TN system in the LV grid

The TN system of the LV grid guarantees safety for both apparatus and human beings. Safety for apparatus is not only a benefit for customers. In nowadays and future networks more and more devices (like smart remote metering applications) will communicate over the electricity network. These applications will also benefit from a good earthing and EMC concept. In order to guarantee the safety, restrictions have to be made for the network length, which also improves the voltage during normal operation.

Impedance earthing in the MV grid

In cable systems, impedance earthing is a good compromise between the advantages and disadvantages of other earthing methods. Single-phase faults in directly earthed MV networks result in large currents and cause dips; the magnitude of the single-phase fault current is large enough to trip the protection. The impact of a single-phase fault is identical to the impact of two- and three-phase faults. Single-phase faults in MV networks with isolated or compensated neutral will result in transient currents and voltages. Because the steady state fault current is low in this case, these faults will not be switched off and can develop in multi-phase faults with large currents and dips. Single-phase faults in impedance earthed MV networks result in currents large enough to be detected by the protection and low enough not to cause extraordinary thermal damage or severe dips. In case of digging damage, the single-phase to earth fault due to contact between the conductor and the cable sheath can be detected and switched off before the second conductor is damaged. This makes impedance earthing the best earthing for cable networks. When dimensioning the impedance for the earthing several items must be considered:

- The magnitude of the single-phase to earth current reduces when the fault is further away from the substation.
- The value of the fault current must be large enough to be detected by the protection.
- The damage to the cable due to the fault current must be large enough to be found by the maintenance crew after isolation of the faulted cable.
- The fault current must be sufficiently low, in order to avoid too deep dips, to avoid safety problems and to prevent large currents in the sheaths. This also reduces the risk of the fault to develop into a multi-phase fault.

The design values for the earthing in the Alliander MV grid are that the single-phase short-circuit current at the substation busbar should be around 2000 A. At the end of the network this value is 700 A. These design values will not result in unacceptable earth potential rise (EPR) nor in too large currents for the cable sheaths. The faults can be detected and switched off by the protection.

Field tests in the Alliander grid

Several field tests were performed in the Alliander grid in order to prove theoretical assumptions.

The first experiment was to investigate the impact of a single-phase to earth fault in the MV network on the step and touch voltages in LV networks [WAES 004] [WAES 005]. Several earth faults were performed in a network with isolated neutral. Here the impact of PILC cables and other cables connected to the earthing point of the LV network (reducing the expected EPR) was clearly visible. It also gave some ideas about the distribution of the currents over the various conductors and earth.

A second experiment was to investigate the impact of a flash-over due to a lightning stroke on an HV tower with GSM antenna [WAES 002] [WAES 003] [WAES 006]. Such a flash-over results in a single-phase to earth fault and an EPR at the LV connection of the equipment feeding the GSM antenna. Without measures this EPR can be transferred towards LV customers when TN earthing is applied. For this experiment the single-phase fault current of a small 10 kV network was injected into the tower. The experiment showed the distribution of the fault current over the tower and the lightning wires. Also step and touch potentials could be measured. The results of this experiment formed the basis for the (international) installation requirements regarding GSM antenna systems in HV towers as described in chapter 3.

A third experiment showed the distribution of fault currents over the MV and HV cables during a short-circuit on the HV side of an HV/MV substation [WAES 007]. In this experiment a relatively small 60 Hz current was injected on the earthing system of the substation. This current was generated in another substation and transmitted over an HV circuit, which was deliberately taken out of service for this experiment. This configuration made it possible to perform many measurements without disturbing energy supply. The current distribution could be measured from the 60 Hz components of various signals in the cables surrounding the substation.

The positive experience with 60 Hz injections on a live system resulted in two more experiments to show the impact of a single-phase MV fault on LV touch and step voltages. These tests were performed in an impedance earthed MV network, where all cables were of XLPE type and a TN earthing system was applied in the connected LV networks.

The first test [ERP 001] showed that no problems have to be expected in networks with several MV/LV ring main units. The lowest earth potential rise (EPR) is obtained in networks, where the sheaths of the cables form a meshed network. In radial feeders without a meshed configuration of the cable sheaths higher EPR will be obtained. This experiment also made clear, that most of the fault current returns over the sheath of the MV cable and the various LV cables.

As EPR problems may occur in radial feeders, care has to be taken when a new feeder is taken into service. The second test [ERP 002] showed that problems with high EPR may indeed occur in this situation, especially when only one ring main unit (RMU) with its LV network is connected. In this case there is no support of earthing facilities created by other RMUs. Furthermore it showed that these problems can be mitigated by adding an extra earthing point in the MV cable.

B Components

Important components in MV and LV networks are lines, cables, transformers, compensating devices (capacitors) and switchgear. In the Netherlands the share of cables significantly dominates the share of overhead lines. Therefore lines will not be discussed in this section.

B.1 Cables

B.1.1 Cable types

MV cables

Most of the MV cables in the Netherlands are three-phase cables. Single-phase cables are mainly used for feeding heavy loads, connecting distributed generation plants and in MV transmission networks.

The three-phase cables consist of three conductors (either copper or aluminium) and a metal sheath. The major part of these cables are so called PILC (paper insulated lead covered) cables as shown in Figure B.1 (see left picture). The conductors are isolated by oil-impregnated paper and the sheath is made of lead. The cables are armoured with a steel tape to protect them from mechanical damage. The outside insulation is often a kind of fibrous material impregnated with bitumen to prevent corrosion of the armouring and sheath. The joints for these cables are oil filled. Heavy loading significantly reduces the lifetime of PILC cables.

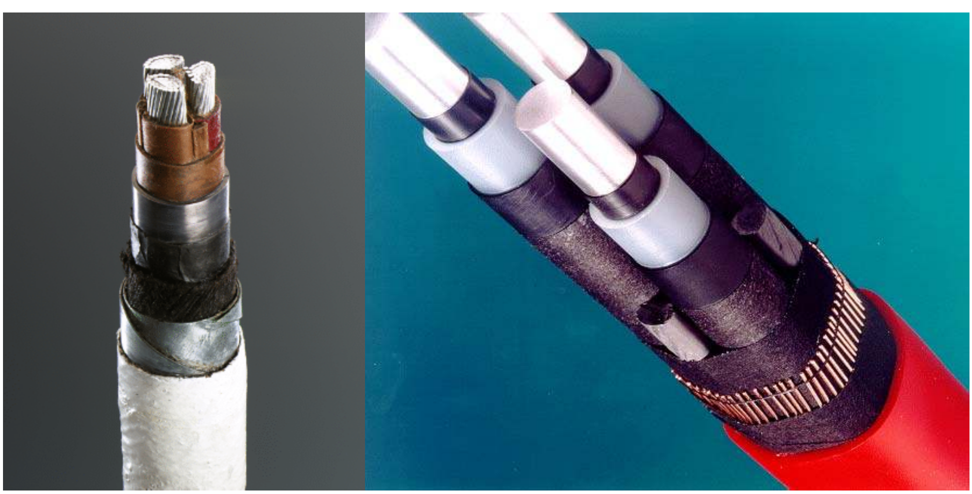


Figure B.1 PILC cable (left) and XLPE cable (right)

Nowadays more and more XLPE (cross linked polyethylene) cables (see right picture in Figure B.1) are used in MV networks. The conductors are isolated by solid XLPE. The sheath consists of copper wires that also function as armour. The outside insulation of these cables is PVC. The joints for XLPE cables are filled with a solid compound. The XLPE cable insulation permits a far higher conductor temperature, so these cables can carry higher currents. The cable, however, is vulnerable for transient over-voltages. This is due to the relatively small tan δ of the insulation material ($5*10^{-4}$ compared to $20*10^{-4}$ for PILC cables) which results in less electrical field stability.

LV cables

Most of the LV cables have 4 conductors (3 phases and a neutral). About 40% of the Dutch LV cables are PILC with a copper core. The other 60% of the cables (shown in Figure B.2) have aluminium cores. The conductor insulation and cable sheath are of XLPE or PVC (PVC isolated, PVC sheathed). In networks where TN earthing is applied, these cables also have a screen made of snaked copper wires so that they can be enlarged when needed. At joints and at the connection to the customer this copper screen is connected to the neutral.

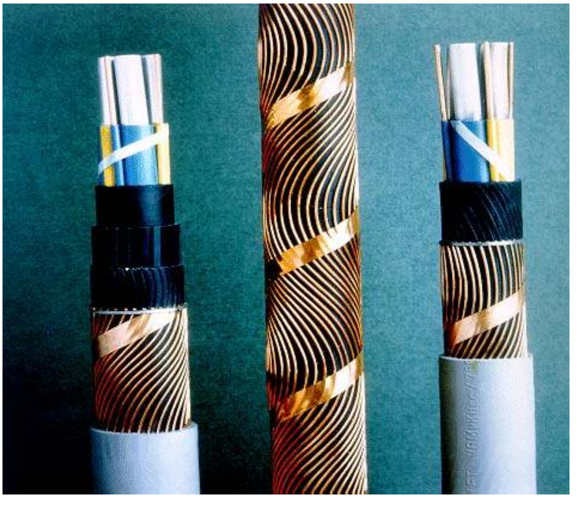


Figure B.2 Typical LV cables

B.1.2 Loading capacity

The maximum loading of cables is determined by the maximum continuous temperature of the insulation and by the drying-out of the soil around the cable, which in the Netherlands happens at an outside earth temperature of 50 degrees. This limits the continuous core temperature to approximately 60 degrees.

For PILC cables the insulation material limits the core temperature to 50 degrees. Due to the negative impact on lifetime, a temporary overloading of these cables is not possible.

XLPE cables allow higher temperatures over the insulation. The core temperature for continuous maximum load may reach 90 degrees. This high core temperature implies a higher risk of drying-out of the soil. Therefore temporary overloading of XLPE cables is allowed only for certain periods of time in specific circumstances.

The calculation of the maximum allowable cable current is normally based on continuous operation on this current. In reality the load changes over the day. Knowledge of the daily cable loading variations and their impact on cable heating and ageing can result in a higher capacity [WOLF 001].

B.1.3 Impedance

Due to the short mutual distances of the cable conductors, the inductance of a cable is low. As the conductors don't have natural cooling like overhead lines, they need to have a lower resistance in order to carry the same amount of current. Therefore the conductor cross-section is larger.

Table B.1 shows some impedances and other specific parameters regarding overhead lines [LAKE 002] [COST 001] and cables [PRYS 001] [NKF 001] [TKF 001].

Name	Voltage level	R (Ohm/km)	X (Ohm/km)	C (µF/km)	Imax (A)
Cable 50 Al	LV	0.73	0.08	0.54	130
Cable 95 Al	LV	0.36	0.08	0.52	200
Cable 150 Al	LV	0.24	0.08	0.72	260
OH Line 25 Al	LV	1.06	0.3		
OH Line 50 Al	LV	0.64	0.28		
OH Cable 35 Al	LV	0.87	0.1		
Cable 50 CU PILC	MV	0.43	0.09	0.28	160
Cable 95 CU PILC	MV	0.22	0.08	0.34	240
Cable 150 CU PILC	MV	0.14	0.08	0.42	310
Cable 95 AL XLPE	MV	0.41	0.1	0.32	215
Cable 150 AL XLPE	MV	0.27	0.09	0.37	280
Cable 240 AL XLPE	MV	0.16	0.09	0.45	360
OH Line Dingo 19/.132	MV	0.22	0.31		525
OH Line 50 Al	MV	0.64	0.4		

Table B.1: Impedances for overhead lines and cables

B.1.4 Impact on network performance

As can be seen in Table B.1 the inductance of a cable is very low, resulting in an X/R ratio below one. Due to this low X/R ratio the influence of reactive loads on the voltage in the network is low [PROV 008]. The influence of network design on power quality is described in [SAKI 003] [GHIJ 001]. The inductance of a cable is about 3 to 4 times lower than of an overhead line. The same yields for the harmonic impedance. Therefore the harmonic voltage level remains low. The advantage of cables on harmonic levels becomes clear when comparing, for instance, monitored results from the Netherlands and France. Long term monitoring shows that harmonic voltage levels in the Netherlands remain far below the permissible level [SLUI 001]. In France, however, there are many problems concerning harmonics [BERT 001] [BERT 002]. Power quality aspects are described in more detail in chapter 3 and appendix E.

B.2 Other components

B.2.1 Transformers

Transformers are mostly used to connect networks with different voltage levels. They are equipped with tap changers in order to control the voltage. Most of the MV/LV transformers have off-load tap changers. The choice for the correct tap is based on the voltage in the MV network. When the tap has to be adjusted due to changes in network operation and loading, the transformer has to be taken out of service. The HV/MV transformers are normally equipped with on-load tap changers. In this way they can continuously control the voltage in the MV network.

Transformers can also be used to connect networks on the same voltage level. These boosting transformers are used to compensate the voltage drop in long feeders.

B.2.2 Switchgear

Switchgear is necessary for clearing faults and for changing the network configuration. On strategic points of the network circuit breakers are used. These circuit breakers are able to break short-circuit currents and are used for selective switching in case of faults. Most of MV/LV ring main units are equipped with manually operated switches towards the cable terminals. These switches are able to break currents occurring in normal operation. Both the switches and the circuit breakers can be used to create a Normal Open Point (NOP) which is an important feature of distribution networks. The transformer is protected by either a circuit breaker or by fuses. In the LV network fuses are used to protect the installations against short-circuit currents.

In MV networks with overhead lines the circuit breakers use auto-reclosing. In this way self-healing temporary faults caused by for example lightning strokes can be cleared and after reclosing the supply can continue. In cable networks there are no self-healing faults so auto-reclosers are not used.

B.2.3 Capacitor banks

Capacitor banks in networks are used to compensate the voltage drop due to the transmission of active and reactive power. Cable networks on LV- and MV level have a low inductance and limited resistance. Therefore, the voltage drop is mainly caused by transmission of active power. Compensation of this voltage loss by capacitor banks is hardly possible due to the lack of reactance. As a result capacitor banks are not used in cable networks.

Capacitor banks are often installed with industrial customers in order to improve their power factor. This is done for reducing active losses in the network and for limiting the voltage drop in networks with overhead lines.

C Reliability

The reliability of a network is often expressed by indicators showing the impact of disturbances on the network and its customers. The three main indicators are:

- SAIFI (System Average Interruption Frequency Index) showing the average amount of interruptions in the electricity supply system on a certain voltage level during a certain period of time
- SAIDI (System Average Interruption Duration Index) showing the average duration of interruptions in the system, which has a relation to SAIFI.
- CAIDI (Customer Average Interruption Duration Index) showing the average duration of interruptions for a certain type of customers.

Requirements on reliability figures can be set by regulators in order to control network operators. In the Netherlands there is a system of penalties and rewards based on the average reliability performance. Network operators who perform better than the average get a reward. Network operators that perform worse get a penalty. This system is known as quality (Q) regulation.

C.1 Comparing reliability in the Netherlands and in Europe

As underground cables are not subjected to weather conditions like storms, lightning or growing trees, the reliability of cable networks is high [PULT 001]. This explains the difference in reliability of networks in the Netherlands compared to other European countries [CEER 001] [CEER 002]. The number of interruptions per customer per year is about 0.4 as is shown in Figure C.1.

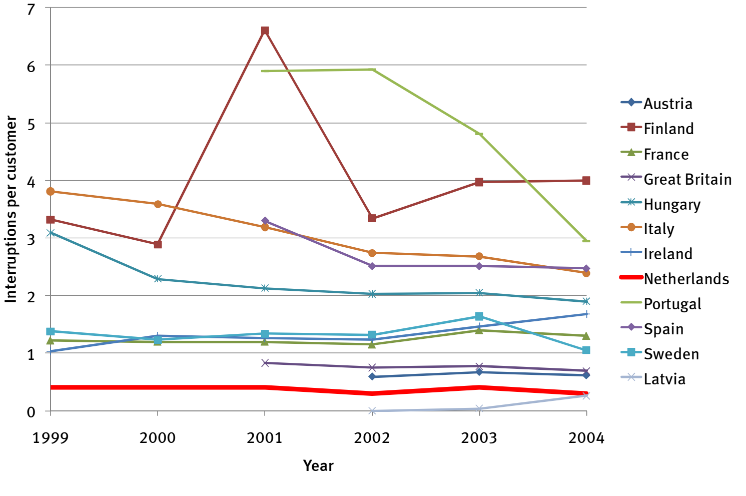


Figure C.1 Number of unplanned interruptions per customer per year excluding exceptional events [CEER 002]

Although the number of interruptions is low, the location of a faulted cable section and the network restoration is time consuming. The average interruption time for a Dutch LV customer is therefore still approximately 20-25 minutes per year. Figure C.2 shows the interruption time for different countries in Europe.

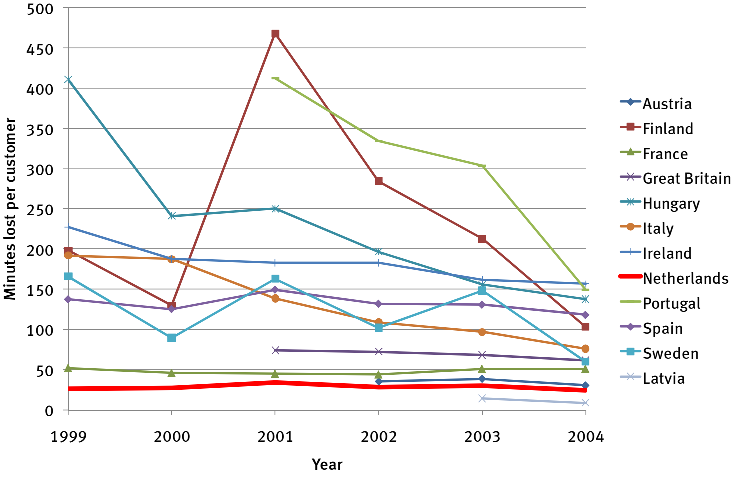


Figure C.2 Minutes lost due to unplanned interruptions excluding exceptional events [CEER 002]

C.2 Reliability in Dutch distribution networks

C.2.1 Current situation

Every year the network operators in the Netherlands have to present the reliability figures of the Dutch networks [ENBI 002] [ENER 007] - [ENER 011]. The number of interruptions over the years due to disturbances on a certain voltage level is given in Table C.1.

	2003	2004	2005	2006	2007	Average
Total	16581	16581	16701	18923	18324	17422
EHV	0	0	0	2	0	0
HV	43	43	52	55	47	48
MV	2114	2114	2107	2442	2138	2183
LV	14423	14423	14542	16423	16139	15190
Other			0	1	0	

Table C.1 Number of interupptions due to disturbances per voltage level in the Netherlands

In this table the item “other” refers to disturbances in networks outside the Netherlands, which had impact on the Dutch networks. One example is the event in November 2006 where a cascade effect in Germany caused large unbalances in the European network, resulting in operation of frequency relays that switched off loads.

Due to redundancy in the networks not all disturbances result in interruptions and the interruption time is usually less than the repair time of the faulted component. Immediate redundancy because of meshed operation is normally the case in EHV networks, most of the HV networks and in the MV transmission networks. In 2007 the percentages of disturbances resulting in interruptions for HV, MV and LV were 43, 82 and 97% respectively. The average customer minutes lost for these years is given in Figure C.3. Most of the interruption time is due to disturbances in the MV networks. In 2007 for instance the outage time per customer in the Netherlands was 33 minutes [ENBI 002]. More than 25% of this time (9 minutes) was due to a crash of a helicopter on an HV line. Due to this event about 33000 households were out of electricity for more than 40 hours.

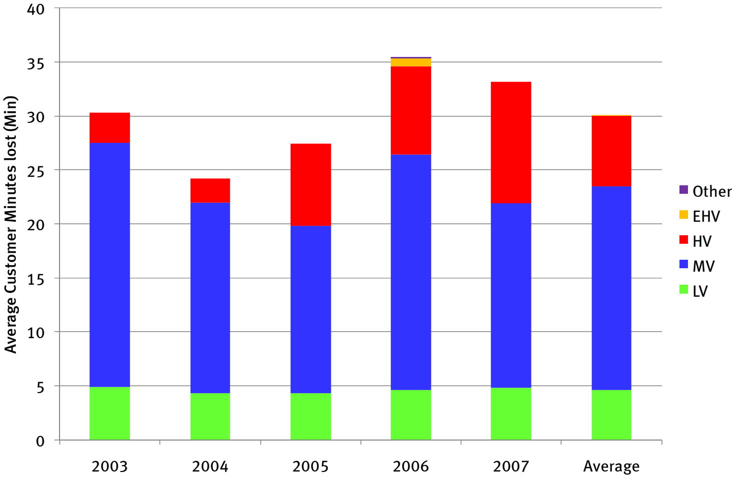


Figure C.3 Customer minutes lost in the Netherlands [ENBI 002]

C.2.2 Improving the reliability

Although the outage time is rather low in the Netherlands, many efforts are put in reducing the time for the location of the fault and reducing the number of faults further.

Causes of interruption

In order to reduce the number of interruptions, it is necessary to know the causes of the disturbances. These are given for different years and different voltage levels in Figure C.4. Digging activities are a major cause for interruptions. Furthermore, faults in cable joints and terminations occur due to technical and operational circumstances. Sinking soil results in broken cable terminations. Variation of cable loading results in damaged joints especially with PILC cables. The heating and cooling cycle causes isolation material to expand and to move. In this way contamination particles can enter the isolation resulting in discharges and flash-overs. These effects are noticed most in cable routings close to the substation.

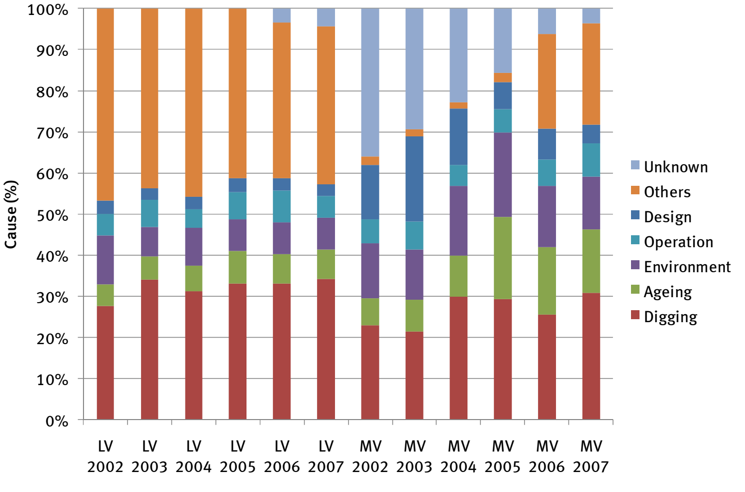


Figure C.4 Causes of interruption in LV and MV networks

Reducing outage time

Several activities can be performed in order to limit the outage time:

- A good administration and information system of cable locations in the streets reduces the number of faults due to digging.
- The introduction of XLPE cables. XLPE cables and their solid joints are less stressed by power fluctuations and will therefore reduce the number of faults.
- Reducing the fault location time. This can be achieved by remote reading of short-circuit indicators [SCHO 001] and by intelligent fault location [OIRS 001] which is described in more detail in chapter 5 and appendix K.
- Replace specific vulnerable components. An example is given in the upcoming section.

Replacement of a specific vulnerable component

The number of MV disturbances in the grid of Alliander (a Dutch network operator [ALLI 001]) during recent years is given in Figure C.5.

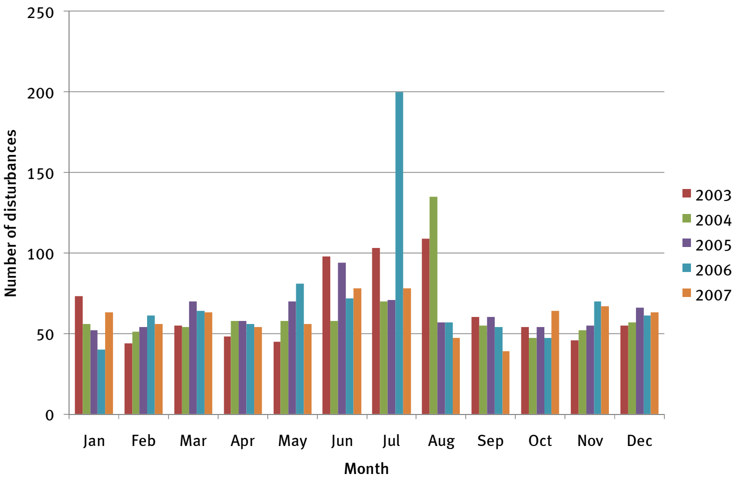


Figure C.5 Number of disturbances in the Alliander MV grid

During summer periods an increase of the number of faults can be noticed. These faults are due to a specific joint type (Nekaldiet). This joint is vulnerable for high temperatures as is shown in Figure C.6 where the origin of the disturbances is split out. Here the influence of some extreme months is clearly visible. A replacement campaign for this type of joints has been started [VOLB 001]. From the figure it can be noticed that this has a big effect on the number of disturbances.

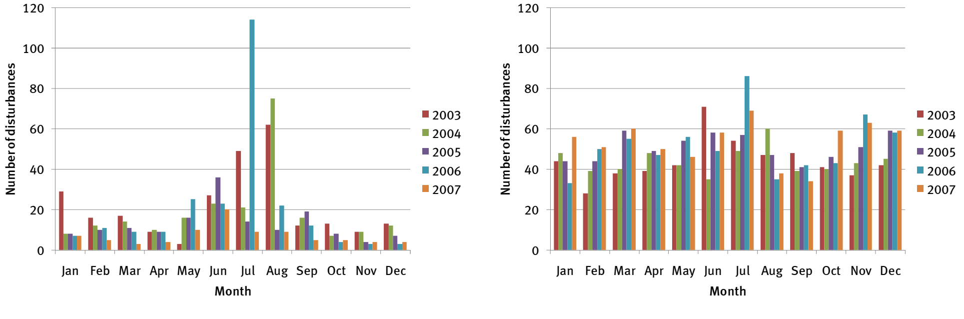


Figure C.6 Number of disturbances in the Alliander MV grid due to “Nekaldiet” joints (left) and other causes (right)

D Electro Magnetic Fields

Voltage and current cause electromagnetic fields. These fields may influence other applications and can be dangerous for human beings. Electromagnetic fields from one application may not damage other applications. A good EMC concept is necessary.

There are no international standards for the permissible EM fields. Some countries have laws others have recommendations. These recommendations differ for people in general and people working within EM fields. In the Netherlands a general value of 100 μT is used while the maximum value for people working within EM fields is 500 μT. For newly built overhead lines a value of 0.4 μT is used. There are no such recommendations for EM fields of underground cables. The trend to reduce the permissible values for EM fields is visible in Europe.

Discussion on the impact of EM fields keeps going on although no evidence is found for health problems for these values. According to publications on the internet already 1% of the Dutch population suffers from electro allergy [EAG 001] or electro hyper sensitivity [EHS 001]. This amount seems to increase with the increasing amount of wireless communication.

Reduction of the magnetic fields around a set of conductors can be obtained by:

- Limiting the current through the individual conductors.
- Symmetric loading of the system (sum of all currents as close as possible to zero).
- Decreasing the distance between the conductors.
- Increasing the distance to the object.

When comparing systems using underground cables with systems using overhead lines, it must be observed that underground LV and MV cables lay less than 1 m deep, and the distance between the conductors is small. Overhead systems hang several meters high and the distance between the conductors is larger than for cables.

In LV networks a large asymmetry between the phases is possible. In order to limit the magnetic field the residual current has to flow through the neutral (and PE) conductor. In a 4 or 5 conductor cable system all conductors will have a small distance to each other and the sum of phase and return currents will almost be zero and therefore also the magnetic field. In overhead lines the mutual distance between the conductors is larger. Therefore, the levelling effect of the currents is lower.

Figure D.1 shows an example of the influence of asymmetry on the magnetic field for an LV cable (left) and an LV overhead line (right). In both cases the currents in the conductors are:

$I_{L1} = 50A, \angle 0^o$

$I_{L2} = 100A, \angle 120^o$

$I_{L3} = 50A, \angle 240^o$

$I_N = -45A, \angle 120^o$

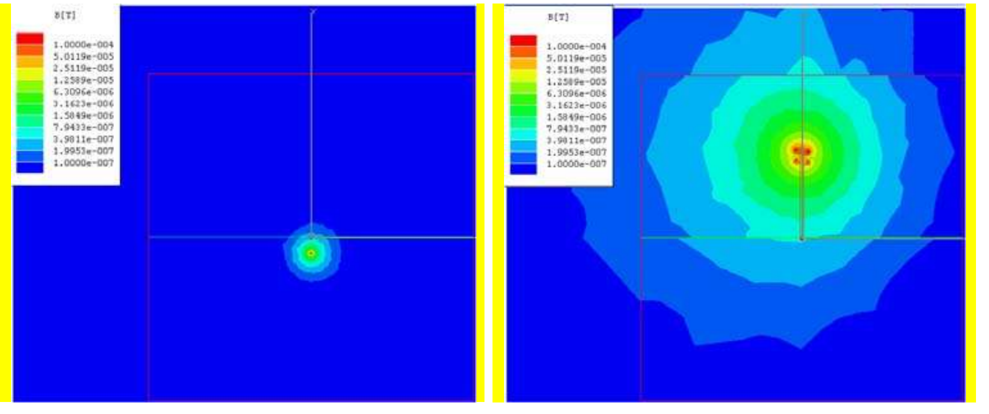


Figure D.1 Magnetic field due to asymmetry in an LV cable (left) and an LV overhead line (right)

Intentionally, not all currents return through the neutral conductor. For the cable, the magnetic field is hardly noticeable above the ground surface (values less than 0.4 μT). The magnetic field is concentrated around the cable. A value less than 0.4 μT is reached from 1 meter distance of the cable. For the overhead line the influence of the magnetic field is noticeable over a larger area. A value of 0.4 μT can be found at about 5 m from the conductors.

The Y-Δ connection of MV/LV transformers in European type networks reduces the risk of asymmetric loading of the conductors in MV networks. In cable networks the use of global earthing forces the residual current into the cable sheaths. Three-phase cables will therefore have small magnetic fields. Single-phase cables are often used to carry a large amount of current. They also have a larger mutual distance and often measures are taken to reduce the current in the sheaths in order to increase the loading capacity. They will, therefore, have a larger magnetic field.

A combination of high currents and large mutual distances can be found in the cables between the LV side of the MV/LV transformer and the LV busbar. Also on the busbar system high currents and magnetic fields can be observed. Reducing the influence of these currents on the magnetic field is the subject of many international studies [HEAR 001] [KETT 001].

Electrical fields are always present when voltage is present. People should be aware of that and switch off unused equipment.

E Power Quality at Alliander

When looking at voltage and current not only 50 Hz phenomena must be considered, but also other characteristics generally known as power quality aspects. In the Netherlands a power quality monitoring (PQM) program started in 1996. Every year about 150 points in the Dutch network were monitored during one week. In the first years the measuring points were equally spread out over HV, MV and LV. In later years such measurements were only performed on MV and LV level. A special measuring program for HV is established. The results of the PQM program are published every year [ENER 002] - [ENER 006] [ENBI 001]. Approximately 60 measurements per year were performed in the grid of Alliander (a Dutch network operator [ALLI 001]). In this paragraph some results will be discussed. As most of the customers are connected on LV level, the focus will be on the measurements on this voltage level.

E.1 Classification

In order to compare the measured results, a classification system is proposed in [COBB 001]. Every measurement takes one week and each PQ aspect is measured for a 10 minute period. This means there are 1008 values for every PQ item. From these values an average value (X_{avg}) and a standard deviation (σ) can be derived and a normal distribution can be assumed. The risk, that a certain value X_{limit} is not exceeded in Y% of the number of measurements is described by the formula:

$$X_{limit} = X_{avg} + k(Y) \cdot \sigma \tag{E.1}$$

Which can be written as:

$$\sigma = \frac{X_{limit} - X_{avg}}{k(Y)} \tag{E.2}$$

This means, that in a graph with the average value on the horizontal axis and the standard deviation on the vertical axis, a line can be drawn for the combinations of average value and standard deviation, for which a certain amount of measurements is below a certain limit. For many of the PQ requirements the value X_{limit} may not be exceeded for 95% of the time. According to [COBB 001] k(Y) equals 1.65 for this case.

An example of the classification the PQ aspect flicker is given in Figure E.1. In case of flicker the limit value according to EN50160 is equal to 1. This means that the limit for this quality aspect is described by:

$$\sigma = \frac{1 - X_{avg}}{1.65} \tag{E.3}$$

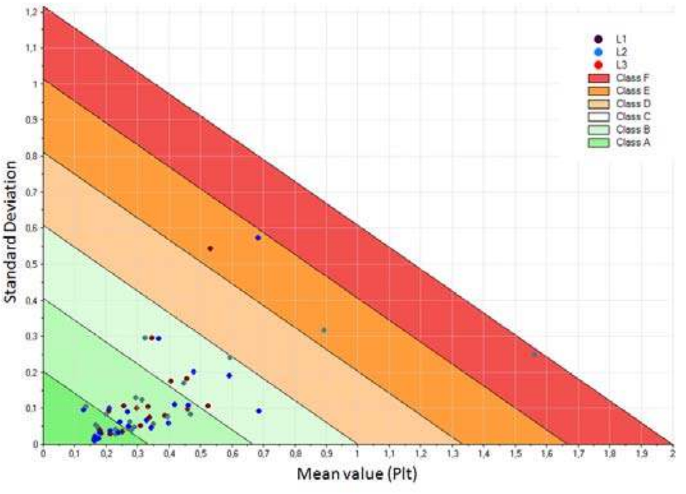


Figure E.1 Classification of the power quality aspect flicker

The limit line intersects the Y-axis at about 0.6 and the X-axis at 1. This line can be seen as the border between good and bad. In order to obtain a better differentiation, five extra parallel lines can be drawn, intersecting the Y-axis at 0.2, 0.4. 0.8, 1.0 and 1.2. This results in 6 areas that can be classified from A to F (see Figure E.1). Here classification A means a very good quality and F means a very poor Quality. The border between C and D is based on the IEC 50160 standard.

Voltage variation has both an upper and a lower limit. This aspect will therefore have a limiting line to the left and a limiting line to the right. In order to observe more than one PQ aspect at the same time, each PQ aspect can be shown on a coloured bar representing the 6 areas defined before. This is described in the next paragraph.

E.2 Results of measurement campaigns from 2001-2007

Figure E.2 shows the main PQ aspects measured in the Alliander grid for the years 2001 until 2007. Every aspect is shown in a separate bar, containing several columns of data points. Each of these columns presents the measurements for a specific year. The measurements of 2001 are shown in the leftmost column of data points in each bar. The measurements of 2007 are shown in the rightmost column of data points in these bars.

The upper plot shows the results for the PQ aspects: small voltage variations, dips, frequency, flicker, THD and unbalance. Most of the aspects have classification A or B.

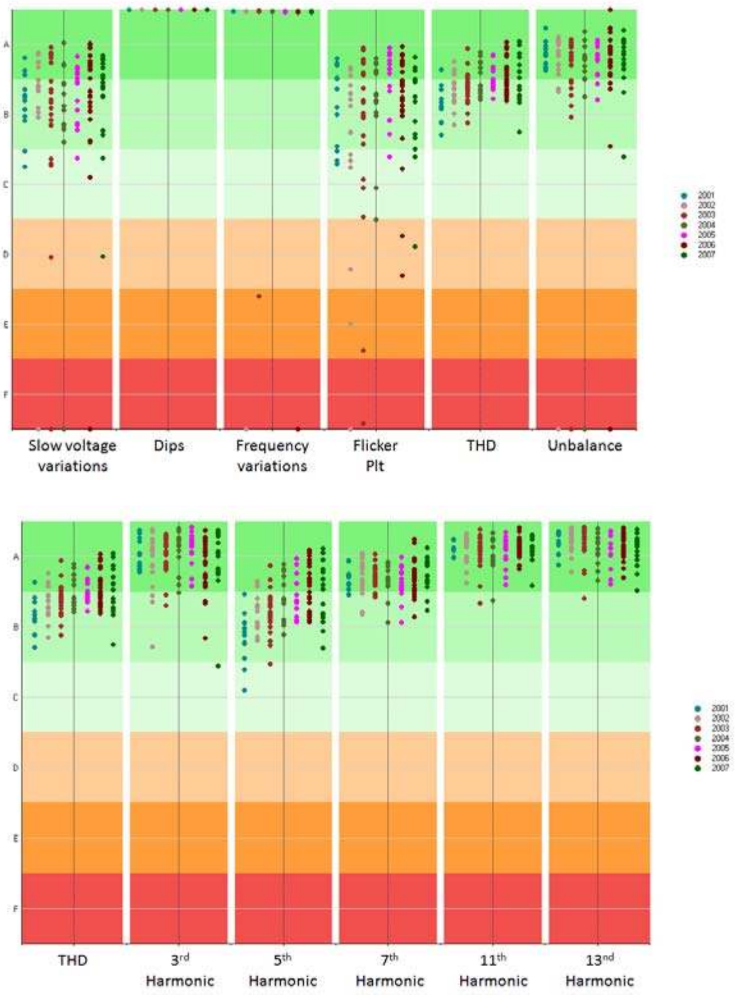


Figure E.2 Classification of PQ aspects in the Alliander grid

The PQ aspect slow voltage variations has a few measurements with a bad classification (D or worse). The aspect flicker shows most of the problems. The lower plot shows the results for specific harmonic voltages (THD, 3^{th}, 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic). All measurements are within the limits stated in IEC 50160. Almost all measurements have classification A or B. The different power quality aspects are discussed in more detail in the rest of this paragraph.

Slow voltage variations

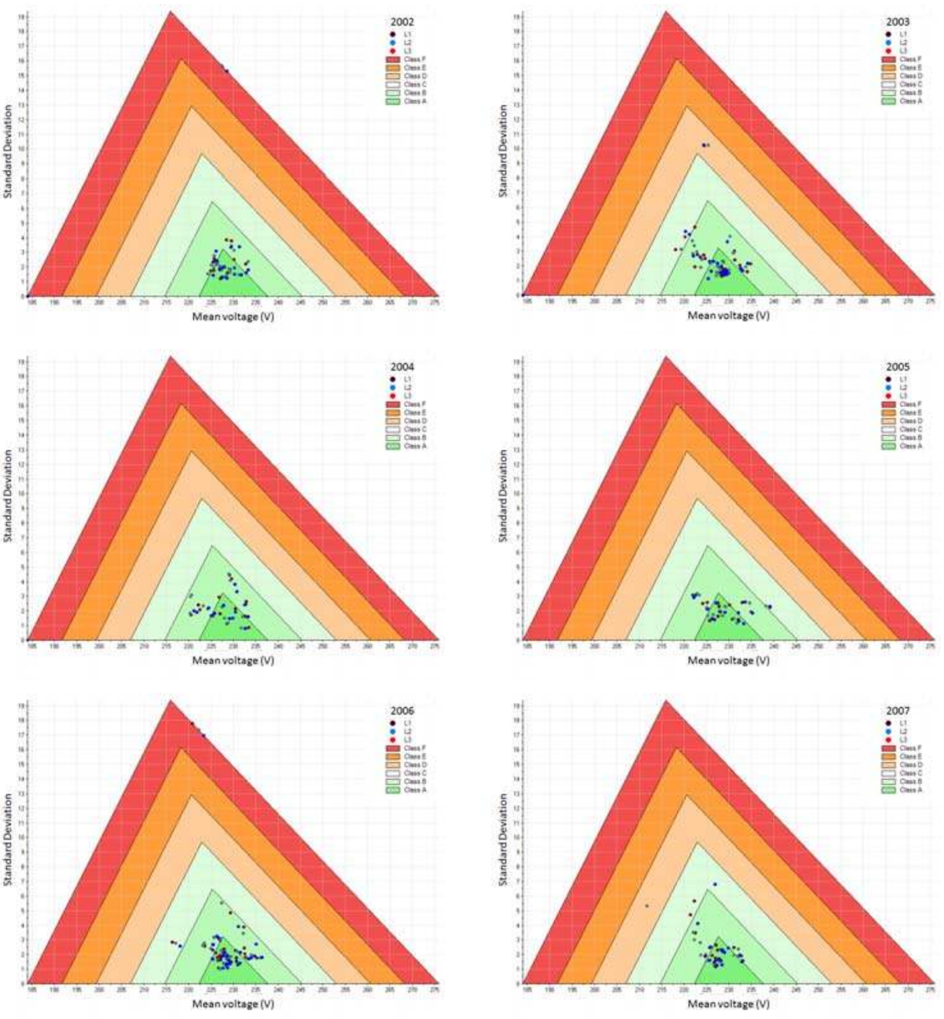


Figure E.3 Classification of slow voltage variations in the Alliander grid for the years 2002 until 2007

Figure E.3 shows the classification of the aspect slow voltage variations based on measurements for the years 2002 (upper left) to 2007 (lower right) in the Alliander grid.

Most of the measurements have an average value around 230 V. Only in 2 occasions a classification worse than C could be noticed. In 2007 this occurred at a location having a rather low average voltage combined with a rather large asymmetry among the three phases (see Figure E.4).

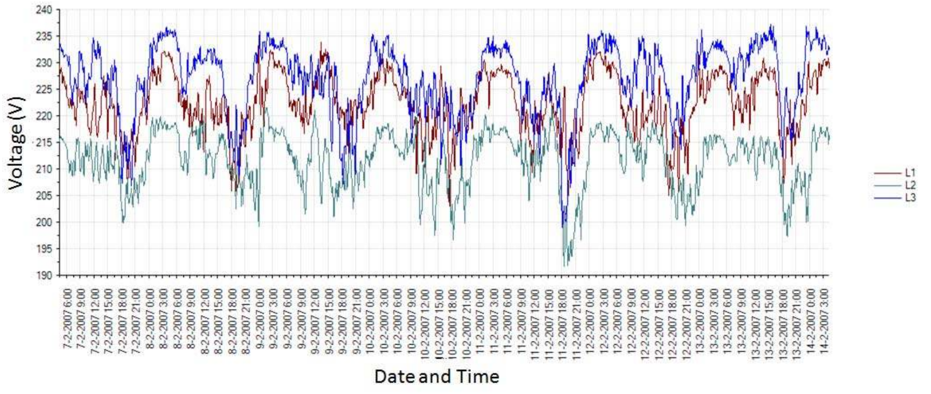


Figure E.4 One week registration at a connection with a low average voltage and large asymmetry among the phases

Fast voltage variations and flicker

Flicker is the main cause of complaints. The switching of loads results in variations of the voltage, which might be repetitive. Apparatus keep functioning if the voltage drop is not too big, but the flickering of the light can be annoying. Flicker problems occur mainly in LV networks. The impact of the load on the voltage depends on the type of load and the network impedance.

In networks with overhead lines the combination of the large inductance of the conductors and the inductive currents (due to for example the starting of a motor) can cause a problem. In cable networks the influence of inductive currents is lower because the resistance dominates the impedance of the cable.

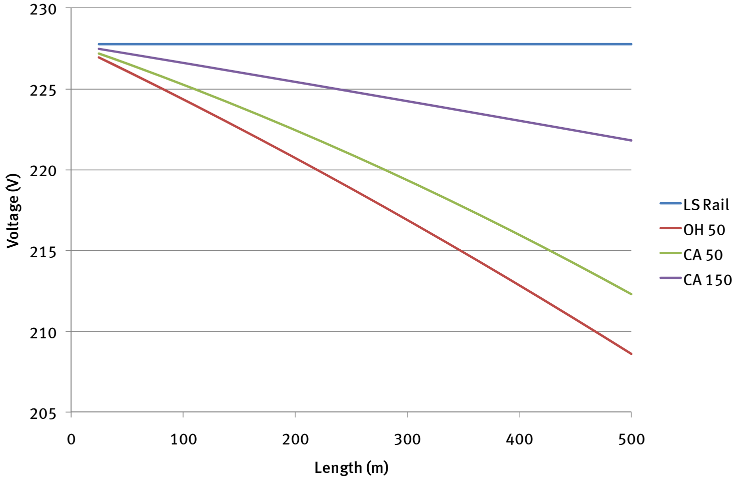


Figure E.5 Influence of motor start on voltage variation for cable and overhead line

Figure E.5 shows the influence of the network design on voltage drops due to motor start. Here the benefits of the small impedance of cable networks are visible. In case of a TN network the neutral conductor and the PE conductor of the cable are interconnected. This reduces the return impedance and in this way also reduces the voltage variation.

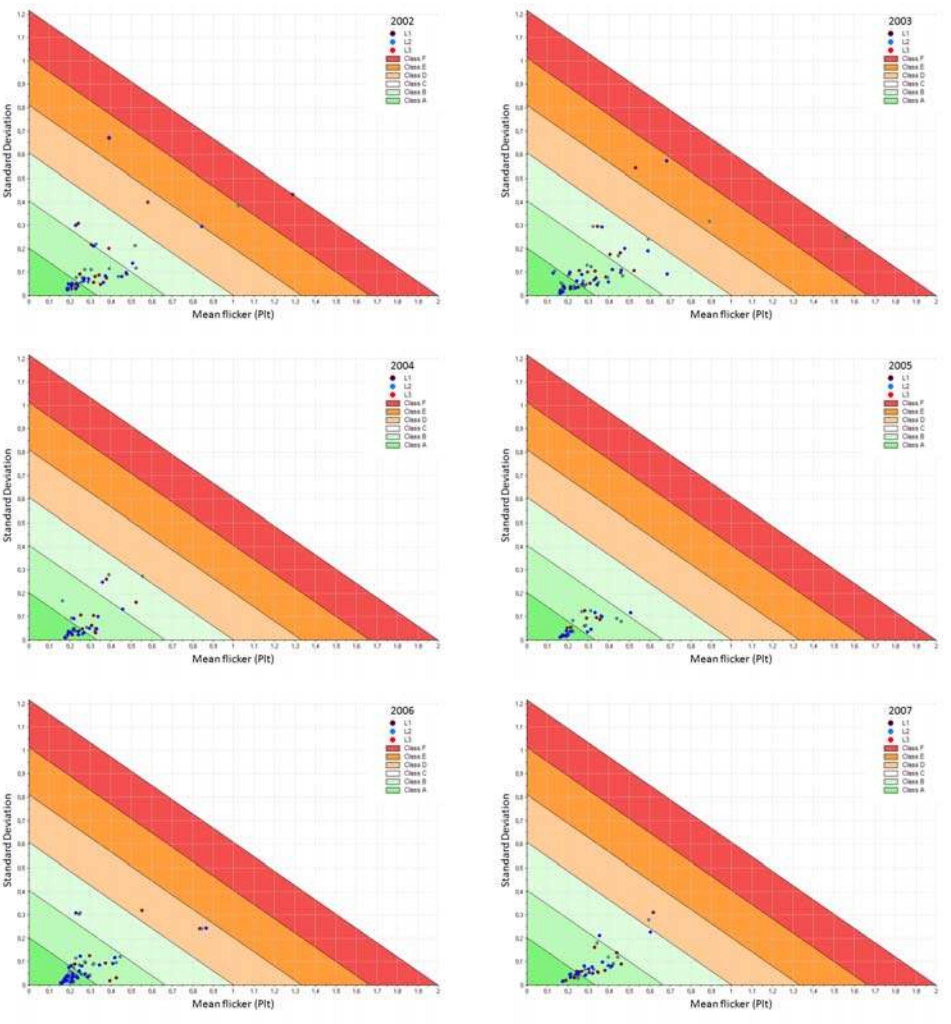


Figure E.6 Classification of the aspect flicker in the Alliander grid between 2002 and 2007

Figure E.6 shows the results of the flicker aspect (P_{LT}) in the Alliander grid of the PQM measurements from 2002 (upper left) to 2007 (lower right). Most of the measurement points have acceptable values (P_{LT}<1) But also some problems can be noticed. Most of these problems are due to disturbances in the MV network and should be excluded from the results.

In the Netherlands problems with flicker mainly occur in rural areas with networks having small conductor diameters. The Dutch regulator has set requirements on the impedance of the network. When the network impedance is larger than 0.283 Ω, the network operator has to improve the network. This value is based on the fact that with this impedance the switching of a specific load will not result in a P_{LT} larger than 1. There are of course other measures to minimise flicker problems like the use of other kinds of lamps [COBB 002] and the use of power electronic equipment [OVER 001] [ABDU 001]. The gradually replacement of light bulbs by energy saving lamps is likely to reduce complaints due to flicker.

Harmonics

Harmonic voltages can cause malfunctioning of equipment. Electronic equipment causes harmonic currents. These currents flow through the network impedances, causing harmonic voltages. In the lower plot of Figure E.2 it was already shown, that almost all harmonic measurements have a classification A or B. Even the 5^{th} harmonic voltage remained within these areas for the last 6 years as can also be seen in Figure E.7 where the results for the 5^{th} harmonic are presented per year.

The reason for these low values is the use of cables. As the frequency increases, the impedance of the network depends more and more on the inductance of the network. Compared to overhead lines, cables have a far lower inductance.

The impedance for a specific harmonic h can be written [ARRI 001]:

$$Z_h = \sqrt{h} \cdot R_1 + jh \cdot X_1 \qquad \text{(E.4)}$$

The harmonic current of most of the rectifiers used in domestic power electronic appliances is:

$$I_h = \frac{1}{h} \cdot I_1 \qquad \text{(E.5)}$$

The harmonic voltage created by this current is:

$$U_h = Z_h \cdot I_h = \left(\sqrt{h} \cdot R_1 + jh \cdot X_1\right) \cdot \frac{1}{h} I_1 = \left(\frac{1}{\sqrt{h}} \cdot R_1 + j \cdot X_1\right) \cdot I_1 < \left(R_1 + jX_1\right) \cdot I_1 = \Delta U_1 \qquad \text{(E.6)}$$

This means that the harmonic voltage created by a device normally is lower than the voltage drop created by that device. In cable networks the resistance dominates the impedance. For a 150 AL LV cable, the value of R is more than 3 times the value of X. For low frequencies the harmonic voltage in cable networks is approximately:

$$U_h \approx \frac{1}{\sqrt{h}} \cdot R_1 \cdot I_1 = \frac{1}{\sqrt{h}} \cdot \Delta U_1 \qquad \text{(E.7)}$$

The harmonic voltage in cable networks for high frequencies is approximately:

$$U_h = X_1 \cdot I_1 \approx \frac{1}{3} \cdot \Delta U_1 \tag{E.8}$$

LV cable networks in the Netherlands are designed for a voltage drop of about 5% at full load. So, the harmonic voltage will be far less than this 5%. Therefore under normal circumstances too high harmonic voltages in cable networks will hardly appear.

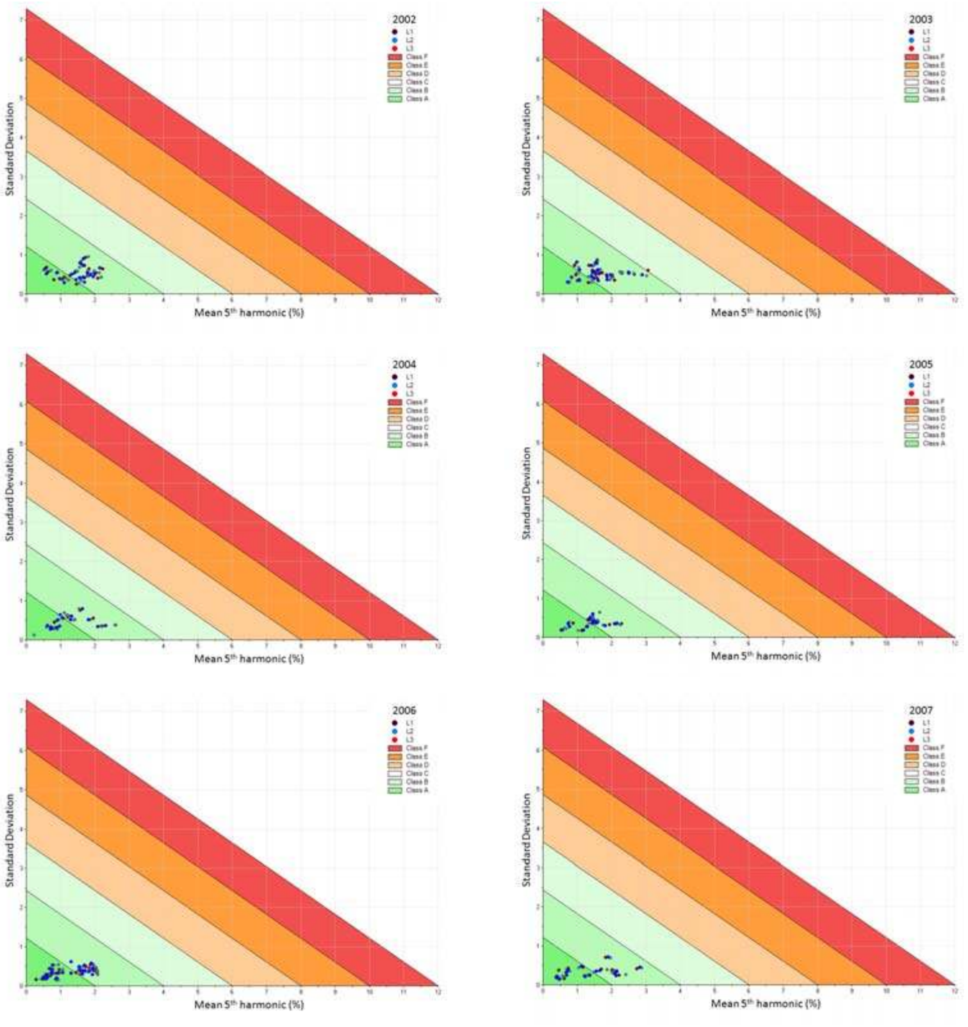


Figure E.7 Classification of the aspect of the 5th harmonic in the Alliander grid between 2002 and 2007

For overhead lines the reactance dominates. The harmonic voltage for such networks is approximately:

$$U_h = X_1 \cdot I_1 \approx \Delta U_1 \quad (E.9)$$

In these networks high harmonic levels may be expected.

High harmonic levels may also occur due to resonances. Small capacitors used in many domestic appliances may cause resonance in combination with the MV/LV transformer. The resonance frequencies sometimes drop below the 15th harmonic. These phenomena have been observed in cases of large penetration of solar cells [ENSL 001] [DYSK 001].

Dips

Voltage dips are caused by short-circuits in the network and by connection of large machines. A voltage dip is defined as “a voltage between 1% and 90% of the nominal voltage during a period of 0.5 cycle to 1 minute” [COBB 001]. In the Netherlands the number of dips is limited to a few per year, because of the large amount of underground cable networks.

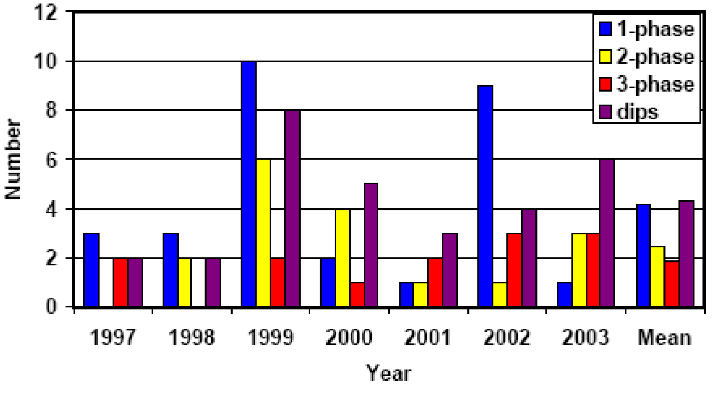


Figure E.8 Number of faults and dips recorded at the 10 kV busbar of substation Zaltbommel

Figure E.8 shows the number of faults and the number of dips recorded at the 10 kV busbar of substation Zaltbommel. The average number of dips is about 4 per year. In MV networks that are not directly earthed only two- and three-phase faults result in dips. The influence of dips on the performance of connected apparatus depends amongst others on the magnitude and duration of the dip, which are depending on the magnitude of the short-circuit current and the fault-clearing time.

F Transient voltages and currents during earth faults

Specific transient phenomena may occur in case of earth faults. When an earth fault happens, transient phenomena can be observed in all phase voltages and in the current of the faulted phase. These transients occur due to the phenomena of discharging the capacitances of the faulted phase and charging the capacitances of the healthy phases. The transients have a frequency larger than the normal power frequency. In networks with isolated or compensated neutral these transients can be large [NIKA 001]. The large value and high frequency of the transient current can result in a fast zero-crossing of the fault current, which may result in spontaneous fault-clearing. The zero-crossing of the fault current most likely occurs at the maximum value of the zero-sequence voltage. Therefore, a large residual (zero-sequence) voltage remains in the system. The magnitude of this voltage reduces in time due to leaking resistances, together with the impedances of cables and lines. In cable networks, the leaking resistances are large and the cable resistances are relatively small. Therefore, the reduction is a slow phenomenon. According to [ANGE 001] a half cycle after the fault clearing, the voltage of the "weak" phase relative to earth will reach a value close to twice the normal line to neutral voltage added on the remaining zero-sequence voltage. This increases the risk of a re-strike. This re-strike, results in new transients and in case of fast self-extinguishing of the fault in a larger zero-sequence voltage. If this sequence of re-striking and self-extinguishing repeats, large over-voltages occur in the system.

The effect of earthing on these transients is shown by the results of some calculations. Figure F.1 shows the current and voltage at the location of the fault during a non-extinguishing single-phase fault in a network with isolated neutral. In networks with compensated neutral similar transients in the current can be observed.

The transients in the fault current cause several extra zero-crossings where self-extinguishing of the fault is possible. Figure F.2 shows the current and voltage at the location of the fault if a single-phase fault in a network with isolated neutral extinguishes at the first zero-crossing of the fault current.

The transient in the fault current causes a zero-crossing after less than 2 ms. Due to this zero-crossing the fault is extinguished. Because the fault is cleared, the voltage will build up again. The magnitude of this voltage is equal to the sum of the zero-sequence voltage and the normal-sequence voltage. The maximum phase to earth voltage is more than twice the normal phase to earth voltage. This increases the risk for a re-strike of the fault.

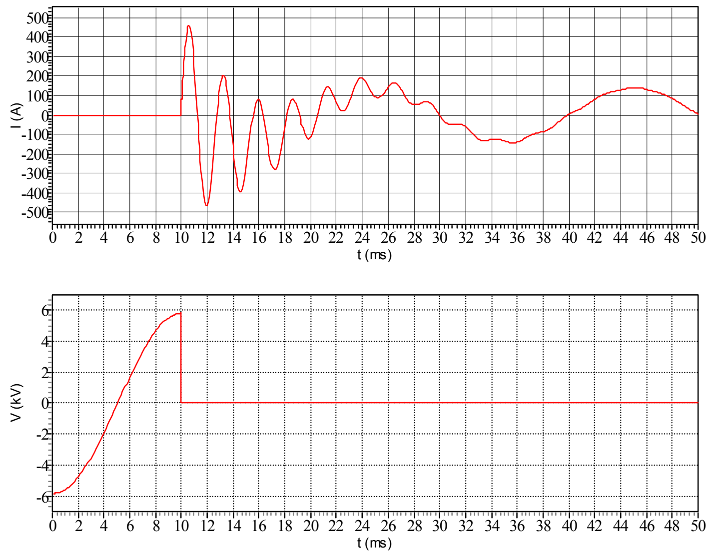


Figure F.1 Calculated current (top) and voltage (bottom) at the location of the fault during a non-extinguishing fault in a network with isolated neutral

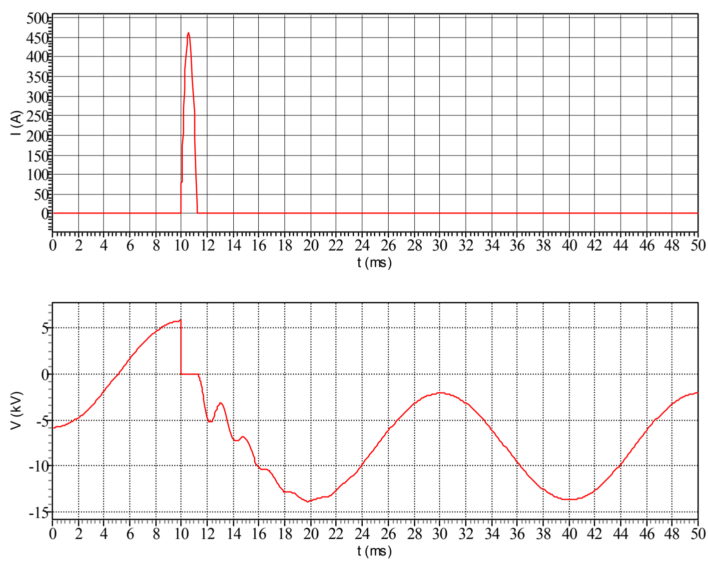


Figure F.2 Calculated current (top) and voltage(bottom) at the location of the fault during a self-extinguishing fault in a network with isolated neutral

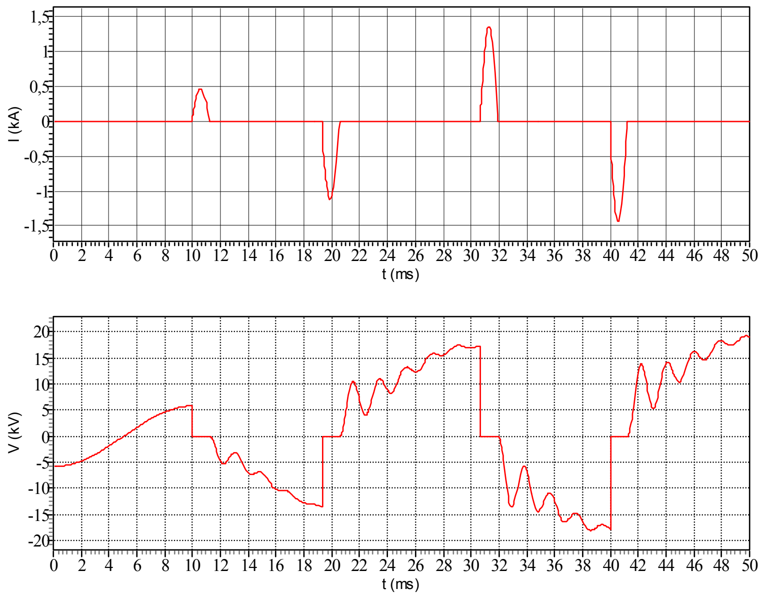
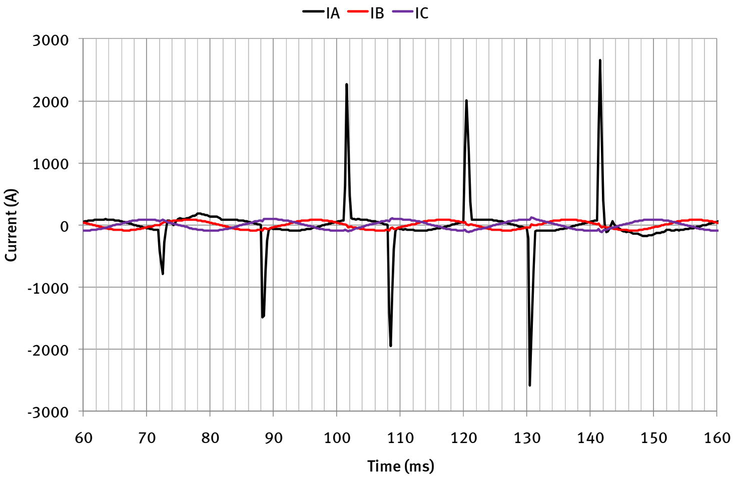


Figure F.3 Calculated current (top) and voltage (bottom) at the location of the fault during a self-extinguishing and re-striking fault in a network with isolated neutral

Figure F.3 shows the effect of repetitive extinguishing and re-striking of a fault. At every re-strike, the transient current increases in magnitude. After every extinguishing, the zero-sequence voltage changes polarity and increases in magnitude. After the fourth event, the phase to earth voltage at the fault-location reaches a value of more than 3 times the normal phase to phase voltage.

These phenomena are in practice observed in the Alliander fault location project. Figure 3.16 shows the current in the faulted feeder and the voltages on the substation busbar, during an extinguishing and re-striking sequence of a single-phase fault in a network with isolated neutral. The upper plot shows the measured currents. The lower plot shows the measured phase to earth voltages and the calculated zero-sequence voltage.

The fault starts at t=72 ms. A transient in the current, followed by a steady state fault current can be observed during the first half period. The busbar voltage of the faulted phase is almost zero. At the zero-crossing of the fault current, the fault extinguishes and the voltage on the faulted phase starts to increase. At t=88 ms, the fault re-strikes. The transient in the fault current results in a zero-crossing of the current and an extinguishing of the fault. At this moment large changes in the voltage can be observed. Five more occurrences of re-striking and self-extinguishing can be observed. During every re-strike, the zero-sequence voltage reverses in polarity and reaches a value of more than 10 kV after the fifth re-strike.



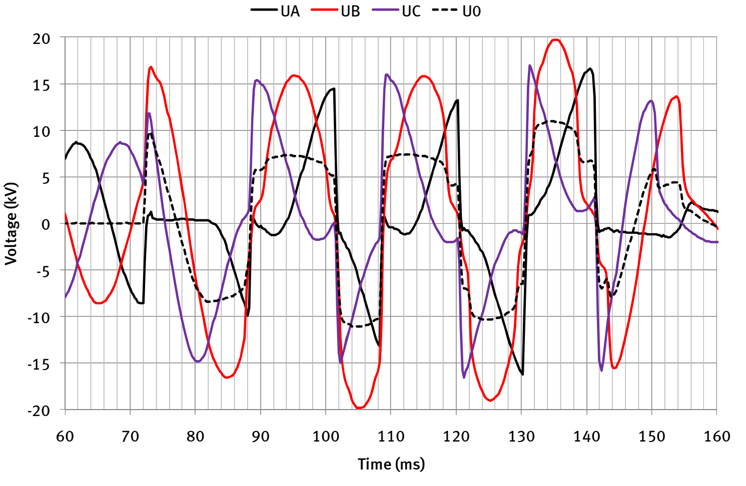


Figure F.4 Measured current in the faulted feeder (top) and voltage (bottom) at the substation busbar during a self-extinguishing and re-striking fault in a network with isolated neutral. This phenomena was recorded at substation Nijkerk on 2007-01-22

As a result of the polarity switching of the zero-sequence voltage, rapid voltage changes of more than 14 kV in less than 1 ms occur on all phases. The phase to earth voltage of all phases reaches values of more than twice the normal phase to earth value. A peak value of 20 kV can be noticed. The transients and high voltages will be noticed in the whole MV network and can result in degradation of insulation. This increases the risk of new faults. Such a fault can occur on a different location, which may result in a cross-country fault.

In networks with impedance earthing and direct earthing the risk of self-extinguishing and re-striking is limited. Figure F.5 shows the calculated fault current during a single-phase fault in networks with impedance earthing and direct earthing. Here the transients are hardly visible due to the large values of the steady state fault current. These transients cause no extra zero-crossings, so self-extinguishing of the fault is not possible.

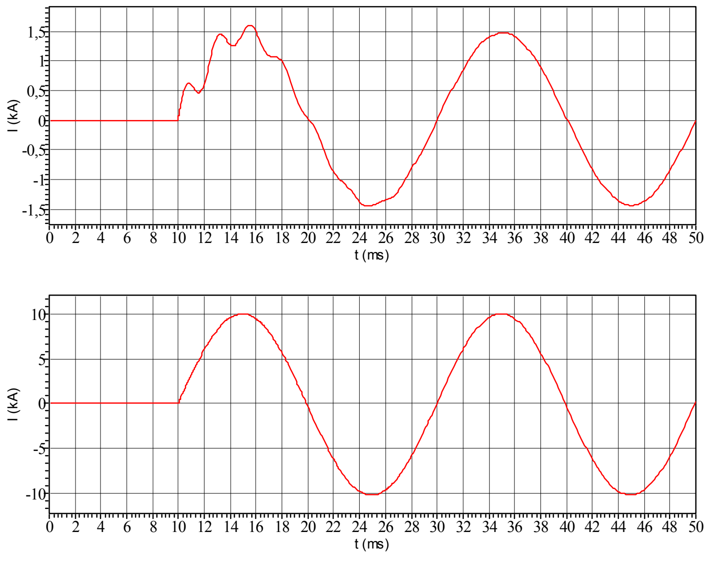


Figure F.5 Calculated fault currents during a non-extinguishing fault in a network with impedance earthing (top) and direct earthing (bottom)

G Coupling of MV networks

In case of disturbance, maintenance or extension in an MV grid, changes in network topology are required. Cable sections have to be isolated, network openings have to be closed and new temporary network openings must be created. In order not to interrupt power supply to the customers, some normal open points have to be closed before the cable section can be isolated. This means that temporarily two network sections are connected. When these two sections are fed by different HV/MV transformers, this will result in balancing- and inrush currents from one network to the other. The magnitude of these currents is amongst others determined by the difference in voltage amplitudes and phase angles in the networks and the power consumed in the network parts. The inrush and balancing currents should not trip the protection devices. And, in order to create a new open point, the balancing current has to be switched off without safety risks.

By estimating the phase angle and actual loads in the two networks the expected switching, inrush and breaking current can be calculated. If they are all below safety limits, the switching actions can be performed. In Amsterdam a pilot on this subject is implemented covering 21 substations [NUIJ 001]. In this project newly developed, cost efficient and unconventional, equipment for measuring and communication is used. A description of this application is given in [PROV 001]. The application obtains real-time information of the voltages and phase angles at the different substations. This information is fed into a load-flow model of the actual network. The application is then able to calculate the currents and gives information on whether or not it is allowed to couple these networks. The magnitude of the balancing current at the switching location depends on the voltages in the HV network, the loads in the feeders and the total network impedance (see Figure G.1).

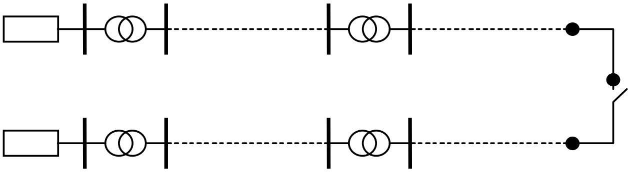


Figure G.1 HV and MV network

The balancing current is relatively small compared to the nominal transformer current and will hardly be noticed at HV level. Therefore the 50 kV and higher voltage grids can be considered strong. Furthermore, in the Amsterdam system there are always two to three 50/10 kV transformers in parallel operation, so their total impedance is negligible.

Using these assumptions, the equivalent network model can be reduced to the two MV systems involved with two equivalent MV voltage sources (see Figure G.2). Neglecting the HV network components decreases the total network model impedance, thus resulting in a larger balancing current than in practice. This is acceptable because, for sake of safety, the application must calculate the worst case and, for sake of acceptance, the application must be simple.

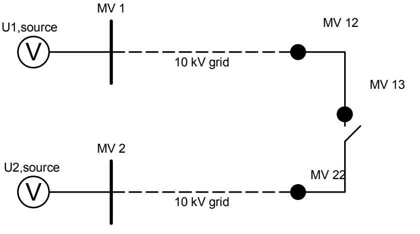


Figure G.2 Equivalent MV network

The balancing current on the switching location can be derived in this way from the voltages U1 and U2 on the feeder bay nodes in the MV substation (nodes MV 1 and MV 2 in Figure G.1 and Figure G.2). These voltages must be known both in magnitude and in angle. The accuracy of the two voltage angles is obtained by synchronising the two measuring systems by using GPS technique. The MV network impedance is calculated from the available GIS network data. The application automatically adds the equivalent sources to the beginning of the feeders. The loads in the feeders are determined using the method described in appendix H regarding pseudo state-estimation.

The application process flow is as follows:

- Request for a switching action.
- Retrieve network data from GIS.
- Select the involved feeders.
- Get measurements of transformer secondary voltages, transformer currents and feeder currents.
- Calculate the equivalent sources and powers being consumed and generated.
- Calculate the pre-closing voltage difference.
- Calculate the post-closing balancing current.
- Generate the go/no-go decision.

In [GROO 001] some practical experience with the system is described. The system operates with satisfying performance and the calculated currents are always on the safe side. The performance of the system depends on the accuracy of the network model. As the MV networks are subject to changes almost every day, effort must be put in daily updating the network models.

H State-estimation in MV networks

In normal load-flow calculations, the load at a certain node is based on the total load divided by the participation or diversity factor. In case of a large variety of loads this factor will vary over time (depending on the hour, day and month). Pseudo state-estimation is estimating this factor based on the (measured) load curve at the beginning of the feeder and the (measured or constructed) load curves at the nodes. This calculation method results in a more realistic calculation of power flows and voltages in the network [WATE 001]. At this moment calculations are performed mainly based on load curves for specific types of loads (shops, households, factories, etc). These curves can be extended towards generation profiles (wind, solar, CHP). The challenge is to obtain accurate generation profiles.

The pseudo state-estimation application combines the HV/MV substation on-line measurements with MV nodes load patterns and insights concerning the behaviour of the several customer groups (composition and profiles). The total load measurements serve as a basis. Determining the simultaneity of loads on time intervals and making use of network analysis techniques yields an improved insight in the real network load and node voltages without the necessity of measuring every node. A description of this application is given in [PROV 001]

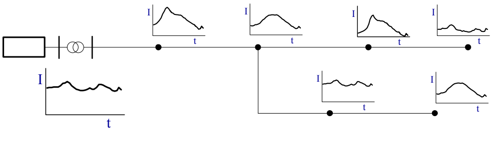


Figure H.1 Individual MV nodes load profiles and transformer load profile [PROV 001]

The network diagram in Figure H.1 shows the MV nodes with their individual (estimated) load profiles, the HV/MV transformer with its on-line measured load profile and the network source. The individual node profiles can be obtained by specific measurements or they can be constructed. The method of constructing is based on the assumption that the node load profiles can be composed from standard profiles, e.g. percentage household, office and commercial. If the composition of standard load-groups is known, the node load profile is the weighted summation of the individual standard load profiles.

The standard load profile curve for standard group number m can be represented by the vector B:

$$\underline{B}_m = \left(b_{m,1}, b_{m,2}, b_{m,3}, \ldots\ldots, b_{m,i}, \ldots\ldots b_{m,N}\right)^t \qquad \text{(H.1)}$$

where N is the maximum number of time intervals.

Then the load for node number j can be represented by a vector $\underline{I}$:

$$\underline{I}_j = a_{j,1}\underline{B}_1 + a_{j,2}\underline{B}_2 + a_{j,3}\underline{B}_3 + ... + a_{j,M}\underline{B}_M \tag{H.2}$$

where N is the maximum number of standard load profiles and the scalars $a_{j,m}$ represent the composition of standard load profiles for node j. The scalars $a_{j,m}$ have to be chosen in such a way that the largest value of all the elements $i_{j,i}$ of vector $\underline{I}_j$ is equal to the maximum load at node j.

The transformer load $i_{transf,i}$ for time interval i must be equal to the sum of the node loads in the feeder. Since the node load profiles are composed independently, for each time interval i a correction factor g_i has to be introduced:

$$i_{transf,i} = g_i \sum_j i_{j,i} \tag{H.3}$$

The correction factors $g_1,...,g_N$ for the M time intervals are contained in the diagonal correction matrix *G*. Multiplying this matrix with the sum of all load vectors $\underline{I}_j$ yields the transformer load vector:

$$\underline{I}_{transf} = G \sum_j \underline{I}_j \tag{H.4}$$

The correction factors g_i for each time interval i are derived from the measured transformer load profile and the individual nodes load profiles:

$$g_i = \frac{i_{transf,i}}{\sum_j i_{j,i}} \tag{H.5}$$

Finally, the node loads $i_{j,i}$ are corrected and the load flow will be evaluated.

The application process flow is as follows:

- Retrieve network data (from GIS).
- Compose the nodes load profiles.
- Get measurements of transformer secondary voltages, transformer currents and feeder currents.
- Select the time interval i.
- Calculate the correction factor g_i.
- Correct the node loads $i_{j,i}$.
- Calculate the load flow.

Based on the known load characteristics in the MV network and based on measurements on the feeders in the substation, the program gives a good estimation of voltages and currents everywhere in the MV network. This is of good help for the operator, performing a network restoration after a fault and for scheduling switching actions in case of maintenance. It is also useful for the asset manager to plan future network extensions.

I Protection

A proper protection philosophy is necessary to avoid damage to network components in case of faults. The type of protection depends on the voltage level and the type of network (distribution or transmission). This appendix summarises some specific items regarding protection in distribution networks:

- Fault interrupting devices;
- Protection relays;
- Protection of components.

I.1 Fault interrupting devices

In distribution networks, the most applied fault current interruption devices are fuses and circuit breakers. Both have their specific advantages and disadvantages.

Fuses

The essential component of a fuse is a metal wire or strip that melts when too much current flows. In this way the circuit in which it is connected is interrupted. This melting time decreases when the current increases. In this way, a large short-circuit current may be interrupted even before the first peak is reached. Especially for LV applications fuses are cost efficient solutions. There are however also a number of disadvantages:

- It takes a long time (more than 2 seconds) to interrupt currents that are less than five times the nominal current of the fuse.
- When a fuse is blown, it has to be replaced by the service crew.
- The thickness of the metal wire must be chosen thick enough to limit heat losses, but small enough to melt during short-circuits.
- The heat produced by the metal wire will warm up the surrounding area of the fuse. Especially in enclosed or encapsulated areas this heat may result in temperatures above thermal limits of the insulation material. Therefore there is a limit in the nominal current of fuses that can be applied in such areas.

Circuit breakers

Circuit breakers are generally operated by an external signal, often generated by a protection relay. Different types of relays are described below. Circuit breakers in MV networks need external mechanical power to open. Therefore it takes some time (around 70 ms) between the tripping signal and the physical opening of the contacts. In this way it is not possible to prevent or reduce the initial peak current of a fault. Circuit breakers in LV applications often function on magnetic and thermal stresses caused by the current. In this way they can operate fast during large currents.

As the tripping signal of a protection relay not necessarily depends on thermal processes, a tripping signal can be given based on the measured current. In this way switching of fault currents with a magnitude little above nominal current is no problem.

I.2 Protection relays

Protection relays are used to send tripping signals towards the circuit breakers. Some commonly used protection relays in distribution networks are:

- Over-current relays. These relays will cause a tripping signal when a certain current has been measured during a specific time. There are two types of over-current relays, the definite time relay and the inverse time relay. The definite time relay functioning is based on a limited set of currents and corresponding times. This was the only possibility for mechanical relays. The inverse time relay functioning is based on a continuous set of currents and corresponding times. This set represents a curve similar to a fuse. When using definite time relays, selectivity can easily be checked manually by simply comparing fault currents and corresponding times. When using inverse time relays, selectivity must be checked with the help of graphs or computers.
- Energy direction relays. These relays over-current relays extended with an energy direction function. This function helps to detect the direction of the short-circuit current contribution. When this contribution is not in the right direction, no trip signal will be given. This kind of protection is often applied in substations where distributed generation is connected, in order to avoid false tripping.
- Differential relays. Differential relays are used to protect a certain object, like a cable or a transformer. The relay uses current signals from all terminals of the object. If the sum of the currents is not equal to zero there must be a fault. When protecting a cable, communication is necessary. The functioning therefore also depends on the reliability of the communication system.
- Distance relays. A distance relay calculates the distance of a fault based on the measured impedance. Distance relays therefore need both voltage and current measurements. Distance relays are more sophisticated compared to energy direction relays. They are more expensive, but act better in case of faults close to the device.
- Frequency relays. Frequency relays act on frequencies that are too high or too low. In distribution networks they are applied at generators and motors.
- Over-voltage and under-voltage relays. These type of relays act on voltages that are too high or too low. In this way specific equipment can be switched off in order to prevent malfunctioning or damage. This type of protection is applied for the protection of generators and motors.

I.3 Protection of components

Cables

Cables have to be protected against over-currents. Large currents cause temperature rise of the conductor resulting in possible degradation of the insulation. During the first seconds of a fault, there is no exchange of heat towards the environment. The heating of the cable depends on the square of the fault current and on the duration of the fault (I^2t). This results in a maximum fault time as a function of the fault current. The protection of the cable must switch off this short-circuit within the related time.

In case of a single-phase fault, the temperature rise is not only caused by the current in the phase conductors, but also by the current in the neutral and PE conductor. The PE conductor is often the sheath of the cable. This conductor normally has a larger resistance than the phase conductors. The maximum allowable current in the cable sheath is therefore generally lower than the current in the phase conductors.

Stationary over-currents result in slow degradation of isolation and in possible drying-out of the soil. As described in chapter 3 this process takes a long time, especially when the over-currents are relatively small. Therefore fast switching is not necessary. This gives time for the network operators to reduce these currents. In case of a small over-current due to a single-phase fault (especially in networks with isolated neutral), this time can be used to locate and clear the fault. In case of a normal overloading, this time can be used to rearrange the network.

In many MV transmission networks single-core cables are used. Here the most common fault is a single-phase fault. For these types of faults, the impedance is not a linear function of the distance, because the fault current can return over several paths. The first path is formed by the sheath of the faulted cable towards the HV/MV substation. The second path is formed by the sheath of the faulted cable towards the MV distribution substation and the sheats of healthy phases and other parallel cables from the MV distribution station back to the HV/MV substation. The non-linear function between the measured impedance and the distance might result in improper functioning of distance protection.

Busbar systems

Busbar systems have to be protected against mechanical and thermal stresses. Mechanical stresses are determined by the peak fault current. Limiting this peak current by protection requires fast switching. This is possible with fuses, but not with mechanical circuit breakers. Another solution for breaking this current is to use solid state switches based on power electronics [MEYE 001] [MEYE 002] [SMIT 001] [DUPR 001].

Limiting the peak current for busbar systems of ring main units, is also possible with measures in the MV network. These measures consist of applying short-circuit current limiting devices. These devices not only limit the peak current, but also the stationary short-circuit current.

Busbar systems in solid insulated switchgear, as is the case in many compact MV switchgear, must be protected also against the thermal aspect of the short-circuit current.

Transformers

Transformers must be protected in case of internal and external faults. MV/LV distribution transformers are protected against internal faults by a protection device on the primary side of the transformer. This protection device is either a fuse or a circuit breaker. When a fuse is used, the nominal current of this fuse must be coordinated with the nominal thermal current of the installation to which it is connected. In the Netherlands many compact enclosed MV installations (Magnefix) are used. These installations have a thermal capacity of 35 A. Therefore, on the primary side transformers up to 630 kVA can be protected by a fuse. Larger transformers must be protected by a circuit breaker.

The MV/LV distribution transformers must be protected against damage due to external faults by the protection in the network or by a protection on the secondary side of the transformer. The protection on the secondary side of the transformer must clear faults on the LV busbar system and act as back up for the protection of the LV network. This protection must be selective both compared to the protection on the primary side as the protection on the LV feeders. When it is hard to obtain this selectivity, the protection on the secondary side will be omitted. In this case, the HV protection must also protect for faults on the LV busbar.

Generators and motors

Generators and motors must not only be protected against over-currents due to a fault, but also for other aspects that can result in malfunctioning such as:

- Over-voltage;
- Under-voltage;
- Asymmetry;
- Under-frequency;
- Over-frequency.

For each of these events specific protection equipment can be installed. The parameters to be used depend on the type of generator and motor. In many cases, generators must also be protected against possible islanding and they also may be suspect to fault ride-through requirements. This may result in specific challenges regarding protection, that are discussed in chapter 6.

J Substation automation at Alliander

J.1 Implementation of substation automation

Already half way the 1990s Alliander (a Dutch network operator [ALLI 001]) started studying the advantages of integrating substation automation and protection functions for the MV network into one device. The goal was to reach a total transparent and simple substation automation system within 10 years. This was only feasible if the costs for substation automation systems were decreased by 90%.

In the first stage (2003) a pilot system was implemented in the substation Zaltbommel. This automation system contained protection, control and diagnostics as well as remote communication. The philosophy was based on reducing costs and using as little as possible linked independent devices. The schematic layout is shown in Figure J.1. Automation and protection for three bays were combined in one device. A LAN linked ten of these devices to a central computer. The system also contained a PQ monitoring application. With the available functionalities it was easy to extend the system with a fault location application. This system is still running without problems.

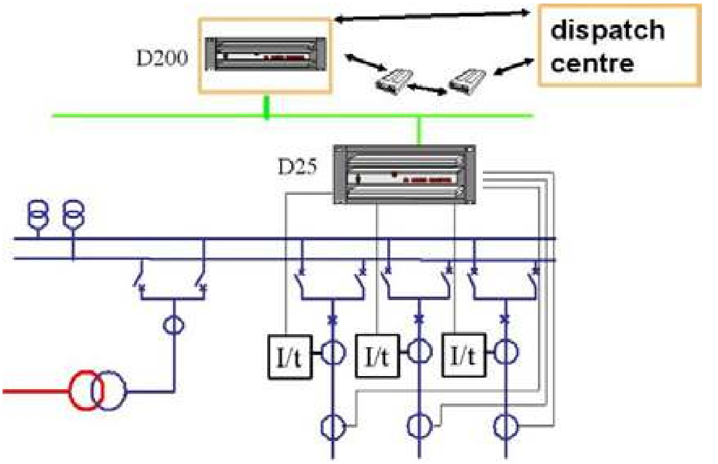


Figure J.1 Schematic layout of automation system in 2003 [RIET 002]

The D20/D200 RTU provides the communication function for the remote control of the whole substation. It is used for the remote diagnostics, remote communication and local control and diagnostics. The main feeder protection is a standard over-current relay. The D25 device integrates the functions of the local protection and control for three feeders in one box. Inside this device, three protections for the three bays are used as backup.

Both protection and control are no longer unique boxes, but transformed towards a software application inside a device. Another function of the D25 is the continuous registration of the currents and voltages with 64 samples per period. This information is used for fault location and protection functions.

The second stage was the implementation of the SASensor concept, which is based on the ideas about future substation automation as given in chapter 5 and which will be described later in this appendix. After the type tests in 2006, a pilot started in which ten substations were equipped with this system. The aim of this pilot was to proof the accuracy of the different parts of the measuring system. The measuring results can be transferred from the substation towards different departments of the network operator, where involved people are able to simply obtain and process the data in order to get proper management and operational information. The system is also used for fault location and power quality monitoring. A new protection has been developed and is tested from 2008 in the pilot substations. During these tests the new protection runs in parallel with the existing protection; however, the tripping signals of the new protection towards the circuit breaker are blocked. This new protection system will be fully in operation in 2009.

Due to the success of the pilots it has been decided to implement the SASensor equipment in all substations where automation has to be refurbished or implemented.

J.2 Development of SASensor

The main features of the SASensor are:

- High sampling rates for measuring voltage and current. This makes it possible to perform harmonic analysis.
- Correcting non-linearity in measuring transformers using software.
- Correcting malfunctioning of a current measuring device by using Kirchoff's law based on all other current measurements.
- Performing updating and checking of the system from the office.

The concept is described in several papers like [BALD 001] [BALD 002] [RIET 001] [RIET 002] [RIET 003]. The system is the result of an evaluation of all involved stakeholders on secondary systems in substations. The system concept is clear and easy to understand and has a variety of physical implementations. It is eventually applicable on all voltage levels of the power system. There are also pilot projects running in LV grids.

Description of the system

The system (see Figure 5.3) consists of a central control unit (CCU) and three types of process interface modules, one for the three-phase current, one for the three-phase voltage and one for indication and control.

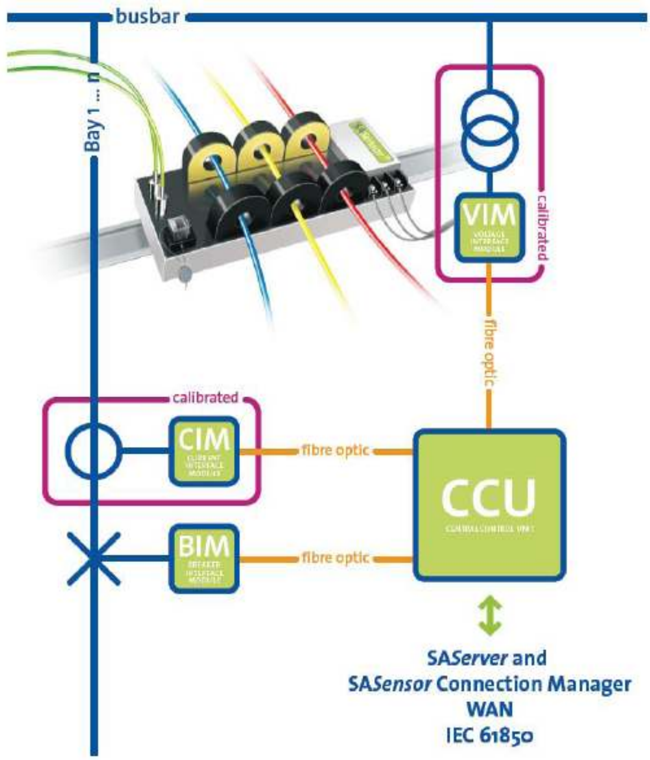


Figure J.2 Schematic view of SASensor lay out [BALD 001]

The interface modules (sensors) are robustly designed with a long lifetime in mind. The current interface module (CIM) and the voltage interface module (VIM) are connected to conventional instrument transformers and covert the analogue signals from these transformers into high sampled digital data. The breaker interface module (BIM) is used for position and alarm indications as well as to open/close the circuit breaker and/or other switching devices. The CIM is equipped with double AD converters to obtain a large measurement range. It is suitable to measure from close to no-load currents (1% I_{nom}) up to large short-circuit currents (100 x I_{nom}). The CIM and the VIM are calibrated to compensate for internal amplitude and phase displacement errors. Software algorithms can be used for compensating for the errors of the primary current and voltage transformers.

In the central system functionalities like control, protection, energy metering and power quality monitoring is implemented. Since all currents and voltages from the substation are available as digital samples, all desired functions can be processed with software. Therefore, other applications can be added to this system as long as they can be written in software.

The CCU has compatible interfaces with IEC61850-8-1 and IEC6 1850-9-2LE, which enables the connection of specific third party apparatus.

Protection and control

The basic functionality of the CCU software includes a (directional) over-current / earth fault protection, which can send a tripping signal to the BIM of the concerned bay. Other protection functions can be performed by external relays connected to the CCU by fibre optics. The central processing unit resamples the high speed, high precision samples of the data acquisition part to the lower speed IEC61850-9-2 process bus. These samples will be used by the third party protection and control devices that will run their own application according to their own specifications. The possible trip messages will be given directly to the actuators on the basis of the IEC61850-8-1 protocol.

Redundancy

The design is inherent robust. When an internal failure occurs, self-diagnostic functions will detect the failure. Furthermore, extra measures are or can be taken to improve redundancy. All functionality is only implemented in the central unit. Therefore it is simple to make a duplication of the system by using a second identical control unit. This creates a redundant system for all functionalities. The interface modules have a double fibre optic channel to send identical data to both control units. Redundancy of the interface modules is a different issue. If availability requirements are high, the interface modules can be duplicated. Some level of backup, however, is already available in the software. The current measurements are normally performed in the incoming and outgoing feeder bays. As a result the system can calculate the sum of the current going to and from the busbar. This calculation can be performed on a sample by sample basis. In case the measurements of one CIM, or even of one phase are lost, the system can replace the lost sample stream by the calculated stream. This improves the availability of data and functions, without extra investments in hardware.

New Opportunities

The SASensor system paved the way for an increasing number of applications, without extra costs, like:

- Energy metering. The system uses the CT and VT correction tables to obtain accurate metering on standard protection cores of any kind. At present the Dutch Metrology Institute (NMi) is investigating this innovative method. Meanwhile an official approval process with the Dutch Office of Energy Regulation (DTe) is started.
- Power quality. The sampling rate of the CIM and the VIM are high, so accurate harmonics measurements can be performed up till the 50^{th} harmonic. In the CCU these data are processed into a harmonic spectrum. The system is not only able to measure harmonics, but also other power quality aspects stated in IEC 50160, like voltage dips, sags, swells, flicker, etc.
- Digital fault location. Automatic monitoring of process disturbances enables the possibility for better process diagnostics. Digital fault recording can be started by user defined events and stores sampled data streams and half cycle RMS values of all relevant process variables. The principle of fault location is described in more detail in chapter 5 and appendix K.
- Simple over-current protection using more than two stages. This will result in a protection system that is fast enough to minimise impacts of dips and retains its selectivity with respect to remote protection in the network, as described in chapter 5.
- Reduction of primary equipment. Due to the correction tables, there is no longer a difference between a measuring coil and a protection coil. Therefore only one type of measuring coil is necessary. The system is able to use data from the protection coil of the MV current transformers for metering. Tests proved that the accuracy in the whole range (1% up till 120% of nominal current) was more than 10 times better than the requirements of the Dutch energy metering regulations.

K Background on fault location

In chapter 5 the fault location in MV networks is described. This appendix shows some background details on:

- Analysing the data.
- Calculating the fault loop impedance.
- Implementation at Alliander (a Dutch network operator [ALLI 001]).

K.1 Analysing the measured data

The measured data contains sampled data of the voltages and currents. By using fast Fourier transformation (FFT) analysis, these data are transformed into amplitudes and phase angles. These data are then transformed into symmetrical components data. From these data it is possible to recognise the fault type, the fault loop impedance and the type of earthing in the network. It is also possible to find out whether the fault is switched off by the circuit breaker in the substation or by a circuit breaker in the network.

K.1.1 Transforming the signal into symmetrical components data

Two examples of the transformation of the sampled data into sequence data will be shown. The first example shows this transformation for the signals due to a single-phase fault, the second example for the signals of a two-phase fault.

Single-phase fault
The registration of the voltage and the current at the main substation during a single-phase fault in the MV network with impedance earthing, is shown in Figure K.1.The fault was switched off after about 800 ms. A remaining current after switching off can be noticed. This leads to the conclusion that the fault was not in the main feeder. The phase to earth voltages in the healthy phases during the fault do not reach the value of the pre-fault phase to phase voltages. This means that the fault is far away from the substation.

Figure K.2 shows the Fourier transformed voltages (left) and currents (right). It can be seen that the voltage in the disturbed phase (UA) decreased and the voltage in the lagging healthy phase (UB) increased compared to the pre-fault voltage. The decrease of the voltage in the disturbed phase and the increase of the voltage in one of the healthy phases is small, which is a result of the relatively long distance of the fault to the substation. As a result the short-circuit current (IA) is relatively low.

Figure K.3 shows the voltages and currents as symmetrical components. The high value of the zero-sequence voltage (U0) during the fault is clearly visible. The three symmetric component currents are almost equal during the fault.

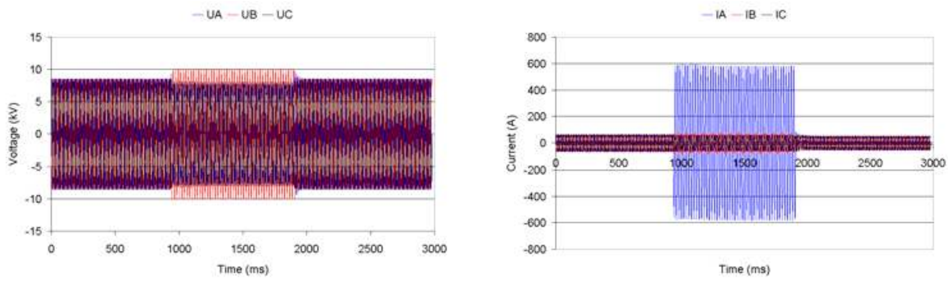


Figure K.1 The recorded data for voltage (left) and current (right) during a single-phase fault

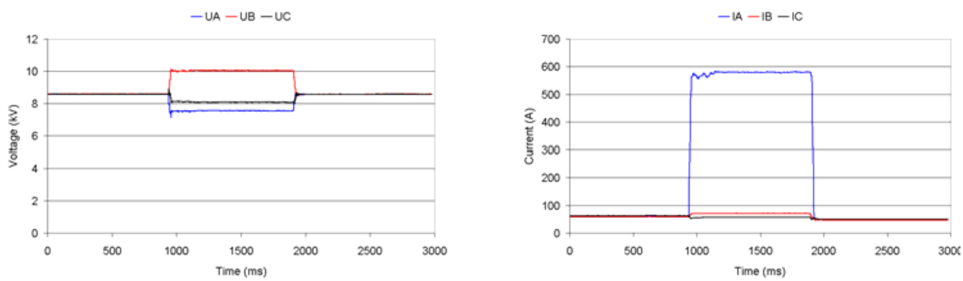


Figure K.2 The magnitude of the FFT signals due to a single-phase fault

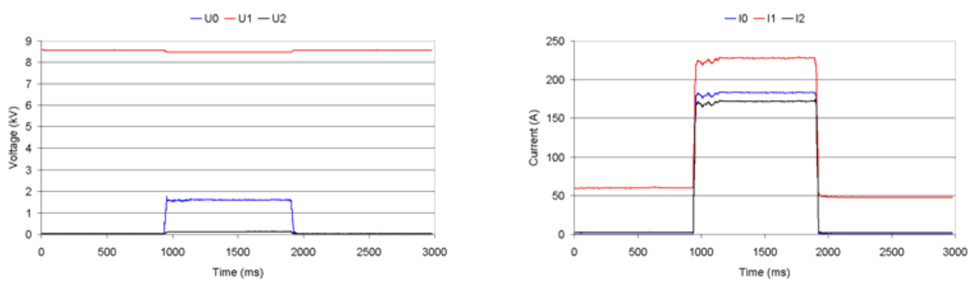


Figure K.3 The magnitude of the voltage and current in the system of symmetrical components

Two-phase fault

The same network was also subject to a two-phase to earth fault. The signals of the measured voltage and current due to this fault are shown in Figure K.4. The fault was switched off after about 1.6 s. There was no remaining current after switching off. This leads to the conclusion that the fault should be located in the main feeder.

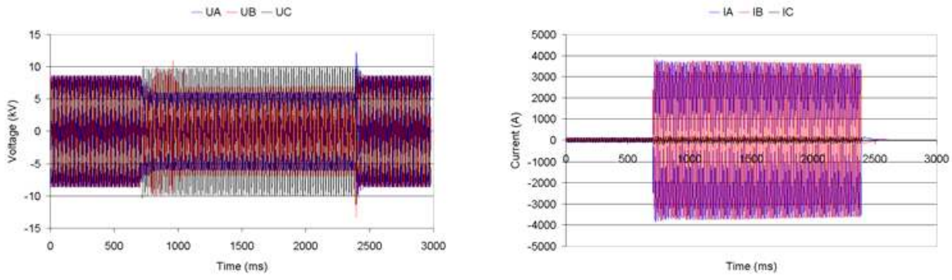


Figure K.4 The recorded data for voltage (left) and current (right) during a two-phase fault

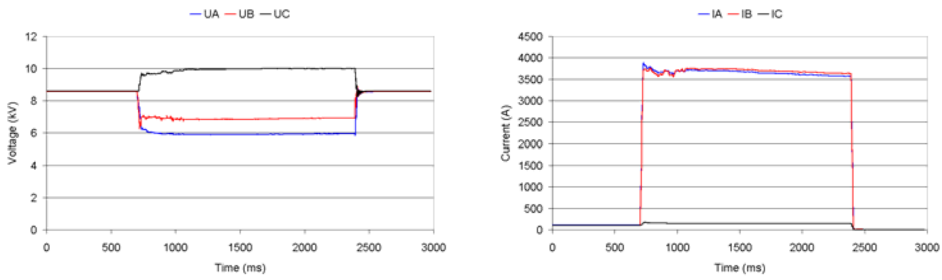


Figure K.5 The magnitude of the FFT signals due to a two-phase fault

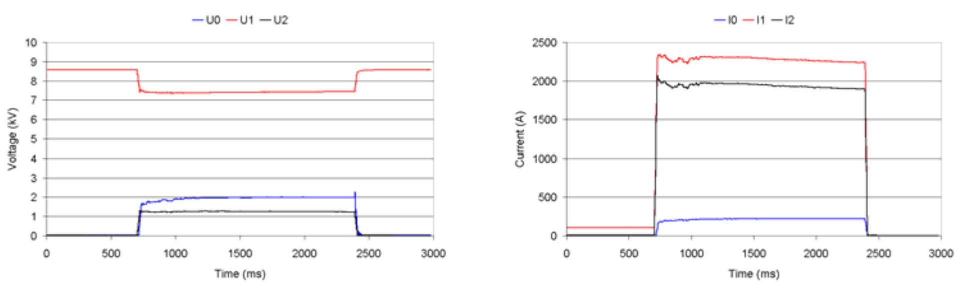


Figure K.6 Decomposition of voltages and currents during a two-phase fault

Figure K.5 shows the Fourier transformed voltages and currents. It can be observed that during the fault, the voltages in the disturbed phases (UA and UB) decrease and the voltage in the healthy phase (UC) increase. The short-circuit currents (IA and IB) can clearly be distinguished and are both much larger than the current in the healthy phase (IC).

Figure K.6 shows the voltages and currents as symmetrical components. During the fault, the positive-sequence voltage (U1) decreases, where the negative-sequence voltage (U2) and zero-sequence voltage (U0) increase. During this state the positive- and negative sequence current (I1 and I2) are much larger than the zero-sequence current (I0).

K.1.2 Recognising the type of fault

The fault type has to be identified based on representative data from voltage and current. Theoretically, it is possible to determine the fault type from the symmetrical components currents. Each fault type has a characteristic behaviour related to the normal, inverse and zero-sequence currents. These properties can be derived from the component networks representing the different fault types shown in Figure K.7.

This simplified network model consists of a source, an HV/MV transformer, an earthing impedance and a cable connection to the location of the fault. In this network model five different characteristic component networks represent the five fault types: a three-phase (3ph), three-phase to earth (3ph-E), two-phase (2ph), two-phase to earth (2ph-E) and a single-phase to earth fault (1ph-E) respectively.

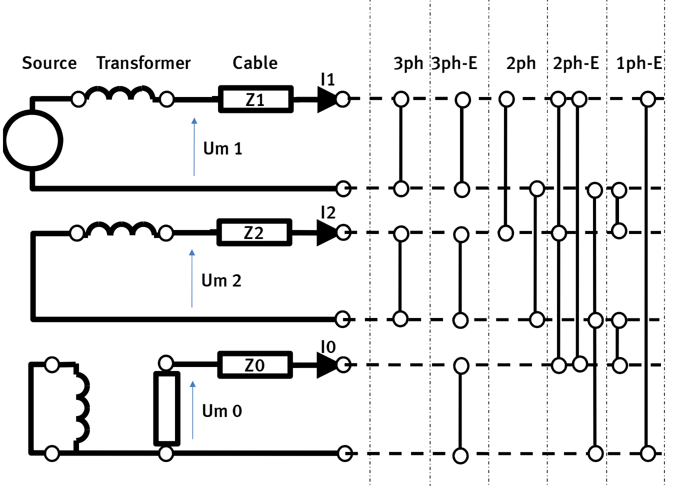


Figure K.7 Symmetrical components networks for various types of faults [OIRS 001]

The following observations can be made with respect to the symmetrical components:

- The positive sequence current (I_1) is larger than the pre-fault current ($I_{1,pre}$) in for all faults.
- A zero-sequence current only flows in case of an asymmetrical fault to earth.
- The difference between the positive sequence current and the pre-fault current ($I_{1,pre}$) is large only in case of a two or three-phase fault.
- A negative sequence current (I_2) only flows in case of an asymmetrical fault.
- The negative sequence current is much larger than the zero-sequence current only in case of a two-phase fault.

Table K.1 summarises the characteristic properties of the different fault types for the theoretical case [OIRS 001].

Fault type	$I_1 > I_{1,pre}$	$I_0 > 0$	$I_2 > 0$	$I_1\text{-}I_{1,pre} \gg 0$	$I_2 \gg 0$
Single-phase to earth	yes	yes	yes	no	no
Two-phase to earth	yes	yes	yes	yes	yes
Two-phase	yes	no	yes	yes	yes
Three-phase	yes	no	no	yes	no

Table K.1 Identifying fault types [OIRS 001]

Since the measured signals always contain unpredictable elements, e.g. caused by a specific load or generation behaviour, it is not possible to use an exact technique to determine the fault type. The above table also uses the terms "larger" and "much larger". Fuzzy logic makes it possible to determine the fault type for all cases. In this technique for each inequality a membership function has to be defined. This can be done by trial and error for a representative set of measurements. In practical applications also other events like inrush currents and self-extinguishing single-phase faults may be measured and have to be distinguished from real faults.

Three-phase faults

Three-phase faults are characterised by large phase currents in all three-phases. As a consequence there is hardly any negative or zero-sequence current. The normal-sequence current is dominating. The fault current is much larger than the pre-fault current. It must be noticed, that generators contributing to a three-phase fault in another feeder, cause currents in their feeder that fulfil these requirements. Therefore the characteristic properties as stated in Table K.1 must be extended with a property regarding generation. This is possible by regarding the angle between positive-sequence voltage and positive-sequence current. If the absolute angle is less than 90 degrees a three-phase fault can be expected. If the angle is larger than 90 degrees the over-current is caused by generation feeding a fault in another feeder.

If all currents exceeding a certain level are comprised in one single file it is possible to use another criterion. When this file is processed, it is likely, that the largest current is caused by the fault. Smaller currents are caused by generators and motors acting on that fault.

Two-phase faults

Two-phase faults are characterised by large phase currents in two of the three-phases. In the system of symmetrical components this results in large values for the positive and negative-sequence currents. The value of the positive-sequence current is much larger than the pre-fault current. In case of a two-phase to earth fault, there is also a zero-sequence current, although this current is generally much smaller than the currents in positive and negative-sequence. Similar to the situation of a three-phase fault a criterion for the contribution of generators and motors feeding a fault in an adjacent feeder can be applied.

Single-phase faults

Single-phase faults are characterised by a larger current in exactly one of the phases. In the system of symmetrical components, this results in certain values for the positive, negative and zero-sequence current. In contrary to a two-phase to earth fault the zero-sequence current is approximately equal to the negative-sequence current. The value for the positive-sequence current is in general larger than the negative and zero-sequence current, because the positive sequence current contains the current of the loads.

There is one practical situation where the results are distorted. This situation occurs when the protection system is tested. During this testing a current is injected in one of the phases of the secondary equipment. This current may trigger a recording device. The recorded signal contains the test currents, combined with the real voltages. For the fault locating system the currents are similar to single-phase fault currents. Without considering the voltage, this will result in a false message, reporting a single-phase fault. When the system additionally regards the voltages, it can decide, that there is no actual fault during the test and the operator will not be disturbed. A typical characteristic of the voltage during a single-phase to earth fault is the high zero-sequence voltage. It is therefore advisable to extend the characteristic properties (based only on current) with a rule based on voltage, stating that the zero-sequence voltage must be larger than zero.

Self-extinguishing and re-striking faults

In case of spontaneous single-phase faults, it may take some time before the fault fully develops. Many recordings of single-phase faults show events that are self-extinguishing and re-striking, causing large transients in the current. Other recordings show transients in the voltage, which make clear that the fault is not stable, however at first glance this is not noticed in the signals of the fault current. This effect can be noticed, not only in networks with isolated neutral, but also in networks that are earthed by means of an impedance.

In case of self-extinguishing and re-striking single-phase to earth faults, especially in repetitive-sequences, the FFT will result in a smoothed registration, that looks similar to a single-phase to earth fault of different duration and different amplitude. As a consequence, the calculated values of current and voltage in these situations will result in an incorrect impedance for the fault, and thus in an incorrect location.

It is therefore necessary to add a criterion regarding self-extinguishing faults as described in [PROV 002]. Such a test on self-extinguishing faults must be performed on the sampled data. Two types of self-extinguishing and re-striking faults can be distinguished in practice:

- Faults for which the re-strike occurs more than a quarter cycle after extinguishing.
- Faults for which the re-strike occurs within a quarter cycle after extinguishing.

When a fault re-strikes more than a quarter period after extinction, the re-strike shows a transient current with high amplitude as described in chapter 3 and appendix F. According to the phenomena in voltage and current, a criterion regarding these types of faults can be based on the following items:

- A threshold value for the absolute value of deviations in the momentary zero-sequence current.
- A threshold value for the absolute value of the zero-sequence voltage.
- The fact that a possible extinguishing fault starts when the deviation of the zero-sequence current is above the threshold value.
- The fact that in the next half cycle, less than half of the deviations of the current must be above the threshold value.
- The fact that the zero-sequence voltage at the end of this half cycle must be above the mentioned threshold value.

It must be noted, that these items also may occur for single-phase faults in networks that are either directly or impedance earthed. However, in these situations it is unlikely that the fault is self-extinguishing. Therefore the test on self-extinguishing faults must be performed when, based on the FFT evaluation, either no fault has been detected, or a single-phase to earth fault in a network with isolated neutral has been detected. If in these situations a self-extinguishing fault has been detected, the system must change its conclusions towards the self-extinguishing fault in the following cases:

- The FFT evaluation did not detect a fault.
- The FFT evaluation detected a single-phase fault, but the previous event of a self-extinguishing fault was a few samples before the calculation moment of the single-phase fault. In this way, a self-extinguishing fault, resulting in a permanent fault during the same registration, will still be considered as a single-phase fault.

When a fault re-strikes less than a quarter of a period after extinction, the re-strike does not show a transient current with high amplitude. In Figure K.8 some registrations of voltage and current in the faulted phase during a stationary single-phase to earth fault are shown. The first two registrations (top and middle) were recorded at the beginning of the fault and after 15 seconds. The last registration was recorded more than one hour after the start of the fault.

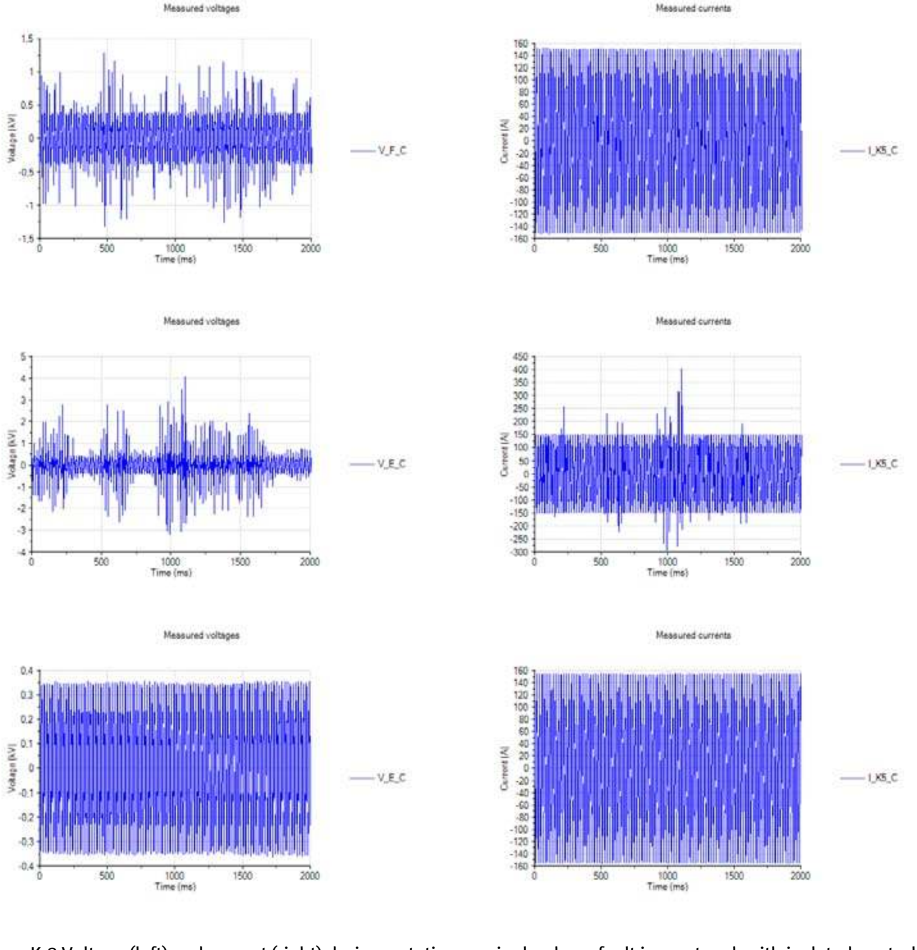


Figure K.8 Voltage (left) and current (right) during a stationary single-phase fault in a network with isolated neutral. These registrations are made at the start (top), after 15 seconds (middle) and after one hour (bottom).

At first glance, it seems that:

- The first registration only shows noticeable variations in the voltage and no variations in the current.
- The second registration shows noticeable variations in both the voltage and the current.
- The last registration shows a stable pattern of both voltage and current.

However, also in the first registration, the current shows variations at the moments of voltage variations. When zooming in on such an event, it can be observed that the fault extinguishes and almost immediately re-strikes. An example is shown in Figure 5.8, where the fault current (I_{Fault}) could be derived from the three measured phase currents. At t=470, the fault current is zero and the fault extinguishes. From that moment the voltage in the faulted phase (UC) starts to rise. When (at t=472) the voltage reaches a value near to 1.3 kV, the fault re-strikes. This can be noticed in the rapid decrease of the voltage and the sudden increase of both the fault current (I_{Fault}) and the current in the faulted feeder (I_C). An identical event occurs at t=480.

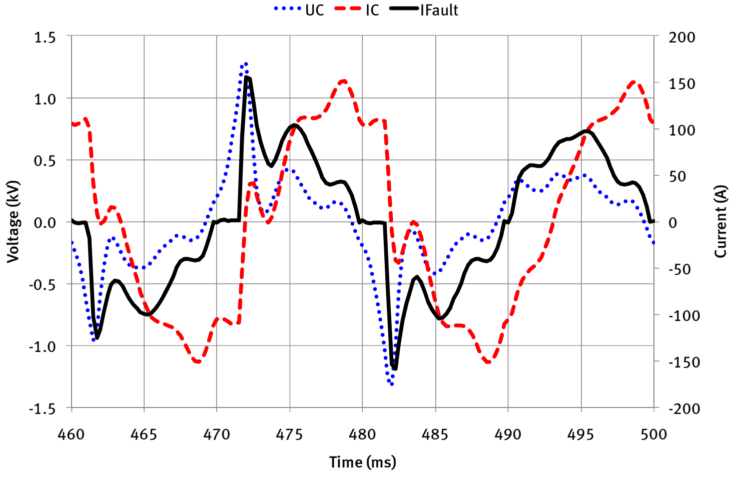


Figure K.9 Detailed waveform of voltage and current during a stationary single-phase fault in a network with isolated neutral.

It must be noticed, that due to the small difference in time between extinguishing and re-striking, the amplitude of the transient current is small. The FFT of such a signal will not result in proper values for voltage and current. This may result in an error of the calculated corresponding impedance. Therefore this time frame is not suited for the fault location algorithm. An algorithm must find a time interval of at least one cycle, in which no extinction or re-strike of the fault occurs. From Figure 5.8 the following characteristics for these events can be deduced:

- An extinction of the fault is characterised by a value close to zero for both the fault current (I_{Fault}) and its derivative.
- A re-strike of the fault is characterised by a sudden change in the fault current, resulting in a derivative that is much larger than the maximum slope of the expected current curve.

Preliminary tests of this algorithm show promising results as is shown in Figure 5.9. Here, the calculated impedance (X_{Calc}) is compared with the calculated impedance of a registration at the moment the fault was stable (X_{Steady}). The correction algorithm was able to identify two stable points for the correct calculation of the impedance to the location of the fault. These points are circled in Figure 5.9.

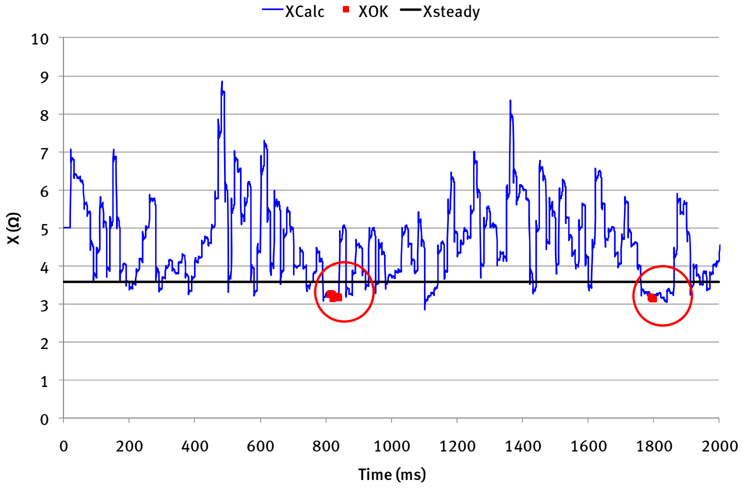


Figure K.10 Deviations in the calculation of the fault impedance as a result of a non stable stationary single-phase fault in a network with isolated neutral.

The corresponding impedances are given as (X_{OK}). The figure shows that the values for X_{OK} correspond well with the values calculated during the registration of the stable fault (X_{Steady}).

Other phenomena

In practical situations, the devices that are used to record potential fault situations will start recording when the measured current is above a certain level. This means, that also other events, like switching large loads, inrush currents of transformers and contributions of generators and motors to faults in other feeders will generate a recording. The system must conclude from the waveforms, that these phenomena are not caused by faults in the monitored feeder. From experience with the fault location project at Alliander, it can be concluded, that this can be achieved by utilising a proper set of threshold values for the different type of faults.

K.1.3 Network earthing

Information about the earthing of the system will be necessary for the network model used in the second stage of fault location. In case of an asymmetrical fault the impedance of the network earthing can be derived from the quotient of the zero-sequence voltage and current, according to:

$$X = \frac{U_0}{-I_0} \tag{K.1}$$

The absolute value and the phase angle of X strongly depend upon the earthing of the network. Table K.2 shows some typical values.

Network earthing	|X| (Ω)	Arg (X) (degrees)
Impedance earthing	7	90
Isolated neutral	200	-90

Table K.2 Identifying network earthing [OIRS 001]

The small value in the impedance earthed network in this table approximately equals the zero-sequence reactance of an earthing transformer. This value differs for networks with other earthing transformers or earthing methods. The large value in the network with isolated neutral approximately equals the impedance of the network capacitance. This value decreases with increasing total length of the cables in a network. In general, earthed networks are characterised by a small inductive value, where networks with isolated neutral are characterised by a large capacitive value.

K.1.4 Additional information

The reactance is calculated for a distance from the measuring point to the location of the fault. However, the feeder may be split into more than one direction. After a splitting point the feeder is divided into the main feeder and a sub-feeder or a dead-end feeder. Without additional information, a fault behind a splitting point can not be uniquely located.

From the registration of a fault, additional information can be obtained about the protection device that cleared the fault. When the fault is cleared by the circuit breaker in the substation, there will be no residual current in the feeder. When the fault is cleared by a circuit breaker or a fuse somewhere else in the network, there will still flow a current after clearing of the fault.

Based on the duration of the fault and the magnitude of the fault current, the applied protection scheme can be used for the decision about the location of the fault behind the splitting points. The analysing system can give information of where the fault has been switched off, the magnitude of the fault current and the duration of the fault. The utilisation of these data are only possible when the applied protection scheme is correctly implemented in the network model, which is used in the second stage of faultlocation.

K.2 Determining the fault loop impedance

In principle, calculating the fault loop impedance is quite simple, especially when radial networks are considered. According to Ohm's law, the impedance from a measuring point to a faulted point is determined by the quotient of the measured voltage and the measured current during the fault. In practice however, it is more complicated. It may be important to incorporate the influence of the existing pre-fault load current. Also the resistance of the fault itself is not known. According to [LEHT 001] it is recommended to disregard the resistance part of the fault impedance. Since the reactance of the fault is regarded to be zero and the cable reactances are well known and not current dependent, the fault locator has to work with the reactance only and the resistance will not be used.

It must be noted however, that in cable networks the resistance might be several times larger than the reactance especially when small conductor diameters are used. This means, that the major part of the total impedance is determined by the resistance. Calculation of the reactance is based on a calculated phase angle. Errors in the calculation of this phase angle have strong influence on the value of the reactance. Errors may occur due to errors in measurement and in the processing of the data.

Using the symmetrical components method on the simplified network model of Figure K.7 a formula for the fault loop reactance can be derived for each fault type. The formulae for the reactance are summarised in Table 5.2. These formulae are based on the following assumptions:

- The cable normal and inverse reactances are equal.
- The reactance of the short-circuit equals zero.

According to this table the normal reactance ($X_{cable,1}$) and the zero-sequence reactance ($X_{cable,0}$) can be calculated from the measured voltages ($U_{m,1}$, $U_{m,2}$ and $U_{m,0}$) and the measured currents (I_1 and I_2) at the time of the fault. Good approximations can be obtained for two and three-phase faults in all network types and for single-phase faults in earthed networks.

Fault type	Reactance from substation to location of the fault
Three-phase	$X_{cable,1}$=Im($U_{m,1}$ / I_1)
Three-phase with earth	$X_{cable,1}$=Im($U_{m,1}$ / I_1)
Two-phase	$X_{cable,1}$=Im(($U_{m,1}$ -$U_{m,1}$)/ (I_1-I_2))
Two-phase with earth	$X_{cable,1}$=Im(($U_{m,1}$ -$U_{m,1}$)/ (I_1-I_2))
Single-phase (earthed networks)	2*$X_{cable,1}$+ $X_{cable,0}$=Im(($U_{m,1}$ + $U_{m,2}$ +$U_{m,0}$)/I_2)
Single-phase (isolated neutral)	to be developed

Table K.3 Calculated impedances [OIRS 001]

In case of a single-phase fault in a network with isolated neutral, the fault current is largely induced by the overall network capacitance and not by the cable impedance from substation to location of the fault. In many cases, these faults are not switched off, because the LV customers will not notice this kind of faults and the fault currents are relatively low. It could however be useful to derive an algorithm for these faults, as it can help the operator to locate and isolate the fault before it develops in a multi-phase fault.

K.2.1 Three-phase faults

In case of a three-phase fault, it can be assumed, that the fault current is much larger than the pre-fault current. Therefore, the influence of the loads may be neglected. From Figure K.7 it can be seen, that in this case the fault loop impedance can be calculated from the positive-sequence values for voltage and current only:

$$Z = \frac{U_{m,1}}{I_{m,1}} \qquad \text{(K.2)}$$

This is valid for both three-phase faults with and without earth contact.

K.2.2 Two-phase faults

In case of a two-phase fault, it can also be assumed, that the fault current is much larger than the pre-fault current. Therefore, the influence of the loads may be neglected. From Figure K.7 it can be seen, that when the impedance of the fault place is neglected, the fault loop impedance can be calculated from the positive and negative-sequence values for voltage and current. According to Kirchhoff's voltage law, applied on the circuit of the positive and negative-sequence it can be found that:

$$U_{m,1} - I_{m,1} \cdot Z_1 + I_{m,2} \cdot Z_2 - U_{m,2} = 0 \qquad \text{(K.3)}$$

Assuming Z_1=Z_2=Z this can be written as:

$$Z = \frac{U_{m,1} - U_{m,2}}{I_{m,1} - I_{m,2}} \tag{K.4}$$

This is valid for both two-phase faults with and without earth contact.

K.2.3 Single-phase faults

In case of a single-phase fault, two aspects play a role:

- The influence of the load may not always be neglected.
- The zero-sequence parameters must be taken into account.

In the situation where the circuit consists of a single type of cable or overhead line, the fault loop impedance may be calculated with the formula:

$$Z = \frac{U_{ph}}{I_{ph} + k \cdot I_N} \tag{K.5}$$

With

$$k = \frac{Z_0^{'} - Z_1^{'}}{3 \cdot Z_1^{'}} \tag{K.6}$$

Where:

- U_{ph} the voltage of a faulted phase;
- I_{ph} the current in the faulted phase;
- I_N the sum of the three-phase currents in the faulted feeder;
- Z_0' and Z_1' the zero and positive-sequence impedance per unit length of the faulted feeder.

The calculated value of Z must be compared with the positive-sequence value of Z. This principle is also used in distance relays. In these types of networks, the value of k can be calculated in advance. In distribution networks, the loads may influence the measured phase currents. In many cable networks also different types of cable are used. Therefore the factor k will not be a constant value and is not known in advance. The fault loop impedance can be determined by applying Kirchhoff's law on the circuit of positive, negative and zero-sequence for the single-phase fault:

$$U_{m,1} - I_{m,1} \cdot Z_1 + U_{m,0} - I_{m,0} \cdot Z_0 + U_{m,2} - I_{m,2} \cdot Z_2 = 0 \tag{K.7}$$

Assuming Z_1=Z_2=Z and $I_{m,1}$=$I_{m,2}$=$I_{m,0}$ this can be written as:

$$2 \cdot Z_1 + Z_0 \approx \frac{U_{m,1} + U_{m,2} + U_{m,0}}{I_{m,2}} \tag{K.8}$$

In the second stage of the faultlocation, this impedance value must be compared with calculations on the network model based on the same principle.

The assumption that all sequence currents are nearly equal is valid for networks where these currents are larger than the currents due to the load. This is in general in networks that are earthed directly or with an impedance. In networks with isolated neutral and in networks with compensated neutral earthing this is certainly not the case. For these networks a different assumption must be developed.

K.3 Implementation in the Alliander network

The idea of implementing faultlocation in the MV networks of Alliander started in the last years of the 20th century. The main objective is to obtain information of the location of the fault within five minutes after its occurrence. The required accuracy is 100 meters for two and three-phase faults and 1000 meters for a single-phase fault. This implies that for a two or three-phase fault its location must be found in either the faulted cable section or the neighbouring section. For single-phase faults the accuracy is set to a lower level because the inaccuracy of the zero-sequence information. Another important requirement for the solution is that it must be cost efficient and not require extra boxes and wiring in the substation.

Since 1997 data from faults in the substation of Zaltbommel have been collected during a pilot for faultlocation [SAHA 001] [SAHA 002]. The principle of the system could be proved, but the costs of implementation were too high. The refurbishment of substation Zaltbommel was used to implement a pilot system based on information from protection devices. Experiences from this pilot system resulted in implementation of a faultlocation system in the substations that were equipped with the new SASensor equipment. The high sampling rate of this system and the various locations in the network showed some new phenomena in voltage and current. Improvement of the SAsensor system and the faultlocation software made it possible to correctly interpret the various registrations, and in case of a real fault, to pinpoint the location close to the real location. The system is now implemented in 10 substations using the SASensor.

K.3.1 Results

The problem with the first pilots of faultlocation in Zaltbommel was that only a limited number of faults occurred. In average about 4 faults in a year. Due to the fact, that SASensor is implemented in 10 substations, more faults could be observed. Table K.4 shows the result for the period between October 2007 and December 2008.

The first column shows the type of fault. The second column shows the number of occurrences of this type of fault. The next three columns show the accuracy of the faultlocation. Here “OK” means that the location of the fault was calculated in the same section as the real fault. “Adjacent” means, that the location was calculated in the section adjacent to the actual fault, which still is within the required accuracy. “> 1 RMU” means that the location of the fault was calculated more than one section away from the actual section. This result is often outside the required accuracy.

	Location			
Fault type	**Recordings**	**OK**	**Adjacent**	**> 1 RMU**
Three-phase	7	3	3	1
Two-phase	10	5	1	4
Single-phase (earthed networks)	4	2	0	2
Single-phase (isolated neutral)	5	3	2	0

Table K.4 Accuracy of the fault location with SASensor

Although it is not fully correct to draw conclusions from this little amount of results, some remarks can be made:

- Most of the locations of the fault are calculated in the correct section or in the adjacent section. This is within the required accuracy.
- Only a few locations were calculated outside the required accuracy. This was due to two reasons. Some of the faults were far away from the substation, so specific assumptions regarding fault impedance were no longer valid. The other reason was the incorrectness of network models. For these cases, the accuracy of the results can be improved by improving the network model of these substations.
- It was expected that the location of single-phase faults would be less accurate than the location for multi-phase faults. However, this is not noticed in practice yet.
- It was expected, that all multi-phase faults could be located within the margin of one section. This was not always the case.
- The applied algorithm for single-phase faults in networks with isolated neutral shows promising results. This algorithm is based on the same algorithm used for networks with impedance earthing.

L Abbreviations and symbols

Abbreviations

µCHP	micro combined heat and power
AC	alternating current
ACN	autonomously controlled network
AVR	automatic voltage regulator
BIM	breaker interface module
CAIDI	customer average interruption duration index
CCU	central control unit
CERTS	consortium for electric reliability technology solutions
CHP	combined heat and power
CIM	current interface module
CIM	customer information system
CT	current transformer
DC	data concentrator
DC	direct current
DER	distributed energy resources
DG	distributed generation
DSO	distribution system operator
DTe	Dutch office of energy regulation
EMC	electromagnetic compatibility
EMVT	electro magnetische vermogens techniek (electro-magnetic power technology)
EOS	energie onderzoeks subsidie (energy research subsidy)
EPR	earth potential rise
FCL HTS	fault current limiting high temperature superconducting
FFT	fast fourier transform
FL	fault locator
GIS	geographic information system
GPS	global positioning system
HV	high voltage
IOP	innovatief onderzoeks programma (innovation oriented research program)
ICT	information and communication technology
IT	information technology
LAN	local area network
LV	low voltage
MV	medium voltage
MVDC	medium voltage direct current
N	neutral
NMi	Nederlands metrologisch instituut (Dutch metrology institute)

NOP	normally open point
OH	overhead
OHC	overhead cable
OHL	overhead line
PE	power electronics
PE	protective earth
PFC	power flow controller
PILC	paper insulated lead covered
PL	public lighting
PLC	power line carrier
PQ	power quality
PQM	power quality monitoring
PV	photo voltaic
PVC	polyvinyl chloride
PWM	pulse width modulation
R&D	research and development
RCD	residual current device
RES	renewable energy sources
RMU	ring main unit
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index
SCCL	short-circuit current limiter
SC-SCCL	super conducting short-circuit current limiters
THD	total harmonic distortion
TN	terre neutral
TSO	transmission system operator
TT	terre terre
UGC	underground cable
VIM	voltage interface module
VPP	virtual power plant
VT	voltage transformer
WAN	wide area network
XLPE	cross linked polyethylene
ZnO	zinc oxide

Symbols

B = standard load profile curve
C = costs
c =
cov = covariance
Dev = deviation
E = mean value
g = coincidence factor
g = correction factor
G = generation
h = specific harmonic
I,i = current
L = load
P = active power
P_{LT} = long term flicker aspect
P_{ST} = short term flicker aspect
Q = reactive power
R = resistance
S = apparent power
s = standard deviation
t = time
U,u = voltage
var = variance
W = energy consumed by a consumer
X = reactance
Z = impedance
Z = impedance
α = empirical based constant
α_{20} = temperature coefficient of electrical resistivity at 20^0 C
β = empirical based constant
ε_r = relative permeability
ρ_e = thermal resistivity

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Curriculum Vitae

Frans Provoost was born in Domburg, the Netherlands on March, 4th 1957. He received his M.Sc.-degree in electrical engineering from the Eindhoven University of Technology (TU/e) in 1982.

Until 1985 he joined ASEA (now ABB) in Ludvika, Sweden, where he was involved in the main circuit design of HVDC projects. In 1986 he joined Nuon, one of the largest energy companies in the Netherlands. There he was involved in many aspects considering the performance of the electricity grid. In the beginning his focus was on planning and design of HV networks. Gradually he became more and more involved with aspects regarding LV and MV distribution networks. These aspects concerned the development and support of network analysing and evaluating tools as well as power quality, earthing, EMC and fault location issues.

In 2003 he started as a Ph.D.-student at TU/e in the project of “Intelligent Power Systems” on the subject of “Intelligent Distribution Network Design”.

Now he is with Alliander, which is the network company of the former Nuon holding.