Long-term Voltage Stability in Power Systems

Alleviating the Impact of Generator Current Limiters

Stefan Johansson

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Department of Electric Power Engineering
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by

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Abstract

The main issues in this dissertation are the behaviour of current limiters protecting synchronous generators, and the interactions that occur with other components in the power system during a voltage instability. The importance of these limiters for the voltage stability is shown both in the analysis of small models and in the simulations of larger networks.

Voltage stability of a power system can be improved by a proper current limiting equipment for generators situated in load areas which have a deficit in power production. Two different remedial actions alleviating the impact of the current limiters are analysed. These are:

- the optimum use of the generators field winding thermal capacity by including temperature measurements into the control.
- the use of mechanical power production increases or decreases as a way to avoid a too high current in the generator.

The system can then be supported locally until both field and armature currents are at their respective maximum steady-state levels, the maximum capability for the system is attained or constraints in the mechanical power production are reached. The dissertation analyses the consequences of active power rescheduling and its significance for field and armature current limiter operation. Aspects as the size of active power changes and its variation in time are discussed on the basis of simulation results.

Long-term voltage stability is also decided by other interactions occurring in the power system. In particular the load behaviour and tap changer control are analysed. The importance of proper modelling of these components and using correct values are discussed.

Keywords: Long-term power system dynamic stability, Voltage stability, Overexcitation limiter, Field current limiter, Armature current limiter, Rotor thermal overloading, Dynamic load modelling, Active power rescheduling

LIST OF PUBLICATIONS

This thesis is based on work reported in the following papers, referred by Capital letters in the text:

A S. G. Johansson, F. G. A. Sjögren, D. Karlsson, J. E. Daalder, "**Voltage Stability Studies Using PSS/E**", Bulk Power System Phenomena III, pp. 651-661, Davos, Switzerland, 1994.

B F. G. A. Sjögren, S. G. Johansson and J. E. Daalder, "**Behaviour of generator current limiters near the point of voltage collapse**", Stockholm Power Tech, STP PS 07-06-0492, pp. 221-226, Sweden, 1995.

C S. G. Johansson, D. Popović, D. J. Hill and J. E. Daalder, "**Avoiding Voltage Collapse by fast Active Power Rescheduling**", International Journal of Electrical Power and Energy Systems, Vol. 19, No. 8, pp. 501-509, 1997.

D S. G. Johansson, "**Mitigation of Voltage Collapse caused by Armature Current Protection**", Accepted for publication in IEEE Power Engineering Society Transactions, Paper Number: 98 SM 094, 1998.

E S. G. Johansson and J. E. Daalder, "**Maximum Thermal Utilization of Generator Rotors to avoid Voltage Collapse**", International Power Engineering Conference -97, Singapore, pp. 234-239, 1997.

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Chapter 1 Introduction

Voltage stability issues are of major concern worldwide. One reason is the significant number of black-outs which have occurred and which frequently have involved voltage stability issues. Major regions (like half of France, 1978) or smaller (as Israel, 1996 and Tokyo, 1987) have been exposed to voltage instability problems. These kinds of blackouts will undoubtedly occur also in the future. It is also believed among professionals that the existing transmission systems will become more and more utilized due to environmental concern which makes it difficult to build new power plants and/or transmission lines. As a result the stress on the existing system will increase. Two examples in Sweden, which are quite much in the news these days, which will influence the load on the existing transmission system, are the ongoing process of a possible shut down of nuclear power plants and a prospective HVDC connection between Sweden and Poland. The government has decided that nuclear power production shall be closed down and the first plant is to be shut down on July 1, 1998. For the HVDC-line, local authorities is concerned of environmentally aspects of the sea floor grounding electrode of the HVDC connection.

The continuing deregulation of the electricity market now occurring in many countries will change the way power systems will be operated. The deregulation will introduce an economical competition between companies. A high utilization of the system may then be beneficial from an economical point of view. There is also a possibility that certain information is kept restricted within the companies due to the competition. The sharing of information between the companies have so far been an advantage from the system operating and stability point of view. These reasons will make the operation of the system as a whole more difficult and hence increases the possibility of stability problems. Much research work is therefore going on worldwide covering many different aspects of system operation where voltage stability is an important feature.

Voltage stability deals with the ability to control the voltage level within a narrow band around normal operating voltage. The consumers of electric energy are used to rather small variations in the voltage level and the system behaviour from the operators point of view is fairly well known in this normal operating state. Equipment control and operation are tuned towards specified setpoints giving small losses and avoids power variations due to voltage sensitive loads.

Once outside the normal operating voltage band many things may happen of which some are not well understood or properly taken into account today. A combination of actions and interactions in the power system can start a process which may cause a completely loss of voltage control. The system will experience a voltage collapse and this results in a rapid loss of electrical supply in wide areas, sometimes affecting millions of people.

The origin of a significant voltage deviation is in most cases some kind of contingency where a generator in a vital power plant shuts down or an important transmission line is disconnected from the power grid. This initiates a voltage change and alters the system characteristics. The system is normally designed to withstand these kind of single contingencies occurring many times a year. However, abnormal operating conditions, several independent contingencies occurring almost simultaneously in time or a completely unexpected phenomena may violate the normal design conditions. This leads to an insecure operating condition threatening the voltage stability of the system. The goal is therefore to try to understand the course of events after such a contingency and propose remedial actions when the control of voltage is insecure.

The main part of this dissertation consists of work presented in 5 papers, all dealing with long-term voltage stability aspects in power systems. Long-term voltage stability is connected with phenomena in the power system which have time constants from a couple of seconds to minutes and even tens of minutes. An important issue in this time frame is the behaviour of current limiters which protect synchronous generators from too high temperatures due to overloading. Generators are *generating* voltage and current and are thus the first link in the voltage control chain from production to load consumption. Several types of interaction can occur between limiter operation and other components in the power system which may disturb or upset the voltage control. The limiters will also impose operating restrictions on the generator which are important to understand.

A generator has two types of windings: the field winding carrying the current which creates the magnetization in the rotor; and the armature winding situated in the stator and carrying the produced power to the grid.

The field winding is protected by a limiter which controls the magnetization (i.e. the field current) of the generator to avoid a too high field current. Normally, the field current is controlled in such a way that the voltage is controlled on the generators terminal and an overloading of the generator is avoided by reducing the field current to its maximum steady state value. The use of a limiter allows the generator to stay connected to the grid, though with a reduced output. The power system demand can then not be fulfilled when the generator becomes limited and a voltage decrease occurs. An overcurrent relay may be used as a backup protection disconnecting the generator if the limiter is unsuccessful.

The armature winding is either protected by an overcurrent relay or an armature current limiter. The overcurrent relay disconnects the generator from the grid when the maximum current limit is violated and all production from that generator is lost instantaneously. An example where the armature winding is protected by a limiter function are the generators of the nuclear power plants in Sweden. The armature current limiter will influence system behaviour and play a major role in system stability.

Excessive winding temperatures will lead to a fast degradation of the insulation material and thereby a decreased life span of the generator. Most likely, limiter operation occurs in situations when the power system is in a need of the production that the limiters obstruct. A trade off between the life span of the generator and system stability must therefore be accomplished to avoid solutions that may become unnecessarily complex or expensive.

The main purpose of this research project is to investigate how to attain an improved support from the generators to the power system in case of a current limiter operation without endangering the generators economical lifetime.

In this dissertation it is often possible to substitute the influence of the armature current limiter action with a tripping of that generator instead, the latter however, is more severe for the power system and therefore a more restricted situation than a mere limitation. The analysis of the armature current limitation may be of general interest despite the fact that not all generators are equipped with such a protection. Certain phenomena are common between the limiter setting and the overcurrent relay setting. In the text, the expression armature current limiter is used extensively and the reader should interpret the analysis as either limitation or tripping of the generator depending on his own prerequisites for that particular study. The term armature current protection is also used implying either a limiter action or an overcurrent relay action.

Several other aspects of voltage stability are discussed in this dissertation. In particular, the relation between load behaviour and tap changer control of transformers is analysed. The dynamic behaviour of this combination is frequently a key factor in the understanding of voltage stability. Due to the introduction of new technology the load characteristics are slowly changing. Examples are new air conditioning equipment and semi-conductor based motor drives. A continuous work is therefore required if voltage stability is to be maintained.

A major part of the dissertation is based on computer simulation of power systems. Both small networks, where the models are kept as simple as possible, and larger, more complex networks are studied. The larger networks often uses as accurate models of the existing components as is possible. Network data is then chosen to correspond with known values. Some analysis have been performed for the small system.

1.1 Background and realization of the project

This dissertation is an extension of a licentiate thesis work [1] which I undertook together with Fredrik Sj gren in 1995. The licentiate project started in 1992 and treated different aspects of important components in a power system. One interesting point presented in that thesis was the behaviour of the generator influenced by its field and armature current limiters. A research project was therefore granted by Elforsk AB within the Elektra research program titled Voltage collapse caused by interaction between generator protection systems and electrical power systems for a further study of this behaviour.

The project started with a half year visit at the Systems and Control group at Sydney University, Australia where the work was concentrated on a radial system with a large generation area and a smaller generator located in the load area. Different operating modes were introduced determined by the behaviour of the current limiters in the system. The small generator was exposed to changes in the active power input for different modes and the system capability as seen in the load point was established for these active power changes.

This analysis was extended by studying the field current limiter where system capability was (temporarily) increased by utilizing the rotor thermal capacity.

To verify the previous results, simulations were performed in a larger network. The analysis was then concentrated on the armature current limiter and system aspects of its behaviour.

1.2 Outline of the dissertation

This dissertation consists of five papers together with supplementary chapters. References are made to the papers with a capital letter together with the corresponding figure number or paragraph.

Chapter 1 gives a brief introduction to the dissertation where the background and motivation to the project are discussed.

Chapter 2 gives a general background to the phenomenon Voltage Stability and is based on a similar chapter in the licentiate thesis [1].

A general overview of the papers is given in Chapter 3, where common issues and important sections are pointed out. The analysis is also extended somewhat concerning the importance of the position of transformers in the grid. The literature for a particular area covered in this dissertation is discussed based on the presented results. Finally, some more background information is given which has not been presented in the papers. The reader may choose to read the papers before Chapter 3 since these can be read as independent contributions and then return to Chapter 3 for a brief summary.

Chapter 4 gives the most important conclusions of this study and Chapter 5 contains suggestions for future work. Finally the papers are presented as separate sections.

1.3 References

[1] S. G. Johansson and F. G. A. Sj gren, VOLTAGE COLLAPSE IN POWER SYSTEMS - The influence of generator current limiters, on-load tap changers & load dynamics , Technical report No. 192L, Dept. of Electrical Power Systems, Chalmers University of Technology, ISBN 91-7197-119-X, Sweden, 1995.

Chapter 2 Voltage stability and voltage collapse

2.1 Introduction

This research area concerns disturbances in a power system where the voltage becomes uncontrollable and collapses. The voltage decline is often monotonous and small at the onset of the collapse and difficult to detect. A sudden and probably unexpected increase in the voltage decline often marks the start of the actual collapse. It is not easy to distinguish this phenomenon from angle (transient) stability where voltages also can decrease in a manner similar to voltage collapse. Only careful post-disturbance analysis may in those cases reveal the actual cause.

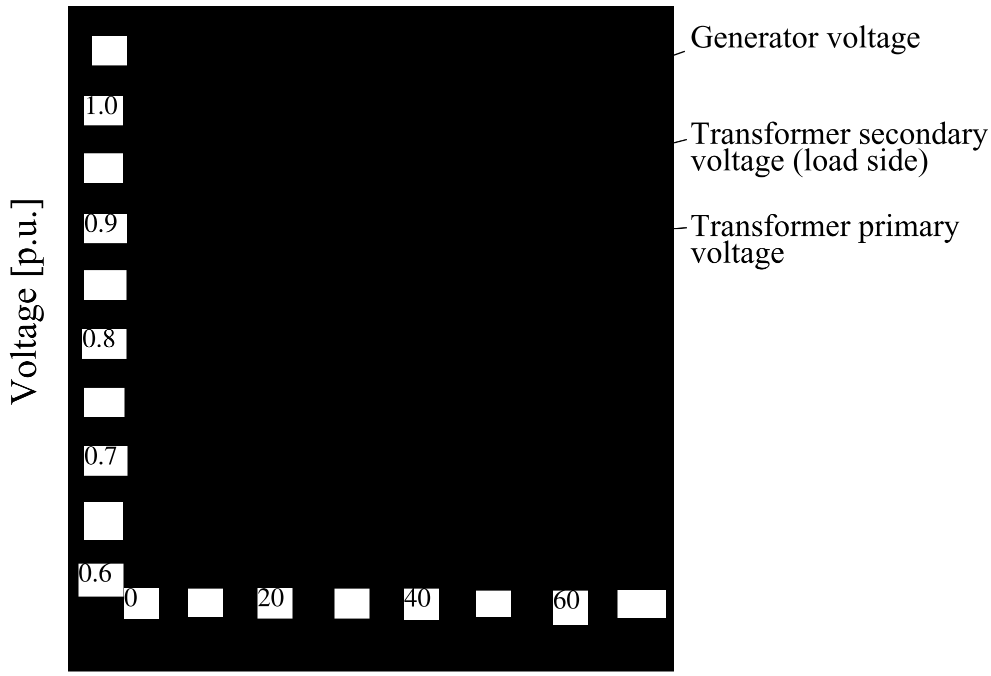

Figure 2.1 Example of a collapse simulation which is transient (angle) stable followed by a voltage decline and a fast voltage drop leading to a collapse. (See Figure A.18).

During the last decades there have been one or several large voltage collapses almost every year somewhere in the world. The reason is many times a higher degree of utilization of the power system leading to a decreasing system security. Also, load characteristics have changed. Two examples are the increased use of air conditioners and electrical heating appliances which may endanger system stability radically. The incidents that lead to a real breakdown of the system are rare, but when they occur they have large repercussions on society.

It is the opinion of many professionals that in the future power systems will be used with a smaller margin to voltage collapse. There are several reasons for this: the need to use the invested capital efficiently, difficulties in supervising a deregulated market and the public opposition to building new transmission lines and new power plants. Voltage stability is therefore believed to be of greater concern in the future.

Nearly all types of contingencies and even slow-developing load increases could cause a voltage stability problem. The time scale for the course of events which develop into a collapse may vary from around a second to several tens of minutes. This makes voltage collapse difficult to analyse since there are many phenomena that

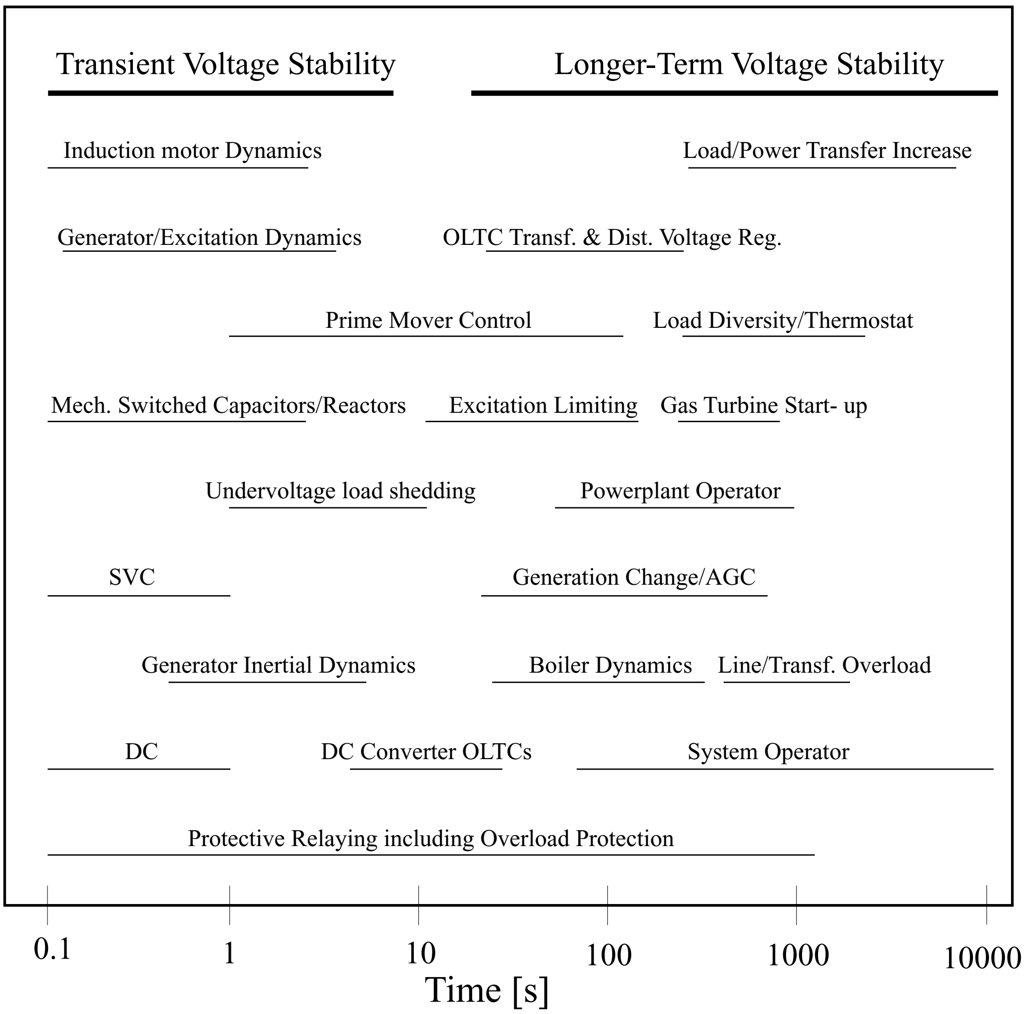

Figure 2.2 Different time responses for voltage stability phenomena [19].

interact during such a time span (see Figure 2.2). Important processes that interact during a voltage decline lasting (several) minutes are among others: generation limitation, behaviour of on-load tap changers and load behaviour. The actions of these components are often studied in long-term voltage stability studies.

An interesting point is that some researchers discard voltage magnitude as a suitable indicator for the proximity to voltage collapse, although this is in fact the quantity that collapses [6, 9].

An ongoing discussion is whether voltage stability is a static or dynamic process. Today it is widely accepted as being a dynamic phenomenon. However, much analysis can be made and insight can be obtained by the use of static models only.

Voltage instability is only one kind of stability problem that can arise in a power system. A typical property of voltage instability is that the system frequency usually is fairly constant until the very end of the collapse. This indicates that the balance is kept between production and active load demand. Power oscillations between different areas in the system can be a limiting phenomenon on its own but may also appear during a voltage instability mixing voltage instability issues with electro-mechanical oscillations.

2.2 Voltage collapses worldwide

Much can be learnt from observed voltage collapses or incidents. Detailed information of the most well known occurrences can be found in [2] and [7].

Analysing real collapses involves two problems. Firstly, the lack of event recorders in relevant locations causes a lack of information about the disturbance. Secondly, it is sometimes difficult to distinguish between voltage stability and angle (transient) stability. There may also be other actions which make the system more difficult to understand, such as human interaction, frequency deviation etc.

Below examples are given of some important events which ended in voltage collapse. Some properties common in many disturbances are pointed out.

•***Transmission system limitations***

The tripping of fairly small generators if situated in areas that need voltage support, could cause a large increase of reactive power loss in the transmission network. Voltage drops results which can initiate stability problems. Examples are the 1970 New York disturbance [7] and the disturbance in Zealand, Denmark in 1979 [2]. In the New York disturbance, an increased loading on the transmission system and a tripping of a 35 MW generator resulted in a post-contingency voltage decline. In Zealand, a tripping of the only unit in the southern part of the island and producing 270 MW caused a slow voltage decline in that area. After 15 minutes the voltages were 0.75 p.u., making the synchronization of a 70 MW gas turbine impossible. Both systems were saved by manual load shedding.

The Belgian collapse in August 4, 1982 was also due to problems with the transmission capacity. The collapse was initiated by a fortuitous tripping of one of the (relatively few) operating production sources. The low load made it economically advantageous to use only a few power plants operating close to their operating limits. When the generator tripped, the surrounding area was exposed to a lack of reactive power and several generators were field current limited. After a while the generators tripped one after another due to the operation of the protection system. The transmission system was unable to transmit the necessary amount of reactive power to the voltage suppressed area and cover the reactive power loss that were produced in the tripped generators. This caused a continuous voltage decline. When the fifth generator was tripped some four and a half minutes after the first tripping, the transmission-protective relays separated the system and a collapse resulted [10].

The collapse in Canada, in B. C Hydros north coast region in July 1979 is also interesting in this respect [7]. A loss of 100 MW load along a tie-line connection resulted in an increased active power transfer between the two systems. The generators close to the initial load loss area were on manual excitation control (constant field current), which aggravated the situation. When voltages started to fall along the tie-line due to the increased power transfer, the connected load decreased proportionally to the voltage squared. This increased the tie-line transmission even more since there was no reduction in the active power production. About one minute after the initial contingency, the voltage in the middle of the tie-line fell to approximately 0.5 p.u. and the tie-line was tripped due to overcurrent at one end and due to a distance relay at the other.

Also Czechoslovakia experienced a similar collapse as B. C. Hydro in July 1985 but on a much shorter time-scale [2]. Before the disturbance, there were three interconnected systems, two strong ones, I and II and one weak system, III, between I and II as can be seen in Figure 2.3. A large amount of power was delivered from I to III, while II was approximately balanced. When the connection between I and III was lost, the II-III connection was expected to take over the supply of power to III. However, one of the overhead lines between II and III tripped due to overcurrent and the remaining transmission capacity was too low and the voltage collapsed in III within one second after tripping of the other line.

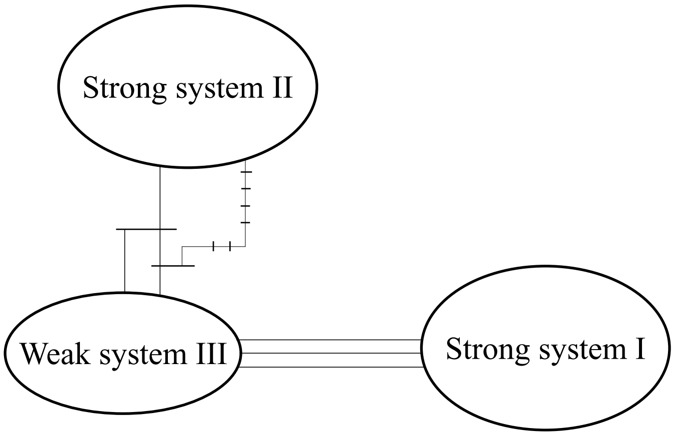

Figure 2.3 The Czechoslovakian network during the collapse.

•*Load behaviour including on-load tap changers*

On 23 July 1987, Tokyo suffered from very hot weather. After the lunch hour, the load pick-up was ~1%/min. Despite the fact that all the available shunt capacitors were switched on, the voltages started to decay on the 500 kV-system. After 20 minutes the voltage had fallen to about 0.75 p.u. and the protective relays disconnected parts of the transmission network and by that action shed about 8000 MW of load. Unfavourable load characteristics of air conditioners were thought to be part of the problem [21].

In the collapse in Sweden, on 27 December 1983, the load behaviour at low voltage levels was also a probable cause leading to a collapse [22]. Transmission capacity from the northern part of Sweden was lost due to an earth fault. Virtually nothing happened during the first ~50 seconds after the initial disturbance when the remaining transmission lines from the northern part of Sweden were tripped. Since these lines carried over 5500 MW, the power deficit in southern Sweden was too large for the system to survive. The cause of the cascaded line trippings was a voltage decline and a current-increase in the central part of Sweden. The on-load tap changer transformers contributed to the collapse when they restored the customer voltage level. Field measurements performed afterwards in the Swedish network have also shown inherent load recovery after a voltage decrease [5, 16]. This recovery aggravated the situation when voltages started to decline. The cause of this load recovery in the Swedish network is believed to be due to the particular behaviour of electrical heating appliances in connection with OLTC response.

A third example of the importance of load behaviour and OLTC actions was the collapse in western France 1987, a disturbance which is interesting due to the fact that the system operated stable at 0.5 p.u. voltage for a considerable time [14] and where operators had to shed 1500 MW of load to restore control of voltage.

Load behaviour is considered to be so important that some researchers define the voltage stability phenomenon as a load stability phenomenon.

•***The influence of protection and control systems***

The protection of the generator plays a major role during voltage instabilities. Often limiters are used as part of the generator protection. These take over control of the generator and try to avoid a tripping of the whole unit when the generator becomes overloaded. The significance of these limiters can be seen in several of the cases presented.

Almost all voltage instability processes are interrupted by protective relays which are disconnecting parts of the system causing a definite collapse. The Swedish power system and the Tokyo network finally collapsed due to (proper) protective relay operations. The collapse in France in 1987 was aggravated by the fact that many generators were tripped by maximum field current protective relays instead of being field current limited [14]. These examples illustrate the importance of taking protection systems into account in the system security analysis. It also implies the necessity of having a well-tuned control and protection system.

The control-systems of a HVDC-link can also affect voltage stability. The Nelson River HVDC-system in Canada and the Itaipu HVDC-link have experienced collapses [19]. In both cases the control-systems affected the cause of collapse. At Nelson River there was a System Undervoltage Protection-system out of service. At Itaipu several disturbances led to a number of DC-control changes.

In virtually all known collapses there is one contingency (or a series of related contingencies) that triggers a sequence of events causing voltage collapse or an insecure operating situation. Every part of the power system, generation, transmission and distribution (including load demand) can initiate, be involved in or interact with the other parts during voltage instabilities. The protection and control systems holds a unique position since it works as an ‘overlay’ or coating to the power system introducing other aspects than mere ‘power flow’ aspects. These systems are also a source of unexpected fortuitous events. The French collapse 1987 and the ones in Itaipu are two examples where equipment have been working inappropriate and aggravating the situation.

2.3 Definitions of voltage collapse

In the literature several definitions of voltage stability can be found. The definitions consider time frames, system states, large or small disturbances etc. The different approaches therefore reflect the fact that there is a broad spectrum of phenomena that could occur during a voltage instability. Since different people have various experiences of the phenomenon, differences appear between the definitions. It could also reflect that there is not enough knowledge about the phenomenon itself to establish a generally accepted definition at this stage. References [17 and 20] reflects the present status in these discussions.

2.3.1 Definitions according to Cigré

Cigré [3] defines voltage stability in a general way similar to other dynamic stability problems. They define:

- A power system at a given operating state is *small-disturbance voltage stable* if, following any small disturbance, voltages near loads are identical or close to the pre-disturbance values.

- A power system at a given operating state and subject to a given disturbance is *voltage stable* if voltages near loads approach post-disturbance equilibrium values. The disturbed state is within the region of attraction of the stable post-disturbance equilibrium.

- A power system undergoes *voltage collapse* if the post-disturbance equilibrium voltages are below acceptable limits.

2.3.2 Definitions according to Hill and Hiskens

Another set of stability definitions is proposed by Hill and Hiskens [6]. The phenomenon is divided into a static and a dynamic part. For the static part the following must be true for the system to be stable:

- The voltages must be viable i.e. they must lie within an acceptable band.

- The power system must be in a voltage regular operating point.

A regular operating point implies that if reactive power is injected into the system or a voltage source increases its voltage, a voltage increase is expected in the network.

For the dynamic behaviour of the phenomenon, Hill and Hiskens propose the following concepts:

- *Small disturbance voltage stability:* A power system at a given operating state is small disturbance stable if following any small disturbance, its voltages are identical to or close to their pre-disturbance equilibrium values.

- *Large disturbance voltage stability:* A power system at a given operating state and subject to a given large disturbance is large disturbance voltage stable if the voltages approach post-disturbance equilibrium values.

- *Voltage collapse*: A power system at a given operating state and subject to a given large disturbance undergoes voltage collapse if it is voltage unstable or the post-disturbance equilibrium values are non-viable.

Hill and Hiskens [6] present different methods to detect these different criteria. These definitions have common properties with the Cigré definitions.

2.3.3 Definitions according to IEEE

A third set of definitions is presented by IEEE [7]. The following formal definitions of terms related to voltage stability are given:

- *Voltage Stability* is the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and so that both power and voltage are controllable.

- *Voltage Collapse* is the process by which voltage instability leads to loss of voltage in a significant part of the system.

- *Voltage Security* is the ability of a system, not only to operate stably, but also to remain stable (as far as the maintenance of system voltage is concerned) following any reasonably credible contingency or adverse system change.

- A system enters a state of *voltage instability* when a disturbance, increase in load, or system changes causes voltage to drop quickly or drift downward, and operators and automatic system controls fail to halt the decay. The voltage decay may take just a few seconds or ten to twenty minutes. If the decay continues unabated, steady-state angular instability or *voltage collapse* will occur.

These definition are more restricted than the others presented above. Only operating points on the upper side of the PV curve are allowed with these definitions (see Chapter 2.4.1).

2.3.4 Definitions according to Glavitch

Another approach is presented by Glavitch [18]. In this approach different time frames of the collapse phenomenon are illustrated:

- *Transient voltage stability* or collapse is characterized by a large disturbance and a rapid response of the power system and its components, e.g. induction motors. The time frame is one to several seconds which is also a period in which automatic control devices at generators react.

- *Longer-term voltage stability* or collapse is characterized by a large disturbance and subsequent process of load restoration or load change of load duration. The time frame is within 0.5-30 minutes.

Glavitch also proposes a distinction between *static* and *dynamic* analysis. If differential equations are involved, the analysis is dynamic. “Static does not mean constant, i.e. a static analysis can very well consider a time variation of a parameter.”

Of these definitions, Hill seems to be the closest to control theory and the IEEE-definition is related to the actual process in the network. The framework in these definitions on voltage stability include mainly three issues: *the voltage levels must be acceptable; the system must be controllable in the operating point; and it must survive a contingency or change in the system.*

2.4 The small system

A small system is generally used to demonstrate particular properties of voltage stability. The system is equipped with a generator, a transmission link and a load as can bee seen in Figure 2.4.

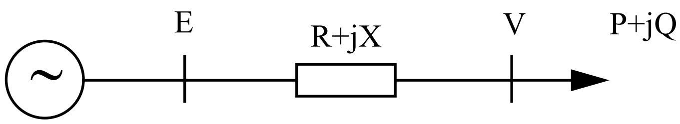

Figure 2.4 A simple model of a transmission system. E and V are the voltages at the generator and the load end, respectively. The transmission link has the impedance Z=R+jX and the load consumes the power S=P+jQ.

More components can be added to the system (transformers, capacitors etc.) and more details included (generator current limitation, on-load tap changer-relays etc.) to study the behaviour during different classes of disturbances.

2.4.1 The PV- and the VQ-curves for the small system

The active power-voltage function for the small system has a characteristic form usually called the ‘PV-curve’ (see Figure 2.5). As can be seen there is a maximum amount of power that can be transmitted by the system. Another property of the system is that a specific power can be transmitted at two different voltage levels. The high-voltage/low-current solution is the normal working mode for a power system due to lower transmission losses. One way to write the equations describing this power-voltage relation is:

$$V = \sqrt{\alpha \pm \sqrt{\alpha^2 - \beta}} \text{ where} \tag{2.1}$$

$$\alpha = \frac{E^2}{2} - RP - XQ \text{ and } \beta = (P^2 + Q^2)Z^2 \tag{2.2}$$

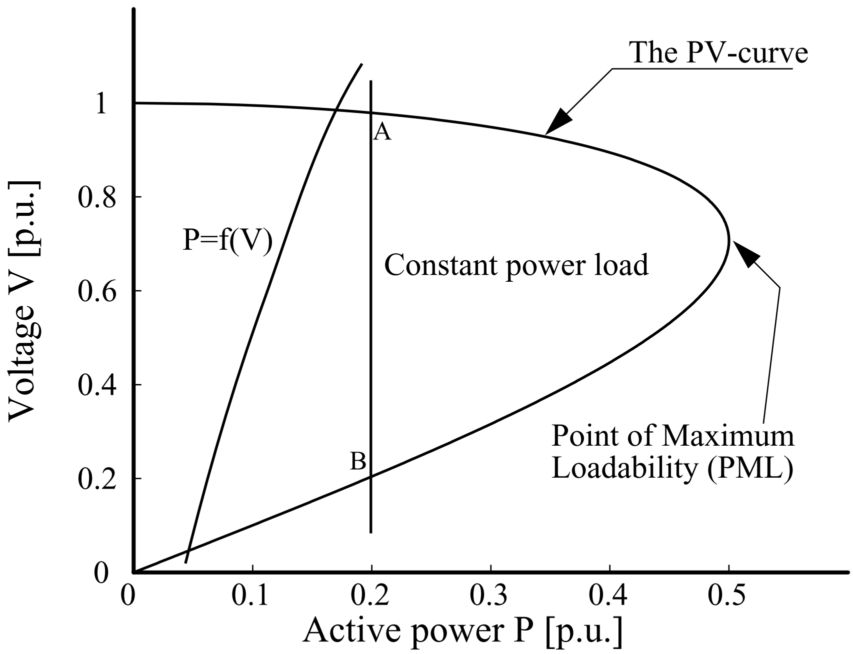

Figure 2.5 The PV-curve in per-unit with different load characteristics added. (E=1.0 p.u., R=0, X=1.0 p.u. and Q=0 p.u.)

The important “Point of Maximum Loadability” (maximum power transfer capability) is indicated in Figure 2.5. This point can be calculated by either solving ‘PML’ from the relation $\alpha^2=\beta$ from equation 2.1, by implicit derivation of dP/dV=0 in equation 2.1 or by evaluating the load-flow Jacobian singularity.

Another possibility to demonstrate the capacity of the small system is to show the V-Q relation. The necessary amount of reactive power in the load end for a desired voltage level V is plotted in Figure 2.6.

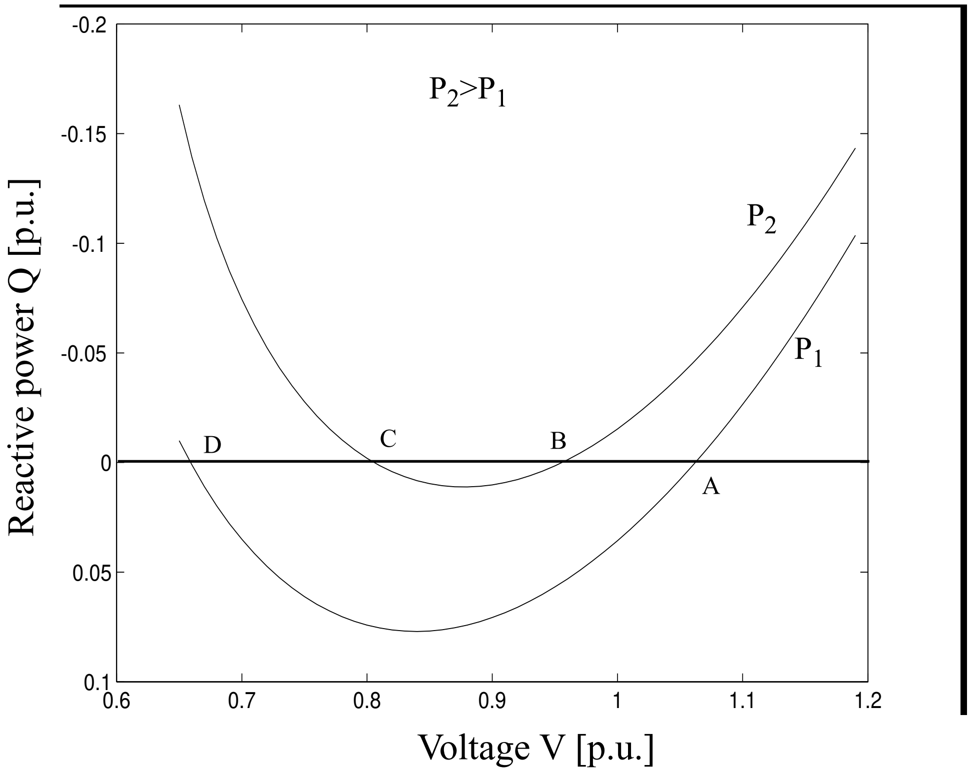

Figure 2.6 The QV curve in per-unit for two different active loads, showing the amount of reactive power to be injected at the load end to achieve a specified voltage. Without any reactive support in the load end, the system will be stable in the working points A and B and unstable in case of constant power loads in C and D [12, appendix 3]. Observe the common practice to 'flip' the Q-axis, i.e. a negative Q means injected reactive power in the load end.

2.4.2 The load demand

The system should supply its load demand at all times. Consequently, the system must manage all load-voltage dependencies without restraints. Electrical loads will behave differently. One way to describe the static voltage-power relation is to use the relations:

$$P = P_0\left[a_0\left(\frac{V}{V_0}\right)^0 + a_1\left(\frac{V}{V_0}\right)^1 + a_2\left(\frac{V}{V_0}\right)^2\right]$$

and (2.3)

$$Q = Q_0\left[b_0\left(\frac{V}{V_0}\right)^0 + b_1\left(\frac{V}{V_0}\right)^1 + b_2\left(\frac{V}{V_0}\right)^2\right]$$

where P and Q are active and reactive power load respectively while P_0 and Q_0 are the powers at voltage V_0. The relations in equation (2.3) are called a polynomial load model. The three terms correspond to a constant power fraction, a constant current fraction and a constant impedance fraction. The sum of $a_0+a_1+a_2$ and $b_0+b_1+b_2$ are equal to 1 but there is a choice to restrict each component to the interval [0,1] or let them vary freely. It is also possible to use an exponential load model:

$$P = P_0\left(\frac{V}{V_0}\right)^{\alpha} \text{ and } Q = Q_0\left(\frac{V}{V_0}\right)^{\beta} \tag{2.4}$$

Values for the parameters of these static load models can be found for instance in [19, page 73] or [15, Chapter 3].

Electrical loads may also have a dynamic voltage dependence. Motor loads have a mechanical dynamic dependence due to the applied load torque but since this load demand depends on the frequency this will have little influence for decreasing voltages as long as the motor can develop the necessary torque. Motors are sensitive to voltage changes and electrodynamic couplings will arise within the winding when voltage changes but the time constants are quite small (one second or less) and they are in the same time-frame as the voltage regulation of generators. This often implies a nearly constant active power load when the mechanical slip has been adjusted to a new operating point after a contingency whereas the reactive power demand may change. Motor load dynamics is therefore mainly connected with transient voltage stability.

There are also loads with slower dynamics where the dynamic behaviour comes from control-systems regulating the dissipated power. Electrical heating appliances controlled by electromechanical thermostats is one example.

Dynamic loads are often composed of a transient and a stationary part. One way to describe these two conditions is (see [16] and Paper A.2.1):

$$T_{pr}\frac{dP_r}{dt} + P_r = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t}$$

and (2.5)

$$P_m = P_r + P_0\left(\frac{V}{V_0}\right)^{\alpha_t}$$

P_m is the active power load demand and P_r describes the part of the load that recovers. Here, the voltage dependence is given by a transient term denoted by the exponent α_t and a static term, denoted by the exponent α_s. Field measurements have shown that α_t is around 2 and α_s can, for certain types of loads, be 0.5. The same relation could be applied to reactive power demand but there has not yet been a relevant physical explanation for a reactive load recovery on its own and it is believed that reactive power recovery is a consequence of active power recovery during longer term voltage stability [16].

Electrical heating appliances can be composed of discrete conductances and a control-system that connects the appropriate amount of conductance to achieve the desired power demand. This gives in the long time-frame a constant power load. This type of load can be unstable in a quasi-stationary sense if it is operating on the lower side of the PV-curve. This can be shown in the following way: If the present working point is located to the left of the desired power demand A (set-point value) in Figure 2.5, the control-system will increase the conductance G and the dissipated power will increase until the working point reaches A. On the curve A-PML-B the dissipated power is too large and the control-system will therefore decrease G which increases the voltage V and the working point moves to A. For the remaining part of the PV-curve from the origin to B the dissipated power is too low and the control-system add more conductance which decrease V even further and lower the dissipated power. Therefore B will be unstable [13]. Note that there are no problems to “pass” PML with this type of controlled load because the load characteristic is transiently a conductance.

More about loads can be found in [15] and [16].

2.5 Different methods of analysis

The analysis of voltage stability can be done using different methods. One approach is the analysis of small networks with mathematical bifurcations as a stability criterion. A special case of this method is the analysis of the smallest singular value or the minimum eigenvalue. Modal analysis, the eigenvectors of the system representation, is also used sometimes. The smallest singular value and modal analysis can also be used on large networks. A second approach is to find the extremes of either the PV-curve or the VQ-curve by some type of load-flow calculations, where the "distance" between the actual working point and the extremes is a stability criterion. Time domain simulations are yet another approach to analysis. Sometimes these different methods are mixed so that two different methods are presented simultaneously to gain further insight into the phenomenon.

It is also possible to divide the different methods in static and dynamic ones. Much work is being done on static load flow models which could be compared with other methods of analysis. In the following some of the different methods are introduced.

2.5.1 Analytical methods

The analytical approach is usually based on continuous mathematical models of the components of interest. Today these models are not as detailed as the models used in computer simulation [11], and it is therefore difficult to explain all events during a computer collapse simulation. The analyst often works with the following system description:

$$\begin{aligned} \dot{x} &= f(x, y, \lambda) \\ 0 &= g(x, y, \lambda) \end{aligned} \tag{2.6}$$

From this set of equations the analyst tries to figure out in which points the time solution changes its behaviour qualitatively. These points are called bifurcation points and are associated with eigenvalues of the Jacobian matrix J of (2.6):

$$J = \begin{bmatrix} \dfrac{\partial f}{\partial x} & \dfrac{\partial f}{\partial y} \\ \dfrac{\partial g}{\partial x} & \dfrac{\partial g}{\partial y} \end{bmatrix} \tag{2.7}$$

The trajectory of the eigenvalues then decides the system behaviour in the bifurcation points. Schlueter et al. [11] indicate more than 10 different bifurcations existing in a power system depending on which models are included in (2.6) and the degree of complexity of the models.

The Point of Collapse (PoC) is a point where a bifurcation occurs and is indicated in Figure 2.7. If the power is increased for the load in Figure 2.7 there will be a bifurcation in the system Jacobian matrix when reaching the PoC [13].

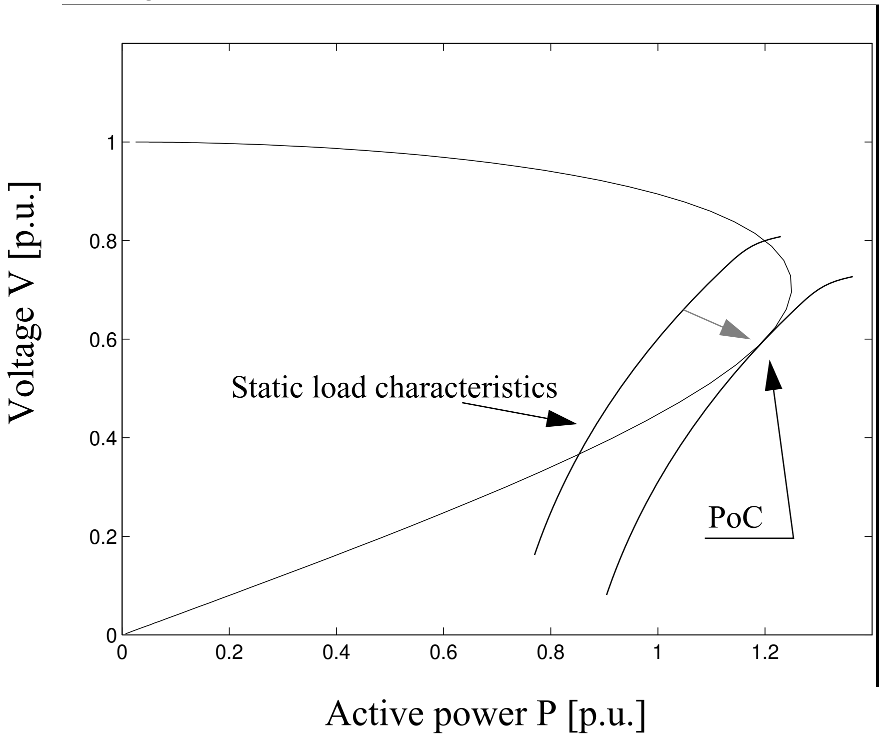

Figure 2.7 A PV-curve and a load characteristic where the load demand is increased. The indicated point of collapse (PoC) comes from Hill and Hiskens, [6] and is also described by Pal [13].

2.5.2 Indexes and sensitivity methods for voltage stability analysis

A bifurcation called the saddle-node bifurcation, is of special interest. It is connected to the singularity of the power-flow Jacobian matrix,

$$\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{P\theta} & \mathbf{J}_{PV} \\ \mathbf{J}_{Q\theta} & \mathbf{J}_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta \mathbf{V} \end{bmatrix} \tag{2.8}$$

where the changes in active and reactive power are related to changes in angle and voltage. If the Jacobian matrix is singular (non-invertible), the system has reached a point where it has no solution i.e. a saddle-node bifurcation. The minimum singular value or the smallest eigenvalue of the Jacobian matrix, can be used as a “distance” or proximity indicator to this limit.

If the Jacobian matrix models the power flow equations, this singularity will coincide with the point of maximum loadability. But if load behaviour etc. are included (extended Jacobian matrix) the singularity will indicate the point of collapse.

If $\Delta\mathbf{P}=\mathbf{0}$, the relation between voltage change and reactive power change can be written as:

$$\Delta\mathbf{Q} = [\mathbf{J}_{QV} - \mathbf{J}_{Q\theta}\mathbf{J}_{P\theta}^{-1}\mathbf{J}_{PV}]\Delta\mathbf{V} = \mathbf{J}_R\Delta\mathbf{V} \qquad (2.9)$$

This matrix $\mathbf{J}_R$ is used as a state space matrix in the analysis. Efficient algorithms [9] have been developed to calculate the minimum singular value for the reduced matrix $\mathbf{J}_R$ which can be used as a voltage stability index.

Modal analysis, calculation of eigenvalues and eigenvectors of the Jacobian matrix can be used to derive weak voltage nodes in the system. If an extended Jacobian matrix (where generators, loads etc. are modelled into the matrix) is used, the participation factors of the states in the models are presented with modal analysis.

2.5.3 Other indexes

Sometimes the distance in MW or MVAr to the maximum transfer point on the PV-curve is used as an index for vulnerability to voltage collapse. The point of maximum loadability can be calculated in many ways. A conventional load flow program can be used if it is capable of capturing the system behaviour near the bifurcation point (the same point as PML when applying constant power loads). This is, however, difficult and special continuation load flow methods for calculating the PV-curve near PML have been developed [8].

There are two indices called $VCPI_{Pi}$ and $VCPI_{Qi}$ (Voltage Collapse Proximity Indicator) presented in [4] that may be useful. They relate the total change of reactive power output to a change in either active or reactive power in a node i:

$$VCPI_{Pi} = \frac{\sum \Delta Q_g}{\Delta P_i} \qquad (2.10)$$

$$VCPI_{Qi} = \frac{\sum \Delta Q_g}{\Delta Q_i} \qquad (2.11)$$

At off-peak load the indexes are near 1 and grow to infinity at the collapse point.

2.5.4 Voltage stability simulation

Simulations in the voltage stability area are usually computer calculations in the time domain where the computer tries to solve the differential-algebraic equations describing the power system. Voltage stability phenomena put standard computer algorithms at new numerical problems. The differential equations are usually stiff, i.e. the time constants vary over a broad spectrum. This sometimes forces the user to choose which phenomena the models should represent. Some algorithms adapt their time-step to reduce simulation time and capture all the modelled phenomena with the same accuracy. Another problem is the way the computer solves the load flow. This could be done in several ways. Some software uses the admittance matrix with current injections and other uses the Jacobian matrix approach. If the software solves the network with a Jacobian matrix, it will have singularity problems near the collapse point but it will have the opportunity to calculate some indexes (see Chapter 2.5.2). Certain continuation load-flow methods have been developed to avoid singularity problems [8].

When the models used in the simulation have a known degree of accuracy, it is possible to simulate very complex systems with these models. The main problem is then to collect relevant input data. Usually, a time simulation only indicates if a disturbance is stable or unstable but, by calculating indexes and sensitivities, this drawback can be reduced. There are other reasons that motivate long-term dynamic simulations and the conclusions in [1] are enlightening in this matter. A summary of arguments for long term dynamic simulations follows here [8, 19 appendix D]:

- Time coordination of equipment where the time frames are overlapping.

- Clarification of phenomena and prevention of overdesign. Time domain simulations forces more careful analysis and modeling.

- Confirmation of less computationally intensive static analysis.

- Improved simulation fidelity especially near stability boundaries.

- Simulation of fast dynamics associated with the final phases of a collapse.

- Demonstration and presentation of system performance by easy-to-understand time-domain plots.

- Education and training.

In analytical modelling, it is difficult to implement protective relaying. In time simulations on the other hand, one can include these relays that may interact at any time during the voltage instability. It is therefore possible to coordinate between automatic regulation, limitation and protection in a time simulation.

There are many software packages available which can be used for long time simulation in power systems. A comparison between several different softwares applied to different test networks can be found in [1]. In this project a software called PSS/E from PTI Inc. has been used. This software is well recognized at power companies worldwide and has also started to be used among universities. PSS/E can be used for load flow calculations as well as short circuit analysis. The dynamic simulation utility in PSS/E can apply both explicit and implicit integration methods on the data set. Especially for long term dynamics implicit integration methods have been found favourable and are recommended to be used.

Some simulations on small networks has been performed in Matlab which is a versatile mathematical tool.

2.5.5 Other approaches

As long as load dynamics, generator current protection or limitation and OLTC-behaviour dominate the system response, is it possible to divide the voltage collapse course into several static phases and solve the load flow for each step. In [8] the system response is divided into the following phases:

1 **T=0 to 1 second**

Voltage excursions due to transient decay in generator flux and changes in motor slip. At the end of the period, voltage regulating equipment is affecting the voltage levels.

2 **T=1 to 20 seconds**

Generator terminal voltage output levels are restored if not limited by VAR-limits. Loads are modelled with transient models.

3 **T=20 to 60 seconds**

Current limiters may affect the output capacity of generators.

4 **T=1 to 10 minutes**

Load tap changers in the distribution network restore customer load.

5 **T=10+ minutes**

Automatic Generation Control (AGC), operators etc. affect the behaviour of the system.

If phase-angle regulators, Automatic Generation Control, combustion turbine starting etc. come into action during the same time-frame, simulations could be necessary to reveal the system behaviour. Governor response on the turbines should also be taken into account if they affect the distribution of power production.

2.6 References

[1] Cigré Task Force 38-02-08, Long Term Dynamics Phase II", Final Report, 1995.

[2] Cigré Task Force 38-02-10, "Modelling of Voltage collapse Including Dynamic Phenomena", 1993.

[3] Cigré Task Force 38-02-12, "Criteria and countermeasures for voltage collapse", 1995.

[4] H. Suzuki, Study group 37 discussion, Cigré, Proceedings of the 34th Session, Vol. II, pp. 37-39, 1990.

[5] G. le Dous, J. Daalder and D. Karlsson, ”Dynamic Load Measurement in a Transmission System”, International Power Engineering Conference - 97, Singapore, pp. 74-79, 1997.

[6] D. J. Hill, I. A. Hiskens and D. Popović, “Load recovery in voltage stability analysis and control”, Bulk Power System Phenomena III, Voltage Stability, Security and Control, ECC, Davos, pp. 579-595, 1994.

[7] IEEE Committee Report, “Voltage Stability of Power Systems: Concepts, Analytical Tools, and Industry Experience”, IEEE/PES 90TH0358-2-PWR, 1990.

[8] IEEE working group of voltage stability, “Suggested Techniques for Voltage Stability Analysis”, 93TH0620-5PWR, 1993.

[9] P.-A. Löf, T. Smed, G. Andersson and D. J. Hill, “Fast calculation of a voltage stability index”, IEEE Transactions on Power Systems, Vol. 7, No. 1, pp. 54-64, 1992.

[10] R. van den Damme, “The incident of August 4th 1982 of the Belgian Electricity System”, Intercom, September 12, 1983.

[11] R. A. Schlueter, K. B. Kilani and U. Ahn, “Impact of Modeling Accuracy on Type, Kind, and Class of Stability Problems In A Power System Model”, Bulk Power System Phenomena III, Voltage Stability, Security and Control, ECC, Davos, pp. 117-156, 1994.

[12] J. Falk Christensen, M. Stubbe, A. W. Grainger, J. Verseille and G. Santagostino, “Planning Against Voltage Collapse”, Cigré report SC 38-01 TF03, 1986.

[13] M. K. Pal, “Voltage stability conditions considering load characteristics”, IEEE Transactions on Power Systems, Vol. 7, No. 1, pp. 243-249, 1992.

[14] Y. Harmand, M. Trotignon, J. F. Lesigne, J. M. Tesseron, C. Lemaitre and F. Bourgin, “Analysis of a voltage collapse-incident and proposal for a time-based hierarchical containment scheme”, Cigré 38/39-02, 1990.

[15] K. Lindén and I. Segerqvist, “Modelling of Load Devices and Studying Load/System Characteristics”, Technical report No. 131L, ISBN 91-7197-038-X, Chalmers University of Technology, Sweden, 1993.

[16] D. Karlsson, “Voltage stability simulations using detailed models based on field measurements”, Technical report No. 230, ISBN 91-7032-725-4, Chalmers University of Technology, Sweden, 1992.

[17] P. Kundur and G. K. Morison, “A Review of Definitions and Classification of Stability Problems in Today’s Power Systems”, Presented at IEEE/PES panel on Stability Terms and Definitions, New York, February, 1997.

[18] H. Glavitsch, “Voltage stability and collapse - A review of basic phenomena and methods of assessment”, Bulk Power System Phenomena III, Voltage Stability, Security and Control, ECC, Davos, pp. 9-14, 1994.

[19] C. W. Taylor, ”Power System Voltage Stability”, McGraw-Hill, ISBN 0-07-063184-0, 1994.

[20] C. W Taylor, “Maybe I can’t define stability, but I know it when I see it”, Presented at IEEE/PES panel on Stability Terms and Definitions, New York, February, 1997.

[21] A. Kurita, T. Sakurai, “The power system failure on July 23, 1987 in Tokyo”, Proc. 27th conf. on Decision and Control, Austin, Texas, pp. 2093-2097, 1988.

[22] K. Walve, “Modelling of power system components at severe disturbances”, Cigré SC 38-18, 1986.

Chapter 3 Alleviating the impact of generator current limiters

This chapter aims to summarize certain important aspects presented in the papers and will pursue some further thoughts.

3.1 Organization

The papers which are a part of this thesis are organized as follows:

Paper A, **Voltage stability studies with PSS/E**; analyses the behaviour of dynamic load demand, current limiters and on-load tap changers. The implementation of these components into the PSS/E software is discussed. Different aspects of component behaviour are shown by simulations.

Paper B, **Behaviour of generator current limiters near the point of voltage collapse**; concentrates on the behaviour of the current limiters and discusses the capability diagram of the generator 'as seen by the generator', i.e. treats the generator as a stand-alone component.

Paper C, **Avoiding Voltage Collapse by fast Active Power Rescheduling**; tries to establish a 'system capability' as seen by the load demand for a small system equipped with current limiters. Different 'modes' of operation are introduced corresponding to the operation of different current limiters in the system. Here the view is shifted from the generator to the load point. The controlled parameter is the active power input to the generator during current limitation.

Paper D, **Mitigation of Voltage Collapse caused by Armature Current Protection**; continues the analysis in Paper C with simulations performed for a more extensive network.

Paper E, **Maximum thermal utilization of generator rotors to avoid voltage collapse**; investigates the use of the specific thermal capacity of a generator on system voltage stability.

Paper A and paper B are mainly dealing with inherent component behaviour, whereas papers C, D and E investigate system aspects and different actions that can be beneficial for the system in case of an impending collapse.

The following sections are a short description of important issues presented in the papers together with some additional information not presented elsewhere.

3.2 The field current limiter

The main issue in this dissertation is the general behaviour of a limiter and not its detailed implementation of which there exists many examples. However, two examples of field current limiter implementations are given in Section A.2.2 and Section E.2. For discussion of the qualitative behaviour of the field current limiter, see Section B.2 and Section E.2.1. More information about field current limiters can also be found in references [6, 7 and 9].

3.3 The armature current limiter

As stated in the introduction, the armature current limiter is not a common component worldwide. However in this dissertation the armature current limiter may in many instances be considered to be equivalent with an overcurrent relay. It is not difficult to implement an armature current limiter in a computerized voltage control/over-current protection device since all quantities are available together with the means of controlling it through the magnetization of the generator. The implementation of the armature current limiter used in Sweden follows closely that of the field current limiter (see Section A.2.2). Armature current limiters will allow generators to produce power in a stressed network for a longer time than an overcurrent relay. This will give other remedial actions more opportunity to support the system.

3.4 The interaction between the limiters

One interesting conclusion from the capability diagram of the generator (Figure B.3) is that a field current limited generator will become armature current limited if it is exposed to a continuously decreasing voltage (Figure B.4). Since virtually all voltage collapses contain a phase with decreasing voltage this transition between the limiters will happen if nothing else occurs before. Events as the activation of protection equipment (cf. distance relays) or the stalling of induction motors will initiate a new phase of the voltage instability creating new conditions which has to be dealt with accordingly. Note however that there are examples of generators where the reactive power decreases for a decreasing voltage during field current limitation. Figure 5.17 in reference [11] and figure 1 in reference [15] indicates such a situation which is very severe for the system. In such a case the influence of field and armature current limiter operation becomes similar. This situation occurs for generators having a high synchronous reactance and/or a low degree of saturation.

Several other constraints will be present in the generator capability diagram besides the two presented here. Reference [1] indicates a max/min generation limit, an auxiliary bus high/low voltage limit, a generator high/low voltage limit, a max/min voltage regulator output, a stator core end heating and a minimum excitation limit as probable sources of restricted operation of the generator. These constraints must also be included in a complete analysis of the generator. Practical aspects and field assessment of generator capability curves can be found in [16, 17] which are of particular interest for utilities and power plant operators. A general observation made during this study is how important the regular maintenance and tuning of the *existing* generator equipment is. Defects and anomalies in the field current protection/control have contributed to several voltage instability problems [21, page 263 and 25, page 30]. Also, short circuits in the field winding due to ageing may arise which will have repercussions on the reactive power capability [16]. Utilities should also update their modelling during security analysis to take into account improved computational resources available today.

3.5 The interaction between the transmission system and the limiters

One way to show the interaction between the generator current limiters and a transmission line is to plot a PV-curve (e.g. Figure B.2). The field current limiter decreases the point of maximum loadability but voltage is still in a sense controlled since the constant field current will keep a controlled voltage within the generator. Armature current limiting is more severe for the system since the voltage will not be controlled any longer and is solely dependent on the loads in the system. Different control mechanisms and certain voltage dependent loads will continuously change the load connected to the generator terminals and hence voltage levels.

For an armature overcurrent relay all operating points to the right of the straight line in Figure B.2 are prohibited and will cause a tripping of the generator. Note that the slope of the armature current in the PV-plane may vary (cf. Section 3.7) and the crossing between the valid PV-curve and an armature current limit can be above or under the point of maximum loadability.

3.6 The interaction between the load and the current limiters

System behaviour is very dependent on load behaviour which in its own is difficult to model. Sometimes the influence of the on-load tap changers is included in the load model [5, 13] or explicitly represented. This must then be taken into account when analysing the system.

A field current limiter will not change the general behaviour of the PV-curve but it will decrease the maximum power transfer and will make the voltage support weaker (Figure B.5). The analysis in the PV-plane of the system will therefore not differ that much between for instance a line tripping and a field current limiter action. However, in case of field current limitation one has to address the non-linearity of the introduced reactance and the saturation in the generator to achieve correct results.

The interaction between the armature current limiter and load behaviour is completely different. The system will become unstable if the load as seen by the armature current limited generator requires more current than the limit value. Figure A.15 demonstrates this performance for a few load models and Section B.2.4 discusses the key aspect to this behaviour. This property is also discussed in Section D.4.

3.7 The interaction between on-load tap changers and the current limiters

In general, tap changers will restore the voltage level and thereby the active power demand. It will also influence the network impedance as seen by the generator [14, page 76]. Since transformers are placed in different positions in the power system relative to generation and load demand the analysis must also take the location into account. Here follows an analysis of a small network containing a transformer as shown in figure 3.1. The model can represent any transformer in the

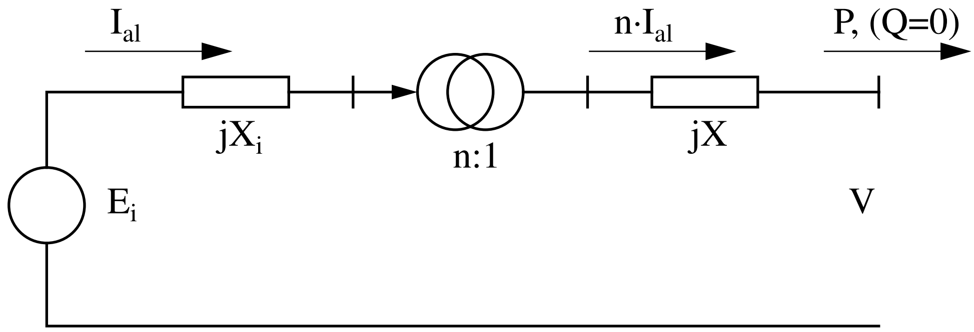

Figure 3.1 The studied system for establishing the interaction between OLTC:s and current limiters. In these examples are $X+X_i=0.1$ p.u.

power system. The load voltage V can be written as

$$V = \sqrt{\frac{1}{2}\left(\frac{E_i}{n}\right)^2 \pm \sqrt{\frac{1}{4}\left(\frac{E_i}{n}\right)^4 - \left(X + \frac{X_i}{n^2}\right)^2 P^2}} \qquad (3.1)$$

A qualitative understanding of the interaction can be studied by examining the point of maximum power transfer P_{max} (or Point of Maximum Loadability). Equation (3.1) can be used to establish

$$P_{max} = \frac{\frac{1}{2}E_i^2}{(n^2X + X_i)} \qquad (3.2)$$

The active power P_{max} will be a function of the reactances n^2X and X_i. By studying the transformer's relative position in the network one can distinguish between two different cases: the transformer is either close to the generator or close to the load.

Case 1: A transformer close to the generator ($X>>X_i$ and $n\approx1$)

An approximate expression of P_{max} is then

$$P_{max} \approx \frac{\frac{1}{2}E_i^2}{n^2 X} \tag{3.3}$$

The family of PV-curves in this case is shown in Figure 3.2 and they illustrate how different tap steps alters the system capability. The load characteristics plotted in the figure show an improved system condition by tap changing operation. P_{max} will increase quadratic with the tap step. Therefore, the system will remain above the PML for all loads with a voltage dependence less than squared for (in this case) a decreasing tap step which increases the secondary voltage level.

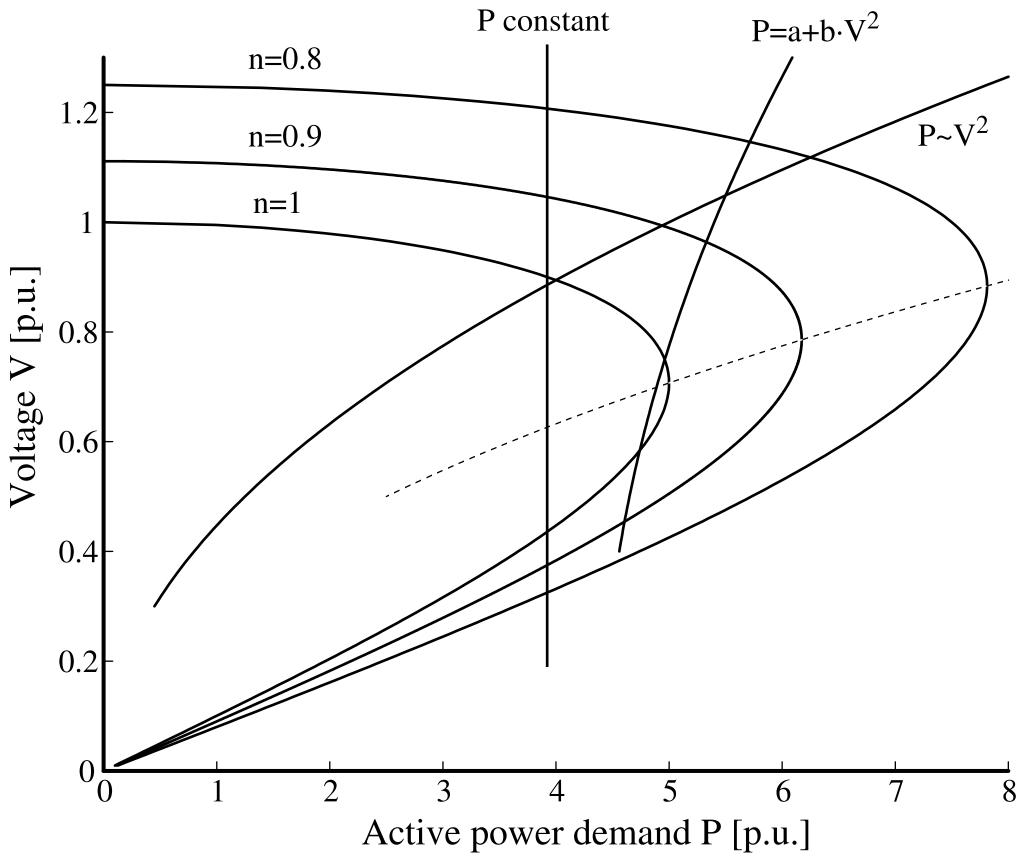

Figure 3.2 Different PV-curves for a transformer close to the generator.

Case 2: A transformer close to the load ($X<<X_i$ and $n\approx1$)

Now one can approximate P_{max} from (3.2) to

$$P_{max} \approx \frac{\frac{1}{2}E_i^2}{X_i} \tag{3.4}$$

i.e. P_{max} will be independent of the tap step. The family of PV-curves in Figure 3.3 clearly indicates that the system can become unstable due to the static characteristics of the load. Also, as discussed in Section 2.4.2, thermostatically controlled load may become unstable on the lower side of the PV-curve. A transformer close to the load may shift the PV-curve in such a way that the latter occurs. The tap changing

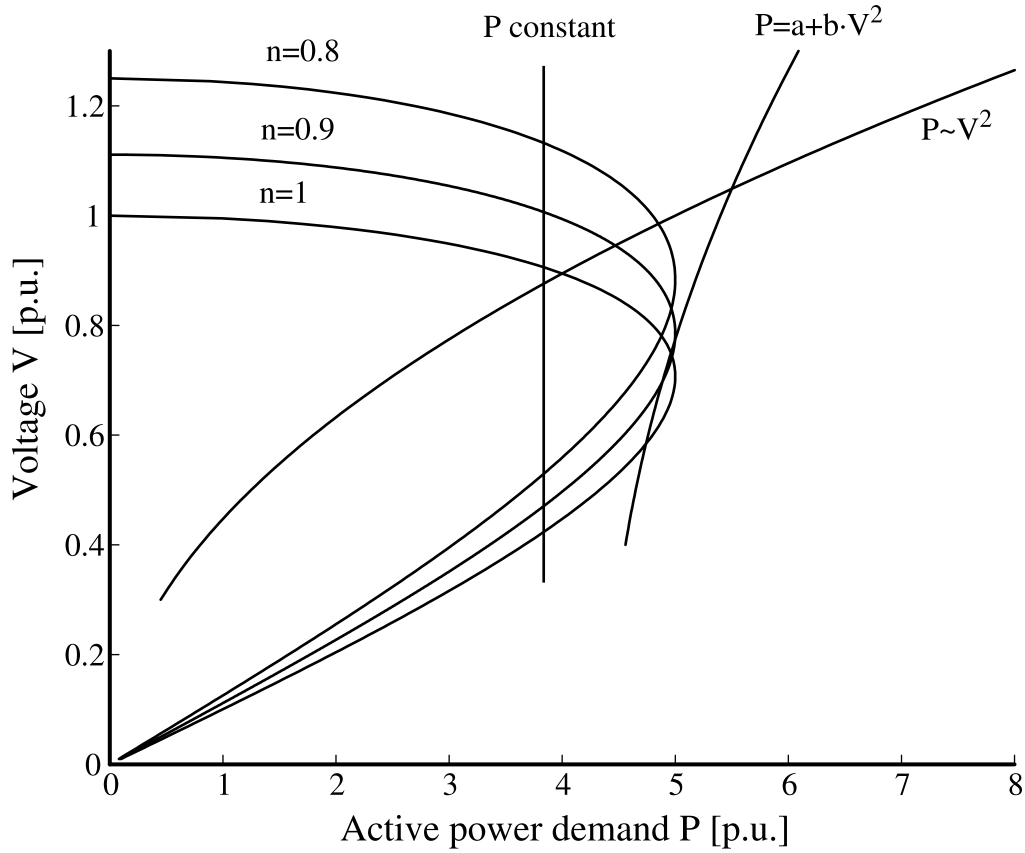

Figure 3.3 Different PV-curves for a transformer close to the load.

control equipment may also initiate an instability when the working point enters the lower side of PML. For certain load types the voltage will then decrease instead of increase for (in this case) a decreasing tap step.

In reality no transformer has a negligible impedance on either side and the response of a specific transformer on different system actions will be a mixture of these two extremes. The following observation can be made concerning the field current limitation:

- A field current limiter in operation will increase the reactance X_i and thereby decrease the maximum power transfer shown in (3.2). As the two cases above indicate, the field current limitation will also move the operation for this small system towards a ‘Case 2’ operation since X_i relatively increases if compared with X. The tap changing action will then be less beneficial for system stability.

From these two cases concerning tap changing actions the following general observations can be made:

- Step-up transformers close to generators are beneficial to ”increase” the tap ratio to avoid voltage stability problems. Usually however they are not equipped with on-load tap changers and can not be used as a countermeasure. If they are equipped with tap changers, the voltage drop might be too small for a control action based on local criteria only. Also, the maximum operating voltage of the transmission system may ‘prohibit’ this action.
- The importance of the load characteristics can not be underestimated. Case 2 shows a situation where both a conductance load and a constant power load are stable whereas a mixture of them might become unstable. The behaviour of dynamic loads such as thermostatically controlled load devices will complicate this (static) analysis even more.

For an armature current limit the tap changer will have a different impact. The most likely tap-changer operation during a voltage instability process is to try to increase the voltage on the secondary side in figure 3.1 by reducing the tap ratio n. This means that the current ratio of the transformer must go in the opposite direction i.e. the current at the secondary side will be $n \cdot I_{al}$. The armature current limit will then decrease for every tap step as seen by the load since I_{al} is fixed. The armature current capability will therefore change in the PV-plane as indicated in figure 3.4. The load demand will be as important as before since it may or may not trigger the limiter.

An example of this process can be seen in Figure A.12 and Figure A.14 where the current on the primary side increases considerably which causes a collapse in the second figure. Load characteristics in combination with the tap changer operation triggers the armature

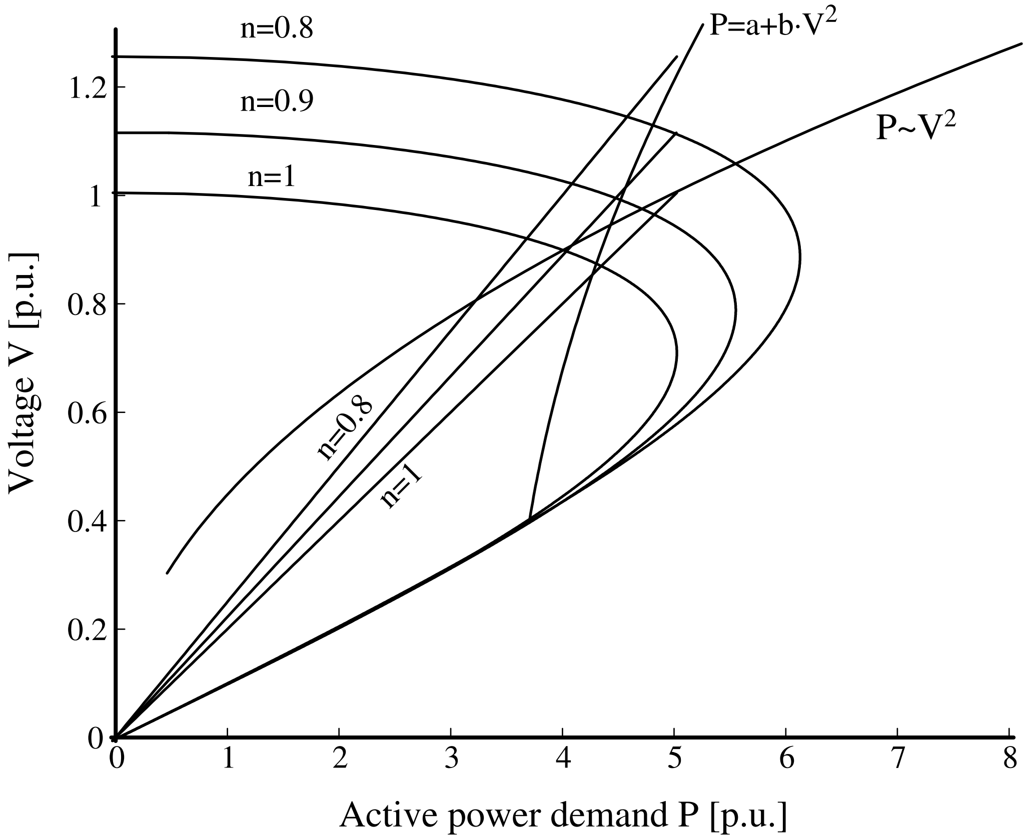

Figure 3.4 The interaction between the armature current limit and tap changings. The PV-curves represents a case when $X=X_i$.

current limiter and the system changes its performance completely leading to a voltage collapse.

The relative position of the transformer in the system is also important in this case. For a transformer close to the load ($X<<X_i$, Case 2) the tap changing causes a power invariant shift in the PV-plane whereas a transformer closer to the generator will increase the maximum capability of the system.

The behaviour of the tap-changer can also be seen as being a part of the load behaviour. One will then have dynamics originating from the tap changer control in the load characteristics instead. Field measurements performed in the south of Sweden [5] show examples of this.

3.8 Remedial actions

Any activation of a current limiter is a serious threat to system voltage stability and should be avoided as long as possible. The armature current limiter appears to be the most critical one even though the field current limiter can cause a collapse on its own.

Papers C, D and E are focused on two possible remedial actions alleviating the impact of current limiters during a voltage instability. The first remedial action aims *to utilize the thermal capacity in the field winding*. The pre-disturbance conditions do not always have to be rated conditions and by introducing temperature controlled current limits will the bias of different pre-disturbance temperatures disappear which can cause unnecessarily strict limitation of the generator.

The other remedial action is *to make small changes in local active power production* during current limitation in order to *increase the system capability* locally. This rescheduling of power will give the generator protection another degree of freedom to set aside too high currents.

In particular, the interaction of the limiters with the rest of the power system is considered when these remedial actions are performed. Both remedial methods are based on a radial system with a comparatively small generator feeding a load with a gross import of active power.

3.8.1 The use of the thermal capacity in the field winding

Many contingences leading to voltage stability problems occur under circumstances where generators are not fully loaded from a thermal point of view. Paper E investigates this aspect during field current limitation. Rather few measurements of the temperature rise in the field winding seems to be available and it is the authors opinion that this aspect has been neglected. Some values are given in [4] and in [19] in addition to [E.9]. These references also discuss the approach to keep field current as high as possible until maximum rotor temperature is reached. Reference [19] indicates decreasing time constants for increasing generator sizes. The settings of protection should therefore vary between different sized generators to make them equally loaded (compared to their respective rated conditions) during contingencies.

A cost effective way to improve voltage stability seems to be the use of existing generators and loading them until they reach their maximum steady-state level from a thermal point of view. A thermal model, temperature measurements of the winding and a field current limiter control equipment based on temperature data are the basic requirements. The cost of upgrading the exciter, if necessary, should also be compared with other methods as capacitive support. Since the thermal capacity is a finite ‘resource’ the limiter must use it carefully. Communication with neighbours indicating a severe situation and asking for support may be useful to implement to keep in view the limited capability.

Some problems encountered in measuring the field winding temperature are described in [18]. The environment is extreme due to a large temperature range with sometimes very high mechanical stresses (considerably above 3000 rpm for the fastest rotating machines) in a highly electrically-noisy environment. The field voltage and current measurements have to be transferred from the rotating shaft. These values give the present field resistance which is indirectly a measure of the temperature of the winding. Reference [18] reports that a temperature accuracy of ±1.5° C can be achieved by existing equipment. This method gives an average temperature of the winding so the problem of so called ‘hot spots’ must also be addressed.

It is tempting to propose a similar approach for armature windings. There are in this case no problems in transferring temperature measurement data from a rotating shaft and the possible problem of exciters having a too low transient rating does not exist as for the field circuit (even though a maximum utilization of the armature may be obstructed by too small power resources). Also, the temperature of the cooling media in the armature winding (if any) will influence the rating which is something a temperature based current limiter can take into account.

3.8.2 Rescheduling of active power production

The second remedial method proposed is an increase or a decrease of mechanical power input to the generator shaft when any of the current limits are violated. In certain cases power plants have this control ability.

Voltage stability problems are many times regarded as a lack of reactive power locally. This causes a declining voltage in that area which increases the reactive power deficit further due to increasing transmission losses. The voltage continues to decrease. If a generator, exposed to this voltage drop becomes **armature current limited** it is impossible to increase the reactive power output from that generator. In fact, the opposite will occur. When voltage declines the active power production will take an increasingly larger fraction of the available armature current. The reactive power output from the generator must decrease which escalates the voltage drop further. By decreasing the mechanical power input during armature current limitation the reactive power production can be held constant or may even increase and keep voltage levels higher. The transmission system uses this extra reactive support and imports the rescheduled active power until a certain (rather low) power factor is reached for the generator.

On the other hand, if the generator exposed to the voltage drop becomes **field current limited** and can not supply enough reactive power, an increase of mechanical power in that generator will ease the transmission losses into the depressed area. This will improve the voltage level somewhat. Reference [8] on the other hand states, based on the capability diagram, that one can generate less active power in favour of reactive power at critical locations. This may be true but not necessarily the best action from the systems point of view at all times. Figure 3.5 indicates two possible positions for the small generator in the network. Case A shows a generator ‘surrounded’ with other generators. If a limitation is initiated in the small generator the system is in this case similar to the one presented in papers C, D and E. Figure C.7 indicates a possible capability curve for the load point. An active power decrease during field current limitation will in that case be an *extra* stress for the system.

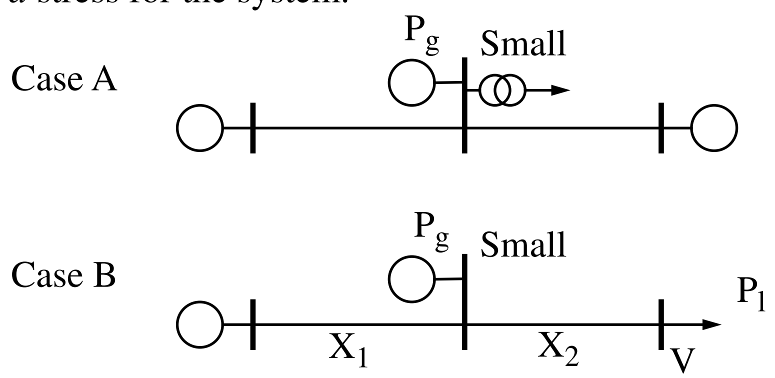

Figure 3.5 Different generator positions.

Also for Case B in figure 3.5 where the load demand has been moved away from the generator node and fed through a transmission line will an active power decrease in the small generator be a burden in certain situations. An example is given in figure 3.6. Two different kinds of PV-curves are plotted in the figure. The first one, where the small generator is keeping its voltage at its set point, indicates the PV-curve for the system containing the reactance X_2. The other three curves represent different levels of active power production in the small generator when it is field current limited. An increase of active power production will push the interception between the two ‘modes’ of operation of the small generator (i.e. the field current activation point) to a higher load demand level. The system will be able to deliver more active power before system characteristics are changed by the field current limiter.

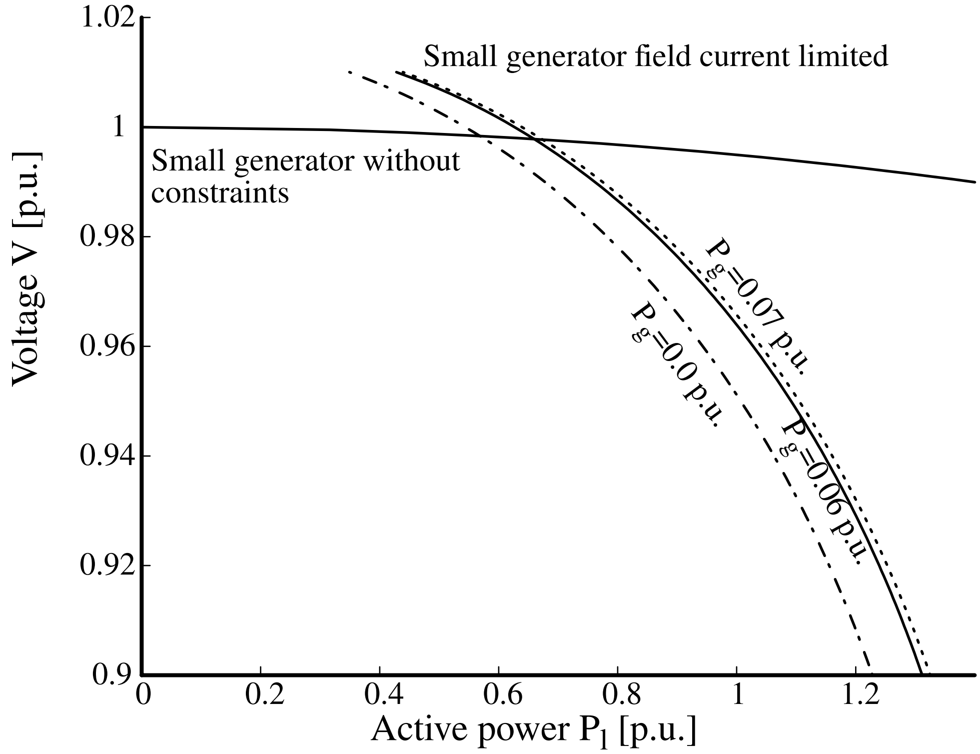

Figure 3.6 The PV-curve for different levels of active power production in the small generator for case B in figure 3.5.

Active power rescheduling as a means of relieving the system during current limitation is hardly discussed in the literature. The idea is mentioned by Taylor [21, page 116] but the concept is probably meant to be implemented as an operator control and can be seen as a slower control mechanism working through EMS/SCADA systems. The concept seems to operate mostly from relieving the transmission system by increasing power transfer to the exposed area on lightly loaded lines. Also Kundur et al. [12] mentions that the generator capabilities changes due to modified active outputs and this has to be taken into account during longer time frames although no further analysis is made.

Another source which mentions active power changes during current limitation is [3]. The capability diagram of the generator is discussed together with a strategy of how to increase system voltages during a load pick up.

The Cigré report [4] is one of the most extensive descriptions of generation based countermeasures during long term voltage stability published so far. Several aspects are discussed including active power decrease during armature current limitation and thermal utilisation of the windings.

In reference [23] active power dispatch is used to alleviate voltage instability. As a criterion for instability a static index is used based on [10]. The index identifies the Point of Maximum Loadability and adjusts active power production to increase the distance to the point of maximum loadability. Another example is reference [20] where optimal power flow is used to reschedule active power production. The criteria used for minimization is either total cost of generation, transmission losses, maximizing of the minimum singular value or minimization of slack reactive injection. A comparison between these criteria is made. A few similar approaches are available but all those seem to be based on off-line calculations.

In Paper D, an Active Power Rescheduler, APR is introduced. The purpose is to try to implement ideas about the influence of a decrease in mechanical power input during armature current limitation and thereby improving the reactive power balance locally. The difference between this approach and the ones presented above is that it is based on local control and work in a time frame comparable to the field and armature current limiters.

It was found in paper D that a rather slow APR giving small decreases of active power production was beneficial. At first, this behaviour was not understood but if figure C.13 is studied a hypothesis can be given. Figure C.13 shows the local system capability when the local generator is armature current limited (Mode 3) and when both generators are limited (Mode 8). When Mode 8 becomes activated the maximum capability of the system is shifted to a higher relative level of local active power production as compared to Mode 3. If the same shift of system capability is applied to the large system the system will only benefit from rather small decreases (i.e. slow) and if the decrease becomes too large there will be a reduced system capability. During the simulated contingencies in the large network one or several generators will become armature current limited and for those cases where voltage collapse occurred the number of limited generators increased during time. This can be seen as a transition from different modes to more complex ones such as in Section C.6.3. A sketch of the system capabilities is made in Figure 3.7.

One can also argue that for every generator that becomes limited in the large system the effective reactance will increase between the load demand and the infinite generation point which gives, if it is translated to the small system, a higher angle δ in equation (C.17) and hence a higher power factor at maximum system capability.

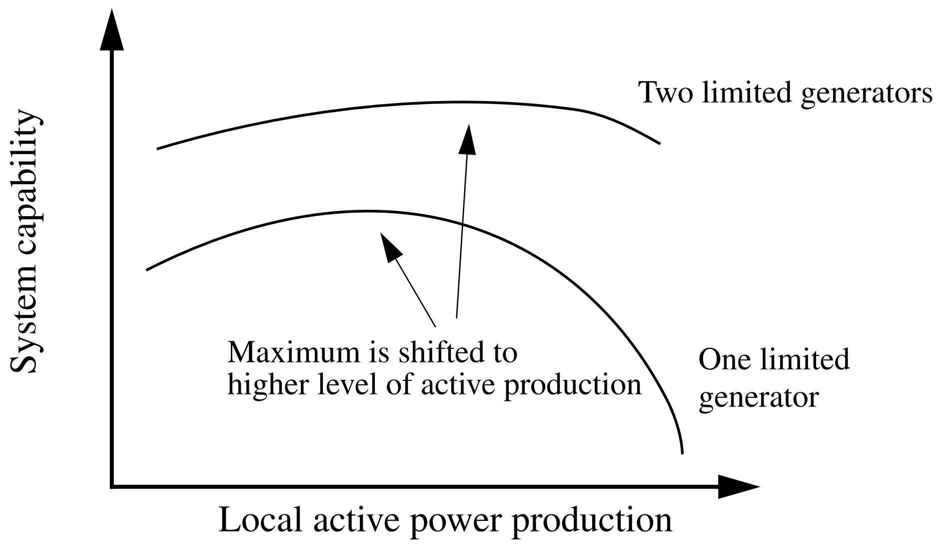

Figure 3.7 The system capability maximum is shifted to the right for increased numbers of limited generators.

Another interesting connection between the more complex simulation performed in paper D and the analysis of the smaller network (paper C) can be studied in figures C.10 and D.12. The total load power demand for the case with and without APR in the voltage depressed area is almost the same in figure D.12 but the dynamic load/tap changer control operates as in C.10 so the maximum energy deficit is reduced and the load excess region is increased for the case with APR. The example is not stable but shows the importance of keeping a high load voltage. A slight decrease of the pre-disturbance situation would have been enough for the APR case to become stable in figure D.12.

3.8.3 Power plant response to a change of active power production

Hydro power plants are fairly easy to control and are often used for frequency regulation. Walve [24] states that the loading from synchronisation to full load takes between 20 and 100 seconds for a hydro power plant. In case of thermal power plants the situation will be more complex. An increase of power may be considered as being a response to a frequency drop and a thermal power plant can accomplish an increase rather fast when steam is available. Baldwin et al. [2] indicates that a transient increase of 25-30% of nominal power is allowed for major frequency drops. For even larger frequency deviations there will be a restriction in the order of 10% of rated load per minute though higher values may be possible. The reference also indicates that for a transient power change of 20%, 5.4% will be accomplished within 3.25 s and the remaining 14.6% within 50 seconds. A power decrease may be achieved by closing the control valve which has a slew rate of typical 40% per second.

For thermal power plants working in constant power mode the available power increase capacity will be more restricted since it takes longer time to change the primary power production in this case. However, Termuehlen and Gartner [22] shows several ways to obtain a fast sustained power increase. The methods used are bypassing of heaters and water injection into the superheater.

Walve [24] gives ‘typical’ response times for mechanical power changes showed in Table 3.1.

Type of change	Unit	Speed
Step response	Oil-fired	2.5% within 5 s 5% within 30 s
	Coal-fired	2.5% within 5 s 5% within 30 s
Continuous frequency control		±2% within 30 s
Ramp (applies within 50-90% of operating range)	Oil-fired condensing	8%/minute Total 30%
	Coal-fired condensing	4%/minute Total 20-30%
	Gas turbines	10%/minute Total 30%

Table 3.1 Response times for power plants [24].

Walve [24] also states that tests show that nuclear boiling water reactors can vary their output by 20% with a time constant of 10 to 20 seconds whereas pressurized water reactors are slower.

The given figures clearly indicate that most power plants will be able to accomplish active power changes deemed by current limit restrictions. Insufficient control equipment and/or opposing operating strategies may obstruct this possibility.

3.9 References

[1] M. M. Abidi and D. P. Milanicz, ”Reactive Capability Limitation of Synchronous Machines”, IEEE Transactions on Power Systems, Vol. 9, No. 1, pp. 29-40, 1994.

[2] M. S. Baldwin and D. P. McFadden, ”Power system performance as affected by turbine-generator controls response during frequency disturbances”, IEEE Transactions on Power Apparatus and Systems, Vol. 100, No. 5, pp. 2486-2493, 1981.

[3] A. Capasso and E. Mariani, ”Influence of generator capability curves representation on system voltage and reactive power control studies”, IEEE Transactions on Power Apparatus and Systems, Vol. 97, No. 4, pp. 1036-1041, 1978.

[4] Cigré, “Criteria and countermeasures for voltage collapse”, TF 38-02-12, Brochure 101, 1995.

[5] G. leDous, J. Daalder and D. Karlsson, “Dynamic load measurements in a 2000 MW system in order to operate power systems closer to their limits”, Preferential subject 39:1, Cigré, 1998.

[6] T. W. Eberly and R. C. Schaefer, ”Minimum/Maximum excitation limiter performance for small generation”, IEEE Transactions on Energy Conversion, Vol. 10, No. 4, pp. 714-721, 1995.

[7] G. K. Girgis and H. D. Vu, ”Verification of limiter performance in modern excitation control systems”, IEEE Transactions on Energy Conversion, Vol. 10, No.3, pp. 538-542, 1995.

[8] IEEE Power System Relaying Committee, “Voltage Collapse Mitigation”, “Working Group Web Pages, Working Group K12 information” http://www.rt66.com/~w5sr/psrc.html, Final version, December 1996.

[9] IEEE Task force on Excitation Limiters, ”Recommended Models for Overexcitation Limiting Devices”, IEEE Transactions on Energy Conversion, Vol. 10, No. 4, pp. 706-713, 1995.

[10] P. Kessel and H. Glavitsch, “Estimating the Voltage Stability of a Power System”, IEEE Transactions on Power Delivery, Vol. 1, No. 3, pp. 346-354, 1986.

[11] P. Kundur, “Power System Stability and Control”, ISBN 0-07-035958-X, McGraw-Hill, 1994.

[12] P. Kundur, K. Morison and B. Gao, “Practical considerations in voltage stability assessment”, International Journal of Electrical Power & Energy Systems, Vol. 15, No. 4, pp. 205-215, 1993.

[13] R. Lind and D. Karlsson, “Distribution system modelling for voltage stability studies”, Stockholm Power Tech, SPT PS 07-05-0357, pp. 215-220, 1995.

[14] K. Lindén and I. Segerqvist, “Modelling of Load Devices and Studying Load/System Characteristics”, Technical report No. 131L, ISBN 91-7197-038-X, Chalmers University of Technology, Sweden, 1993.

[15] P.-A. Löf, G. Andersson and D. J. Hill, “Voltage Dependent Reactive Power Limits for Voltage Stability Studies”, IEEE Transactions on Power Systems, Vol. 10, No. 1, pp. 220-228, 1995.

[16] N. E. Nilsson and J. Mercurio, “Synchronous generator capability curve testing and evaluation”, IEEE Transactions on Power Delivery, Vol. 9, No. 1, pp. 414-424, 1994.

[17] A. Panvini and T. J. John, ”Field assessment of generators reactive capability”, IEEE Transactions on Power Systems, Vol. 10, No. 1, pp. 288-296, 1995.

[18] R. H. Regan and K. Wakeley, ”Rotor monitoring and protection for large generators”, Electrical Machines and Drives, IEE Conference Publication No. 412, pp. 203-207, 1995.

[19] Ph. Sattler, ”Konzepte zur Generatorseitigen Spannungs-Blindleistungs Begrenzung”, VDI Berichte 801, pp.143-161, 1990.

[20] K. N. Srivastava and S. C. Srivastava, “Effect of generation rescheduling on voltage stability margin”, International Journal of Electrical Power & Energy Systems, Vol. 19, No. 1, pp. 11-17, 1997.

[21] C. Taylor, ”Power System Voltage Stability”, ISBN 0-07-063184-0, McGraw-Hill, 1994.

[22] H. Termuehlen and G. Gartner, ”Sustained fast turbine-generator load response in fossil-fueled power plants”, IEEE Transactions on Power Apparatus and Systems, Vol. 100, No. 5, pp. 2486-2493, 1981.

[23] T. Tran-Quoc, L. Pierrat, “A strategy for prevention of voltage instability by generation dispatch”, SPT PS 06-05-0455, Stockholm Power Tech, Sweden, pp. 179-183, 1995.

[24] K. Walve, “Understanding dynamics and design of power systems”, Svenska Kraftnät, Stockholm, January 1994.

[25] Western System Coordinating Council, “Disturbance Report for the Power System Outage that Occurred on the Western Interconnection, August 10, 1996”, Approved by the WSCC Operation Committee on October 18, 1996.

Chapter 4 Conclusions

A necessary requirement when making computer simulations is to use accurate models and enter correct parameters into these models. The user must also understand the general behaviour of the system in order to verify and validate the results. The modeling aspects are illustrated through the detailed implementation of several different components in this dissertation. Field and armature current limiters, dynamic load model and on-load tap changer relays all show more aspects than a “straightforward” model would give. Armature current limiter models must prohibit the transition from overmagnetization to undermagnetization and tap changer relays may have a completely different response time depending on the characteristic chosen. The choice between constant or inverse time operation and constant or pulsed control signal can give a variation in response time of several multiples for the same time setting on the tap changer relay. Given also the fact that the impact of a tap changer operation on the system depends to a high degree on the relative position of the transformer in the grid, the response to a disturbance may vary considerably. Tap changing actions electrically close to generators are better from a voltage stability point of view than tap changings close to the load demand. Without a general understanding of such phenomena on their own some simulation results would be difficult to understand.

All papers presented in this dissertation conclude to the importance of the load behaviour and the necessity to implement accurate load models to achieve proper quantitative results. The interaction between an armature current limited generator and a load demand having a voltage dependence around constant current can be used as an example. The outcome is very sensitive to the load behaviour and a voltage dependence slightly larger than constant current will give a stable case whereas a collapse will occur for a load dependence slightly less than constant current. Tap changer relay operations and load demand also show a considerable coupling and may interact in such a way that an overshoot in power demand occurs. Since the system is already stressed due to the initial voltage drop this overshoot in power demand can make a considerable burden on the system.

It is also shown that the field and armature current limiters do not work independently. A voltage stressed situation where the generator is not able to keep the voltage from decreasing due to a field current limitation will eventually lead to the maximum steady state armature current where an armature current limiter operation/overcurrent relay tripping may result. Both kind of limiters have a major impact on system stability and it is important to try to avoid their activation.

Given the major influence that the two different current limiters have on voltage stability the question can be raised on how to alleviate their influence. The way they interact with the system indicates that a limitation of reactive power from the generator is severe and therefore a study was made of how active power changes could relieve a stressed system. A small system with models of current limiters, dynamic load and tap changer operation was used to investigate 'Active Power Rescheduling' during current limitation. By dividing the operation of the system into different 'modes' corresponding to different combinations of activated current limiters, the system capability in the load point can be calculated. Already for two generators the system capability becomes a complex function of these modes.

It was found that the local system capability depends on the active power production during both field and armature current limitation in the local generator. The results show that the system benefits from a local active power *decrease* when the local generator is **armature current limited** i.e. when extra reactive power becomes available and is injected into the system. For **field current limiting operation** an *increase* of active power is beneficial. Sometimes these reschedulings can result in a situation where the generator becomes both field and armature current limited i.e. the generator is then fully loaded.

The local system capability characteristics in case of armature current limitation in the local generator shows a maximum. The question can then be stated as follows: Which power factor should a constant current source have to support the system capability as much as possible? The answer shows a relation between the power factor and the power angle (the angle between the voltages) to the remote generation area.

The derived system capability is based on a static analysis. In order to investigate the dynamic response of the system to an active power rescheduling a dynamic load fed through a tap changing transformer was simulated and analysed for a particular case when the local generator was armature current limited. It was found that active power rescheduling changes the dynamic response of this on-load tap changer/dynamic load combination. The energy deficit in the load demand that occurs after a contingency was decreased and the load excess region increased in the state space plane when an active power rescheduling was performed. This has two advantages. The power overshoot in load demand would not be as severe as without an active power rescheduling and the region in the state space plane where the system has a possibility to recover to a steady state operating point is increased.

A simple controller was implemented which took advantage of the derived relation for the maximum system capability and was found to be very efficient in the small system.

More complex combinations of current limiter operations were then investigated and it was found that local active power rescheduling also can support other generators further away. A rather uncommon situation was shown where a voltage *decrease* actually led to a stable case. The reason for this was a starting operating point on the abnormal side of the maximum of the system capability curve. The simulation showed that the system can make use of the active power rescheduling also going in the opposite direction.

Given the promising results in the small system a large system was simulated. A simple Active Power Rescheduler, APR, was implemented operating during armature current limiter operation and the outcome of a number of disturbances was analysed.

One empirically learned experience in the larger system was that a rather slow and small APR was most beneficial for a broader spectrum of contingencies. This is attractive from the view of power plant operation where slow active power changes appear to be more easily incorporated but this also restricts the type of contingencies which can be alleviated with APR to longer term voltage instabilities.

It was shown that the APR can be used either to increase the transmitted power over a critical transfer corridor or prolong the time before collapse for the same active power transfer. A combination of these benefits can also be achieved. Two kinds of load models were used and the static one was found to be generally more stable than the dynamic one. The time to collapse was also generally longer for the simulations with the static load model.

The next remedial action studied was to exploit the generators field winding thermal capacity by including on-line temperature measurements. This will allow the generator to feed more reactive power into the grid and keep voltages higher until the field winding reaches its maximum temperature. The benefits that could be gained when fully utilizing the thermal capacity of the generator are dependant on the pre-disturbance loading of the generator and the thermal time constants of the rotor. Since many voltage collapses start with a contingency not necessarily occurring at maximum generator power output there will be cases where this extra capacity is available. This is a limited resource and measures must be taken to cover this fact. One way may be to use communication to neighbouring ‘voltage resources’ and inform that the voltage is ‘boosted’ and that an overloading will occur shortly. Today a field current limitation will show up as a voltage depression around the generator which will inform the surrounding area about the critical situation through the grid voltage. As before, a voltage drop will increase the energy deficit due to the load/tap changer response and also decrease the load excess region.

A general observation made during this study is how important the regular maintenance and tuning of the *existing* generator equipment are. Defects and anomalies in the field current protection/control have contributed to several voltage instability problems.

Chapter 5 Future work

The generator is one of the most controlled and protected components in a power system. It is connected mechanically through a shaft to a thermal-mechanical system which is very complex regarding operation, control and protection. On the other side the generator is a part of the power system which also is quite complex and not fully understood on its own. To propose changes in the control of the generator is therefore some challenge; on the other hand the advantages obtained from a coordinated analysis can become substantial.

A coordinated field-and-armature limiter is proposed which is a part of the normal generator controller responsible for voltage regulation and other features as power system stabilization. The limiter has inputs such as the temperature of the windings and the ”mode of operation” of generators which are, electrically seen, neighbours. Another input is information about the active power transmission through nearby located ”critical tie-line sections”. As output signals the current limiter uses field voltage and mechanical power control. In case of a contingency which violates the capability of the generator the limiter evaluates the situation according to the following rules:

- All thermal capacity in the rotor and stator should, if necessary, be used within a certain time (say one minute) after which only maximum stationary levels of the violating current (and hence winding temperature) are allowed.
- If possible, power plant active power production should be increased until it reaches either armature current limit or maximum power plant production.
- Power plant active power production should be decreased either until it runs the risk of becoming field current limited; maximum system capability is reached; or the angle over the transmission tie-line section becomes too large initiating power oscillations.
- The limiter should inform its generator neighbours and if required, apply for support. Both active and reactive power might be supplied by the neighbours if they are not under any kind of restriction. This will prevent that an overloaded generator will keep voltage levels within its dead band until its resources are completely exhausted without its neighbours being aware of this. The communication does not need to be fast. Regular Supervisory Control And Data

Acquisition/Energy Management Systems (SCADA/EMS) are probably sufficient communication channels since the likelihood of both current limitation and an inoperable SCADA system is relatively low. The neighbours must naturally be equipped with similar controllers and have the potential of rescheduling power.

- The limiter should make sure that input signals from power system stabilizers are fed through the complete control system in a proper way. It is no use saving the system from a voltage collapse if a power oscillation arises causing a collapse due to ‘blocked’ power system stabilizers when needed most in a voltage weak situation. Since this proposal already contains active power control during current limitation, this feature may also be used for damping (the slowest) power oscillations. This leads into a parallel and completely different research area [e.g. 1]. Maybe the combined benefits can motivate the implementation of new control equipment including active power control.

Many interesting aspects of this coordinated limiter are still to be investigated. In particular is the phase when the thermal capacity is used up interesting. A decreased voltage will relieve the system load demand initially but the system will, as load recovery starts and continues, be more and more strengthened by a high voltage. One implication which needs more attention are those generators with a high synchronous reactance and a relatively low degree of saturation as discussed in Section 3.4. For example, will the system response change when a field current limited generator works ‘below’ Point of Maximum Loadability?

The restoration process after a voltage collapse is, at least in Sweden, dependent on the success or failure of changing to household operation of the major power plants. Assuming that a generator becomes armature current limited, can an Active Power Rescheduler be tuned in such a way that the probability of a successful household operation increases? An effective APR-function will keep the local voltage higher and is able to decrease the steam production somewhat. The higher voltage level will decrease the risk of a generator tripping or that auxiliary equipment within the plant stalls or switches off due to low voltage. A reduced steam production will decrease the turbine overspeed in case of a grid isolation and hence lower the risk of an emergency shut down. Both these aspects are worth considering in a future work.

Depending on the future of electrical energy storage such as Superconducting Magnetic Energy Storages or fuel cells some analysis presented here may be beneficial to implement in Flexible AC Transmission System-devices. In particular is an armature current limit and maximum rated current for semiconductor valves comparable. In situations when the output current of such valve is limited by its maximum level the controller has to choose the mixture of active or reactive power supplied to the system. This is roughly the same problem as presented here but probably with another time delay. Such devices may have a comparable small active power capability (small active power storage units will be the ones most likely to be available first) and hence working with rather low power factors. Situations will then occur when an active power increase will be beneficial for the system during maximum rated output current (cf. Figure C.6). Quite interesting system responses are in such cases ”forecasted” (cf. Figure C.12) during long term voltage instabilities.

The load model mostly used in this dissertation can be extended by taking the voltage dependency for lower voltages into account. Since the parameters used here are based on field measurements rather close to normal voltages the power demand will not be correctly represented during low voltage levels and during the fast voltage drop of a collapse.

The external system around a limited generator is in the small system represented as a Thevenin source in this dissertation. It is shown that the limiter operation depends somewhat on the Thevenin source. Reference [2] shows a way to estimate the voltage stability limit locally by means of the impedance in the Thevenin source. One could pose the question if the coordinated limiter proposed here can make use of the information gained from reference [2].

5.1 References

[1] A. M. Sharaf and T. T. Lie, “An artificial neural network coordinated excitation/governor controller for synchronous generators”, Electric Machines and Power Systems, Vol. 25, No. 1, pp. 1-14, 1997.

[2] K. Vu, M. M. Begovic, D. Novosel and M. M. Saha, “Use of Local Measurements to Estimate Voltage-Stability Margin”, 20th Int. Conf. on Power Industry Computer Applications, pp. 318 -323, 1997.

Paper A Voltage stability studies with PSS/E

Paper presented at “Bulk Power System Voltage Phenomena III, Voltage Stability, Security & Control”, 1994.

Abstract

A study of simulations of voltage stability phenomena using the PSS/E program (Power System Simulator) is presented. The objective is to explain how the interaction of different components, such as on-load tap changers, field and armature current limiters and dynamic loads, can endanger the voltage stability of a system. Special attention is given to the user-written models that have been implemented in PSS/E.

A computer model has been designed for a voltage regulator combined with field and armature current limiters. This combination is used for nuclear power plant generators in Sweden. Two different models for an on-load tap changer control unit commonly used have also been implemented in the program. The dynamic load model with load recovery is based on field measurements. Furthermore, some problems in using simulation tools are discussed, as well as the importance of parameter determination for some of the models implemented. The simulations highlight the importance of the generator current limiter and its interaction with the on-load tap changer and the type of load model chosen.

Keywords

Voltage stability, simulation, dynamic load model, on-load tap changer, armature current limiter.

A.1 Introduction

The problem of voltage stability and voltage collapse has been under consideration for 10 to 20 years. The approach to the phenomenon ranges from power system recording analyses, simulations of voltage collapses and incidents experienced by the power companies, to thorough theoretical mathematical studies. Researchers in the field have not yet been able to agree upon definitions of voltage collapse and voltage stability. Concordia defines voltage stability in a straightforward way, using words well known to utility companies: "...in terms of the ability to maintain voltage so that when load is increased, load power will increase, and so that both the power and voltage are controllable" [A.4]. Kwatny, on the other hand, uses static bifurcation theory for voltage collapse definition [A.12]. The authorities in this field also continue to discuss whether the voltage collapse and stability phenomenon is a static or a dynamic problem [A.15]. Researchers in close co-operation with power companies often view voltage collapse as a static problem, since it can be analysed with ordinary load flow programs. In the academic world, where the bifurcation theory is predominant, voltage collapse is regarded as a dynamic problem.

In addition to study of the phenomenon of voltage stability and collapse itself, stability margins and indices have been defined and methods to derive such quantities have been developed [A.13]. Some authors in the field use simulation in order to include the dynamics of load, tap changer and generator reactive power capacity limits in the voltage collapse studies [A.5, A.16]. A good survey of the voltage stability discipline can be found in reference [A.9], where both analytical tools and industrial experience are presented.

A voltage collapse can be initiated by either a primary fault or an unexpected load demand increase, in combination with insufficient reactive power reserves or transmission capacity. In order to avoid collapse, a detailed knowledge of the reactive power capacity in stressful situations, for large generators close to load centres, is essential.

The aim of this report is to provide models for load devices, on-load tap changer control systems and generator reactive power output capacity limits, based on data and experiments, and to compare our models with previous ones in simulation technique for voltage stability studies. The methods and models used in the report are designed to be easily accepted, both within the power industry and in the academic world. The simulation technique is well accepted in the power industry, and many of the dramatic simplifications sometimes necessary for analytical studies are avoided. Furthermore, well established and tested programs can be used to hold and solve the load flow case.

We believe that more attention should be directed to the importance of load dynamics, on-load tap changer control dynamics and generator limits in research on voltage collapse. In the variety of papers already published, detailed transfer limits, stability indices, etc., have been derived, while omitting, or only roughly modelling such important aspects as load recovery, tap-changer control systems and generator field and armature current limiters. While there is value in developing advanced mathematical tools based on simple system component models, we have to keep in mind that the voltage levels in the post-fault load flow case and the static nose curves (P/V and Q/V curves) are still used as criteria for power transfer limit settings within many power companies. To be accepted by power companies and used as practical tools for system design and operation, research results must be related to the data and methods used within the power industry today. The results reported here are intended to be suitable for use as refined methods for voltage collapse studies within power companies.

A.2 Computer model implementation

In order to simulate the dynamic events that cause voltage instability, it is important to know how to specify relevant models of the equipment that affects the long-term voltage stability. A survey of components affecting the long-term voltage stability is given in [A.3]. It is also important to balance sufficient accuracy in the models against unreasonably long simulating time for large power systems. The test systems that have been used in this paper include dynamic load models, generator voltage controllers with field and armature current limiters, and on-load tap changing transformers. These models are all based on field and laboratory measurements.

A.2.1 Dynamic load model

The dynamic model proposed by Karlsson [A.10] is a special case of a dynamic load model given by Hill [A.8]. The model implemented is described by the following equations:

$$T_{pr}\frac{dP_r}{dt} + P_r = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \qquad \text{(A.1)}$$

$$P_m = P_r + P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{A.2}$$

where

V = supplying voltage [kV],
V_0 = pre-fault value of supplying voltage [kV],
P_0 = active power consumption at pre-fault voltage [MW],
P_m = active power consumption model [MW],
P_r = active power recovery [MW],
α_s = steady state active load-voltage dependence,
α_t = transient active load-voltage dependence, and
T_{pr} = active load recovery time constant [s].

$$T_{qr}\frac{dQ_r}{dt} + Q_r = Q_0\left(\frac{V}{V_0}\right)^{\beta_s} - Q_0\left(\frac{V}{V_0}\right)^{\beta_t} \tag{A.3}$$

$$Q_m = Q_r + Q_0\left(\frac{V}{V_0}\right)^{\beta_t} \tag{A.4}$$

where

Q_0 = reactive power consumption at pre-fault voltage [Mvar],
Q_m = reactive power consumption model [Mvar],
Q_r = reactive power recovery [Mvar],
β_s = steady state reactive load-voltage dependence,
β_t = transient reactive load-voltage dependence, and
T_{qr} = reactive load recovery time constant [s].

When there is a voltage drop of 5-10% on load nodes, field measurements show that α_t is around 2. This means that the transient behaviour of the load can be regarded as a constant impedance. In most of the measurements, α_s is well below 1, which indicates a changed voltage dependence for the active power, and the load characteristic tends to be more like constant power (figure A.1). The time constant T_{pr} for this changing phase is around some hundred seconds. This phenomenon has been explained by the power characteristic in electrical domestic heating [A.11].

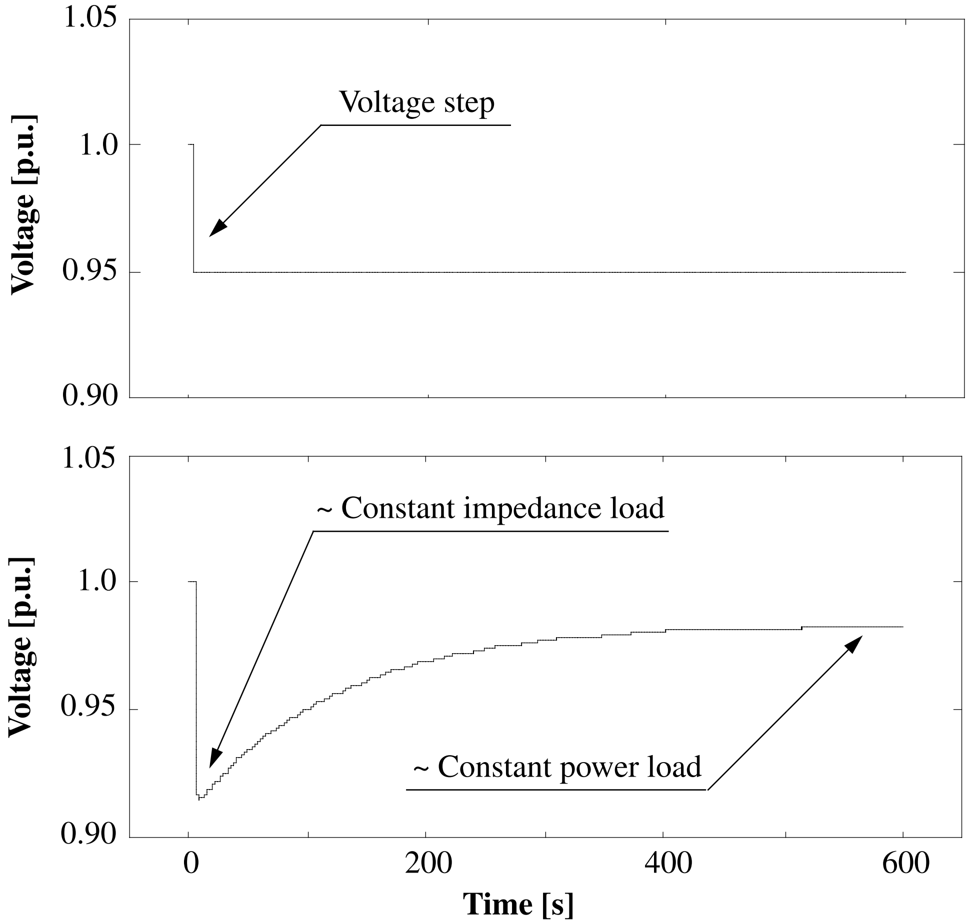

Figure A.1 The active power recovery caused by a voltage step.

An important experience when implementing the load model was finding that the voltage dependence had to be included during the iterations. Since the time step in the integration procedure is several thousand times smaller than the time constants in the dynamic model, the voltage dependence during load flow iterations was not taken into account in the beginning. This did not work well all the time; numerical instabilities occurred and it was necessary to expand the implementation to include voltage dependence during the load flow calculations, see figure A.2. A delay of one time step between the iterated voltage and the corresponding load demand was eliminated by the implementation.

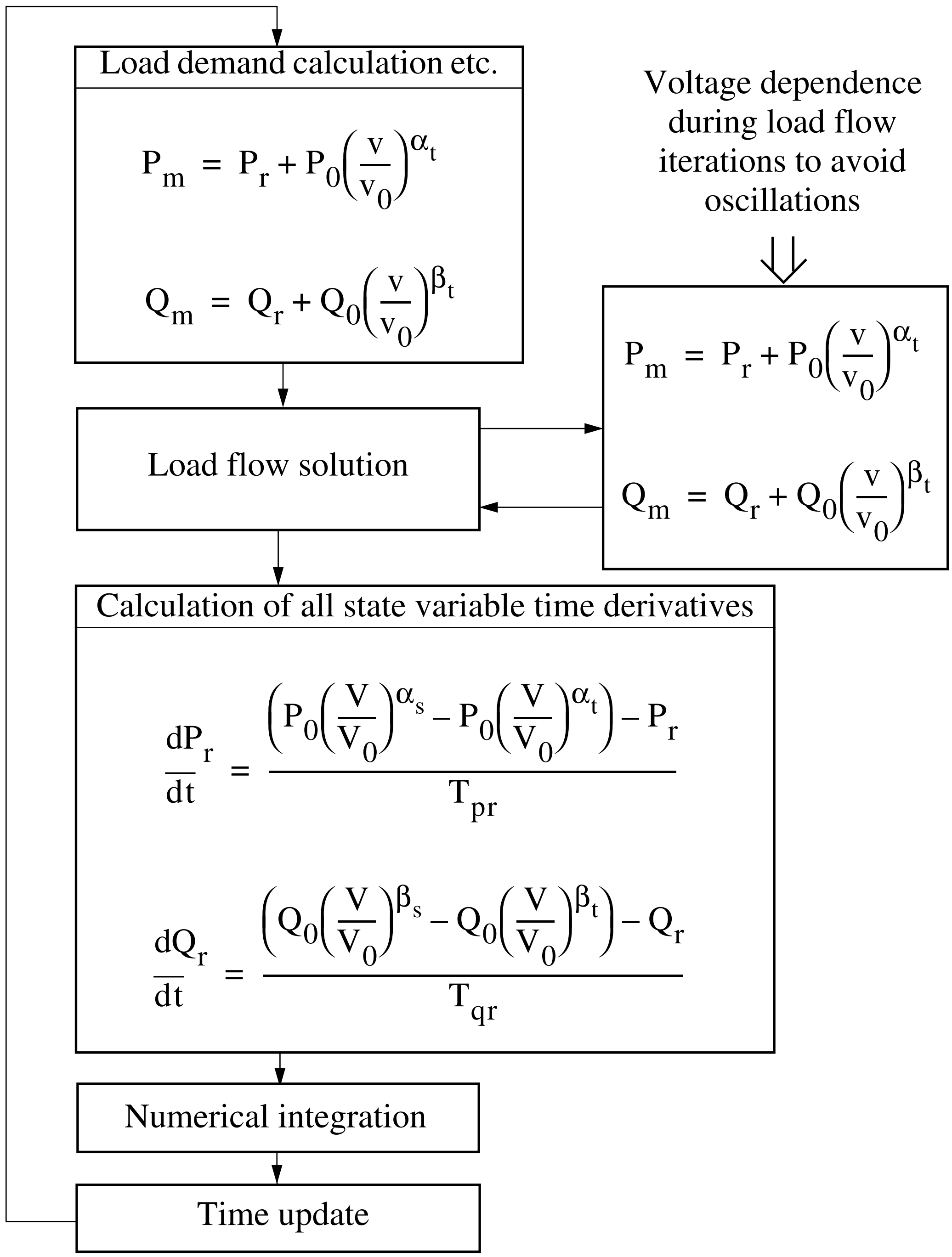

Figure A.2 The solution algorithm for the dynamic load.

A.2.2 Voltage regulator, including field and armature current limiters

A model program for the FREA[1] excitation system has been written, based on a graduation thesis [A.6] in which the dynamics of the system were measured and identified. The FREA system consists of different

1. Manufactured by ABB

units, among which the voltage regulator represents the basic one. The model of the FREA system used in the simulations contains two units, a basic one for voltage control, illustrated in figure A.3, and an another for field and armature current limitation, illustrated in figure A.4.

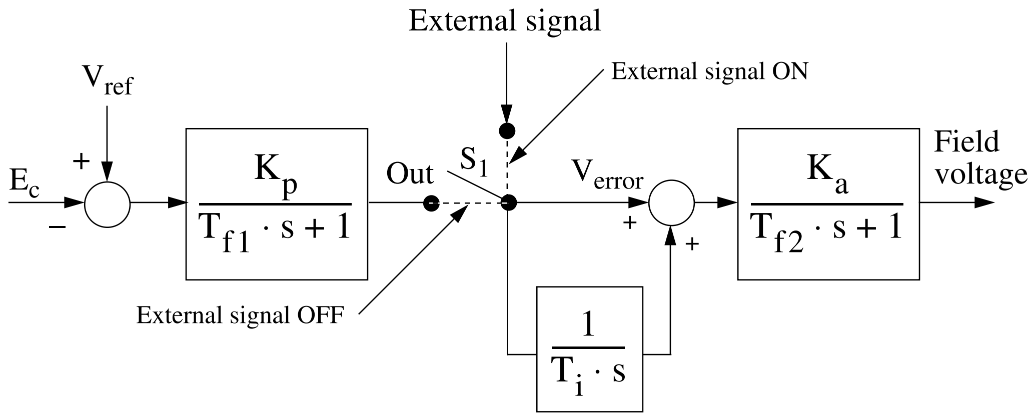

Figure A.3 Block diagram of the voltage regulator.

The external signal is the connection between the two units.

Typical parameters for the model are:

$K_p = 10\text{-}100$, $T_{f1} = 25$ ms, $T_i = 2\text{-}5$ s, $K_a = 1\text{-}40$ and $T_{f2} = 1\text{-}40$ ms.

Since the limitation of the field or the armature currents affect the reactive power generation, it is important to simulate these.

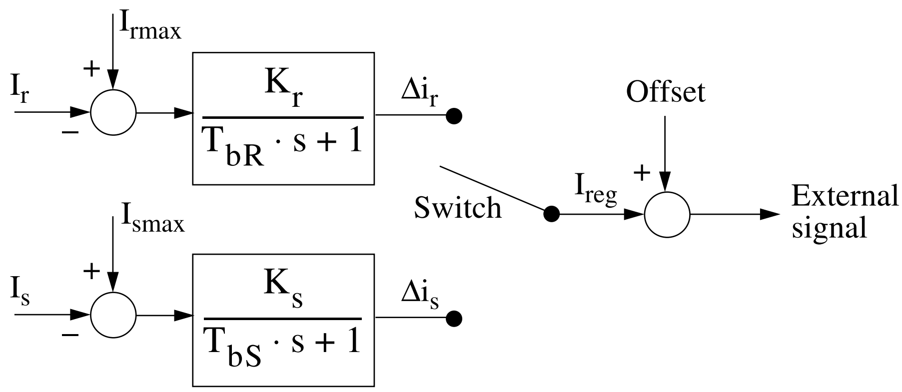

Figure A.4 Block diagram of the field and armature current limiters.

Typical parameters for the model are:

$K_r = 2–10$, $T_{bR} = 25$ ms, $T_{bS} = 25$ ms and $K_s = 2–10$.

Using the two units above provides a model with the following functions. The regulated field voltage is normally controlled by the difference signal V_{ref}-E_c. When one of the currents exceeds its permitted maximum, a timer that controls the switch S_1 starts and the current limiter takes control over the field voltage after a delay of t_1 seconds. The timer delay is a protection against undesired limiter functions i.e. short-circuits. When the timer value is greater than the delay time t_1, the limiter controls the field voltage instantaneously when an overcurrent occurs. This condition is maintained for at least t_2 seconds or until the timer is reset.

The two conditions that activate the current limiters are:

1. $I_s > I_{smax}$ or $I_r > I_{rmax} \Rightarrow$ timer starts, and
2. Timer value $> t_1$

The two conditions to reset the timer are:

1. $I_s < k^*I_{smax}$ and $I_r < k^*I_{rmax}$, and
2. Timer value $> t_2$

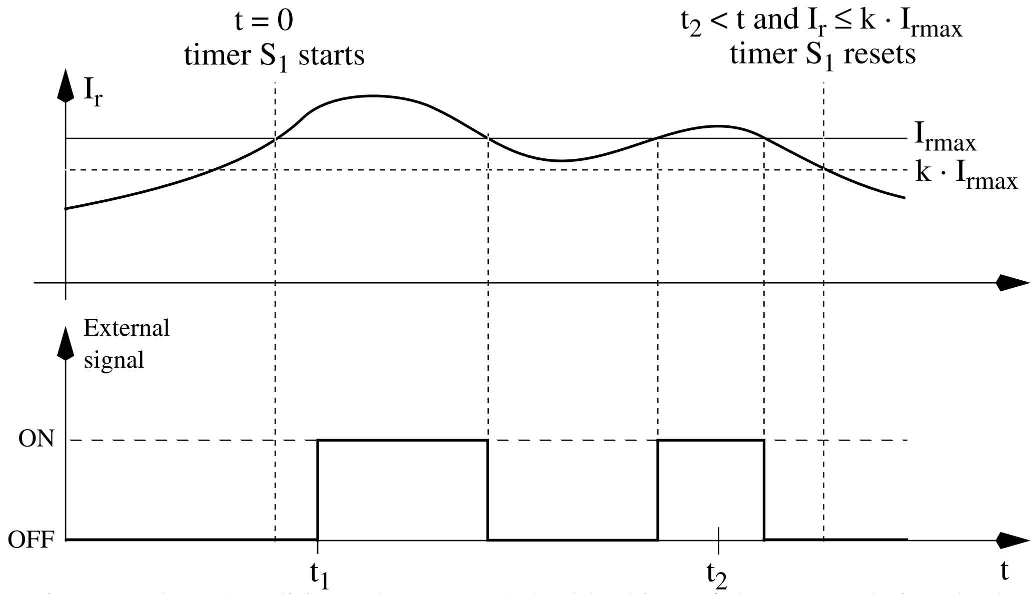

Figure A.5 Conditions that control the blocking of the external signal when $I_r > I_{rmax}$.

Figure A.5 illustrates the course of events when I_r is outside its limit. The sequence when I_s is outside its limits is analogous. When I_r and I_s are both outside their limits, the external signal will be assigned the largest value of $|\Delta i_r|$ and $|\Delta i_s|$.

Since the generator is permitted to operate only in an over-excited mode when the current limiters are active, it was necessary to implement a blocking signal. This signal also blocks the limiter when the terminal voltage falls below a permitted value. If this were not done, the simulations showed that the reactive power[1] changed sign and the generator became more and more underexcited. This blocking of the current limiter is important in order to prevent underexcitation and to avoid incorrect regulation. It was noticed that the blocking was the source of large torque steps in mechanical power. Consequently, it is unlikely that this running condition can be allowed for more than a short time.

A.2.3 On-load tap changer models

Two different types of OLTC-relays (On-Load Tap Changer) commonly used in the Swedish utility network have been modelled [A.1]. The purpose of these relays is to keep the secondary voltage within a specific dead band around a set-point value. The time from the point at which the voltage deviation exceeds the dead band until the relay triggers the tap changer mechanics on the transformer is called the functional time of the relay. This time interval depends mainly on two things: a) the basic setting time of the relay, chosen by the operator, and b) whether the relay is working in constant time mode or inverse time mode.

When the voltage deviation is large and one step change on the transformer is not sufficient to restore the voltage, then two other things must be taken into account. One is the time it takes to reenergize the tap changer mechanics after a changing. The other is whether the mechanics use a pulse or a constant control signal from the relay to trigger the tap changer. The effects of these conditions will be discussed later on. As the operation time needed for an energized tap changer to change step is within a few periods of the network frequency, it is considered negligible in these models. When the relays are exposed to a large voltage step (~several dead bands/second), the functional time becomes reduced for reasons unknown. More identification of the relays is necessary to model this phenomenon. The two relays modelled are the RXCE41[2] and RV902[3].

1. Originally wording: regulated field current.
2. Manufactured by ABB
3. Manufactured by Siemens

A.2.4 Description of the RXCE41

The RXCE41 relay has several settings that control its behaviour. On the front panel of the relay, the operator has to tune in one of the basic setting times: 15, 30, 60, 90 or 120 seconds. All actual time delays are scaled to one of these basic settings. Also the voltage set-point value and the deadband on the relay must be tuned. Finally, one of the four working modes of the relay has to be chosen.

I) Constant time mode and pulsed control signal

The functional time is independent of the amount of the voltage deviation. A short pulse of approximately 1 second triggers the tap changer, after which the relay is restarted. This means that this mode is the slowest way to restore voltage.

II) Constant time mode and constant control signal

The functional time is independent of the amount of the voltage deviation. If several tap changing steps are necessary to restore the voltage, the reenergizing time delay of the tap changer mechanics controls the speed with which the voltage is restored.

III) Inverse time mode and pulsed control signal

The functional time is dependent on the amount of the voltage deviation. When large deviations are present and several tap changing steps are necessary in order to restore the voltage, the time delay of the first steps is controlled by the delay in the transformer. When the voltage approaches the desired voltage, the time between tap changings is controlled by the relay. The functional time of the relay, in this mode, may be shorter than the reenergizing time of the tap changer mechanics. If this is so, trigger pulses will be lost due to the fact that the mechanics have no memory. Although the voltage will be restored (if possible without running the tap changer into an end stop), but it will take a longer time.

IV) Inverse time mode and constant control signal

The functional time is dependent on the amount of the voltage deviation. A larger deviation means a shorter functional time of the relay. If several tap changing steps are necessary, the steps following the first are controlled by the mechanical delay. This is the fastest way to restore the voltage deviation.

The different characteristics of these modes are shown in figure A.6. It can be seen from the figure that the relay settings affect the time constants of the voltage restoration. This is important when a dynamic load is connected to the transformer.

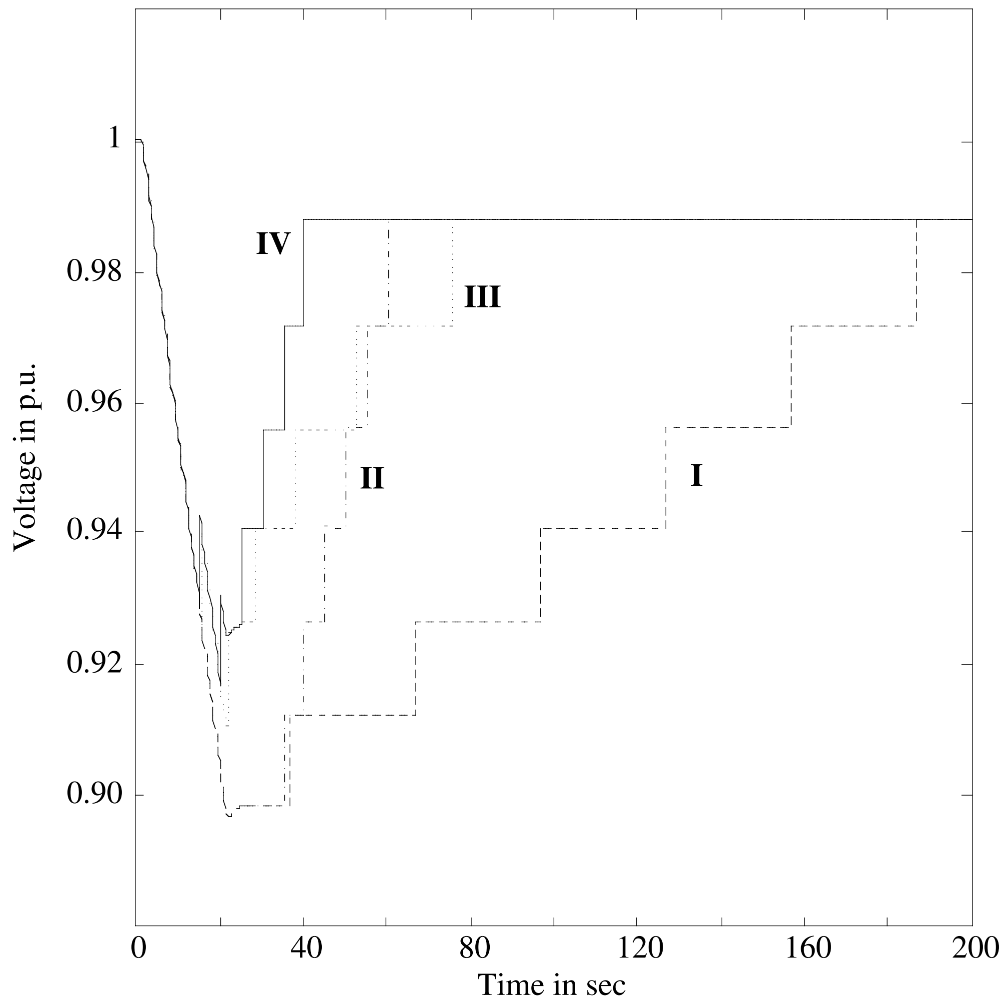

Figure A.6 Different modes for the RXCE41 relay.
I) Constant time mode and pulsed control signal,
II) Constant time mode and constant control signal,
III) Inverse time mode and pulsed control signal,
IV) Inverse time mode and constant control signal.

The relay timer is started when the voltage exceeds the dead band, and reset when the voltage deviation is less than the return ratio multiplied by the dead band. A hysteresis effect on the function of the relay is thus achieved.

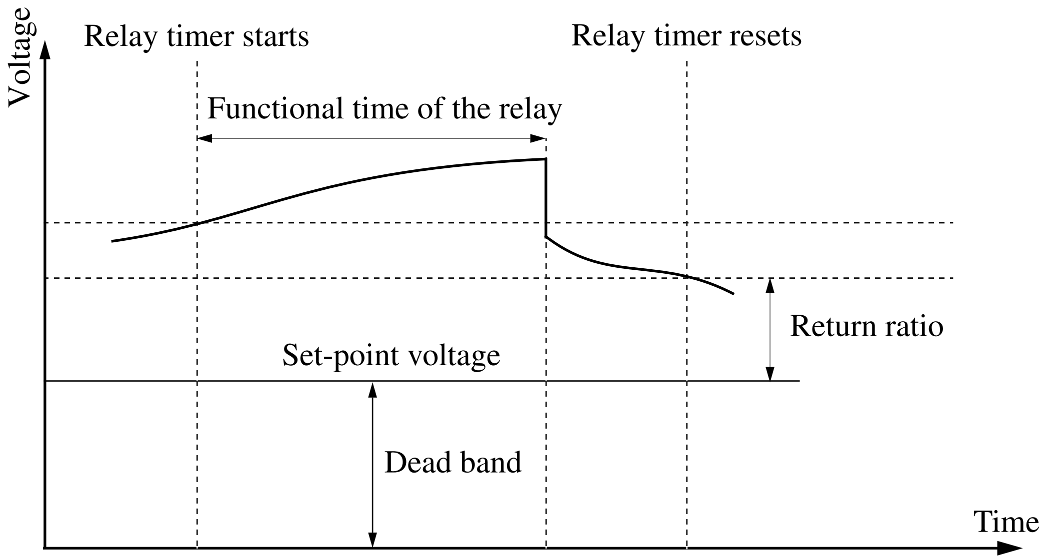

Figure A.7 One tap changing manoeuvre and the corresponding timer actions. The return ratio is around 0.75 times the deadband.

In inverse time mode, the deviation is not integrated in the usual sense. It is the voltage deviation that actually gives a functional time. If the relay time is greater than this functional time, the tap changer receives an order to change. The voltage deviation divided by the dead band is defined as δ and calculated for every time step. If δ is greater than 1, the voltage is outside the dead band and the relay timer is running. When δ is below the return ratio the timer is reset. The five different basic setting times offer different functional times, T_{ds}. If the operator has chosen the basic functional time ΔT to 15 seconds, the model calculates the functional time from

$$T_{ds} = (\Delta T - 2) \cdot e^{\frac{-(\delta - 1)}{1.25}} + 2 \qquad \text{(A.5)}$$

If the voltage is just outside the deadband (δ = 1), it will take 15 seconds for the relay to operate. Note that the formula is also valid for 1 > δ >'return ratio', when the timer is running. Therefore, it is possible to have quite long delays even in the inverted time mode. Similar formulas are valid for the other basic functional times.

The calculated functional times have a maximum discrepancy of 1.5 seconds (3 seconds for T = 120 s) between the model and the relay.

A.2.5 Description of the RV902

The RV902 relay works as an inverse time relay. It does not use a constant control signal to the tap changer. It has no timer-function and the voltage deviation is integrated all the time.

The model integrates the voltage deviation in the following way. First, δ is calculated as the deviation from the set-point value divided by the dead band. This gives a value greater than 1 (or less than -1) when the voltage is above (or under) the dead band. Two other constants are calculated,

$$m = 1.4 \cdot (\text{deadband}), \text{ and} \tag{A.6}$$

$$k = 1.014 \cdot (1 - e^{-(1.2 \cdot (\text{dead band})^{1.5})}) \tag{A.7}$$

and the model sums up the level with the following formulas:

$$\Delta\text{level} = (\delta - k \cdot \text{level}) \cdot m \cdot \frac{\text{time step}}{\text{delay time}} \tag{A.8}$$

$$\text{level} = \text{level} + \Delta\text{level} \tag{A.9}$$

When this level value is greater than the top level, the relay is functioning.The top level is usually chosen as 0.98. The function of the RV902 is similar to the RXCE41 when working in inversed time mode and pulsed control signal. Therefore the RV902 essentially works as in the III curve in figure A.6.

A.3 Simulations

The computer program used for all the dynamic simulations is the PSS/E program[1] which has the modelling capacity to account for the important dynamics of voltage stability analysis.

A.3.1 Description of the test systems

To demonstrate dynamic analysis techniques and to illustrate the basic phenomenon of voltage instability, two test systems were used. One was a very simple radial network, System 1, and the other a meshed

1. Manufactured by Power Technologies, Inc.

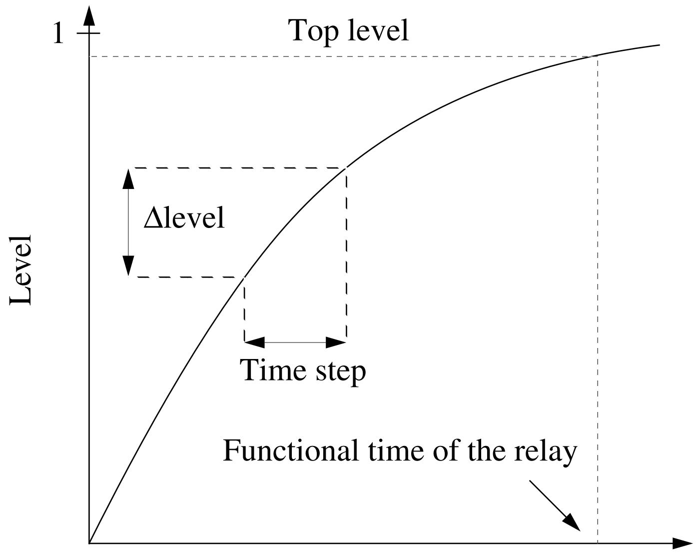

Figure A.8 The integration process for the RV902 relay.

27-node network, System 2. System 1, shown in figure A.9, consists of 4 buses, 4 branches and 1 generator. Most of the important factors influencing system voltage stability are readily identified in this simple system. One of the two lines in parallel has twice the reactance of the other, in order to show distinct results.

[redacted]

Figure A.9 Test system 1

System 2, shown in figure A.10, consists of 27 buses, 33 branches and 17 generators. The simulations conducted using this representation give a better picture of the dynamics of voltage stability in a large power system.

When the simulations are initiated, the parameters of the different components decide the behaviour of the system. The parameters used in the following simulations are taken from field measurements [A.10]. Some parameters for the small network are given in the appendix.

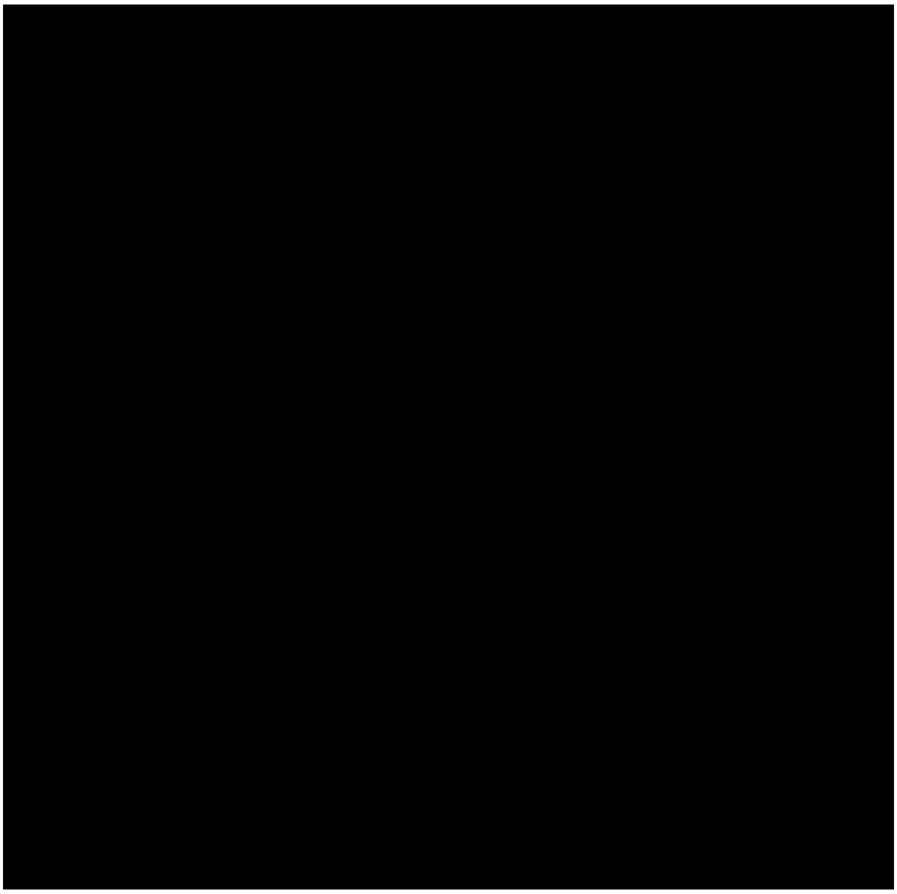

Figure A.10 Part of test system 2, showing where the simulated fault was applied. The X-marked lines and one of the two identical generators at node 427 were disconnected. The asterisk (*) marks a generator with a current limiter.

A.3.2 Response of the dynamic load including the OLTCs and current limiters: System 1

A disturbance initiated by opening the line with the lowest reactance was studied for two cases, A and B. The simulations were conducted for up to 350 seconds, using the models described for dynamic load, OLTC transformers and generator current limiters.

Case A demonstrates the combined effects of one OLTC and a dynamic load. In figure A.11 it can be seen that system voltage stability is maintained though there is a low voltage level on the primary side of the transformer at the load end. The voltage level at the secondary side is restored by the transformer in a few minutes. For every tap changing step, power demand increases, which gives a current increase on the load side of the transformer (figure A.12). This increased current is amplified on the generator side by the transformer tap changings and gives an increased voltage drop over the line.

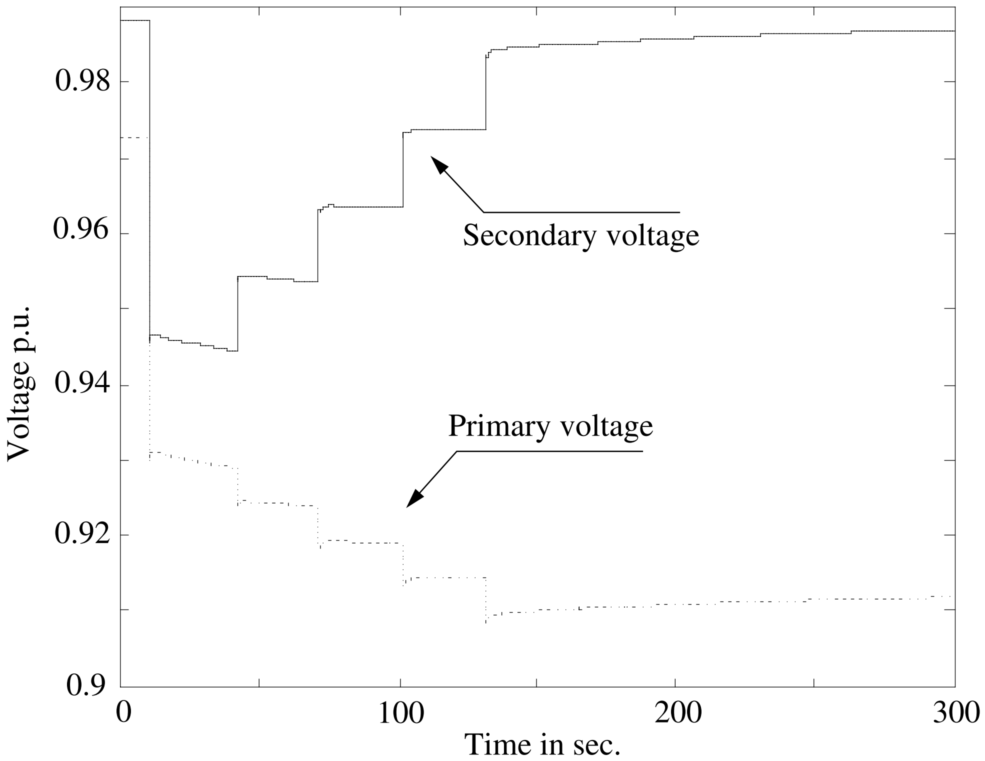

Figure A.11 Case A: The voltage on both sides of the transformer at the load end.

When the time needed to restore the voltage level by the regulating transformer and the time constant of the load recovery are in the same time domain, an overshoot in power demand can appear. In figure A.13 one can see the combination of these effects.

Case B is similar to case A except that the current is higher than the settings of the current limiter. The generator is limited in order to study the effects of the armature current limiter (figure A.14). It can be seen that as soon as the armature current limiter is operating the load voltage starts to decline, due to the tap changing manoeuvres and the armature current limitation. Since the delayed operation of the current limiters is usually a few seconds, just a short period of overcurrent is sufficient to activate one of them, which puts the system into a very critical situation.

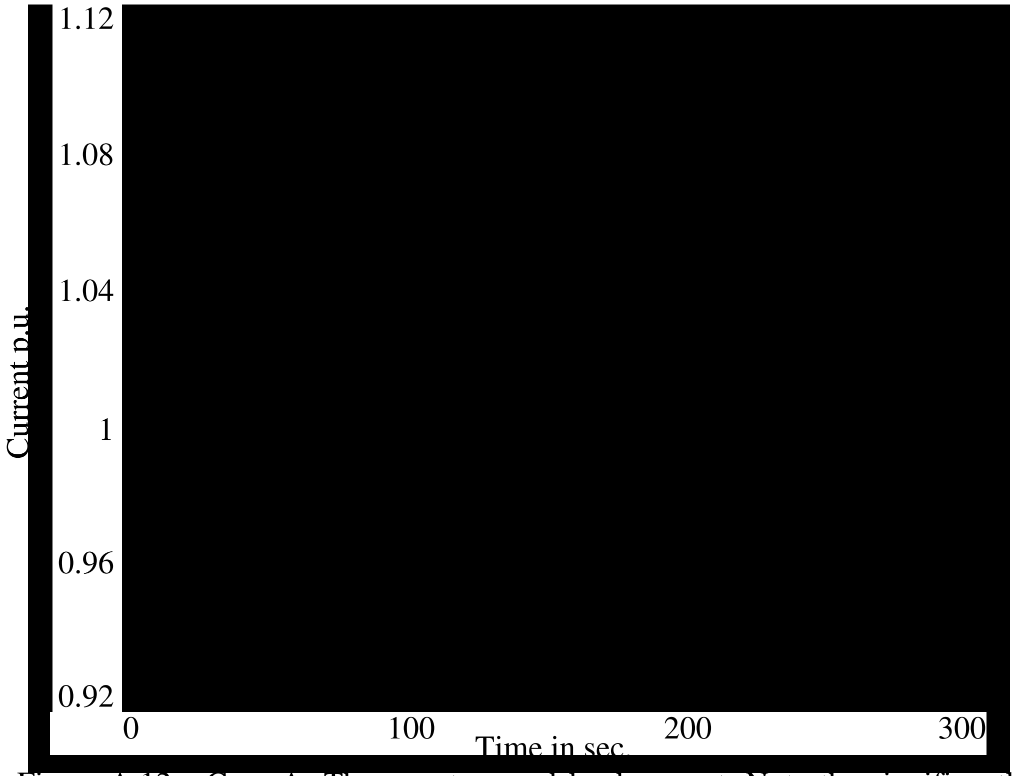

Figure A.12 Case A: The armature and load current. Note the significantly larger armature current during the recovery.

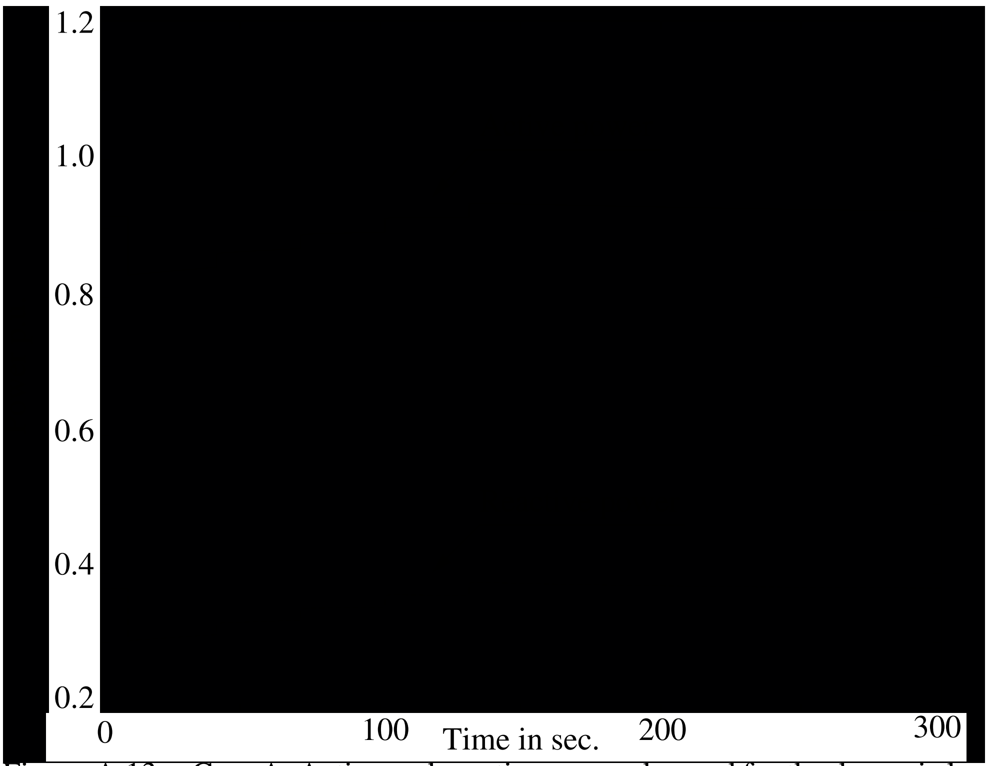

Figure A.13 Case A: Active and reactive power demand for the dynamic load.

When there is a disturbance in a large meshed network, this overshoot may not occur. Variation in the parameters of both transformers and loads spread out the overshoot. However, the generator current is increased due to the tap changers and load recovery, and this can, in a system under stress, cause the limiter to activate. The outcome of the current limiter action depends on the generator size and the network around the generator. An example of a collapse where the current limiters had a major impact is the French collapse of 1987 [A.7]. The importance of the current limiters is also mentioned in [A.3].

For a network without load recovery, one could get the effects described above from several levels of voltage regulating transformers, working unselectively. This could be the source of large armature currents, when a voltage disturbance is not restored sufficiently fast by the transformers near the origin of the disturbance.

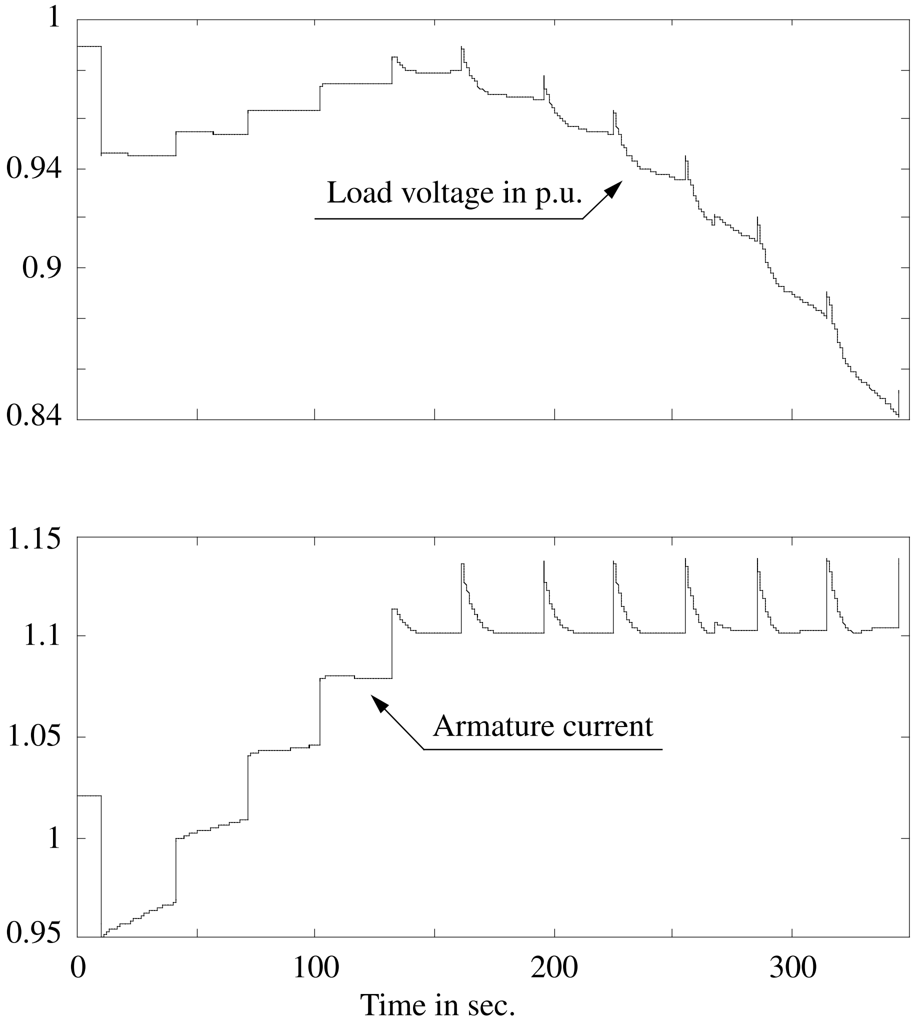

Figure A.14 Case B: Voltage and armature current where the current is limited to 1.1 p.u. It can be seen that the tap changer tries to restore the voltage while the current limiter decreases the current within a few seconds to the limiting value.

A.3.3 The importance of the load model chosen: System 1

In the event of a disturbance, power systems, depending on their load representation, can respond with completely different characteristics.

The following simulations, on System 1, illustrate the statement above. The limiting factor in these simulations is the armature current limiter. The system is disturbed by a 5% voltage step down on the generator set-point (i.e. disconnecting reactive support at the generation end). Figure A.15 shows four simulations with different load models; in figure A.16 there are the same simulations with the OLTC transformer relay at the load end activated. After the disturbance, the small system is not able to supply power to the constant power model at all (curve a in figure A.15). There is no stable operating point for the voltage. As the voltage decreases, the current would increase if it were not prevented form doing so by the current limiter.

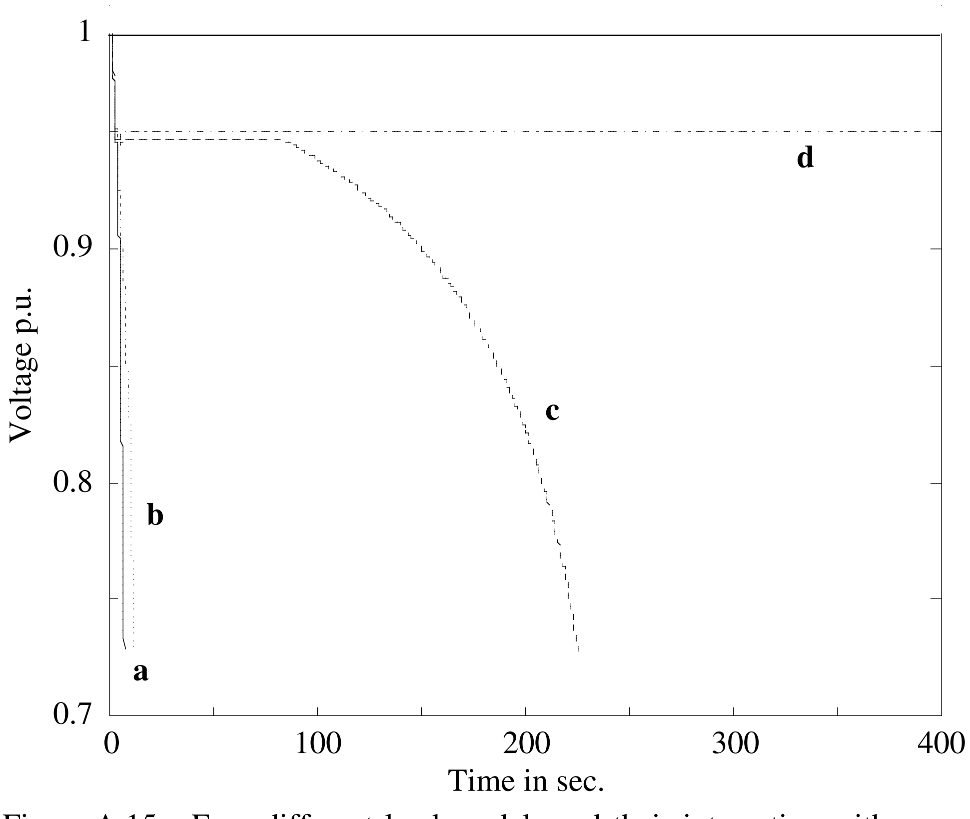

Figure A.15 Four different load models and their interaction with a current limited generator. The reactive power demand is independent of the voltage in simulations a, b and d.
a) Constant power model for P.
b) $P=P_0 \cdot (V/V_0)^{0.8}$
c) A dynamic load model according to Section A.2.1
d) Constant impedance model for active power

If the active power demand is nearly proportional to the constant current, the system responds nearly the same way (b in figure A.15). Curve d shows that when the load is more voltage dependent, the system is stable. With this model, current demand decreases when the voltage decreases and the current limiter is not activated. Thus, a stable working point can be found.

The dynamic load model, described in Section A.2.1, has two voltage phases in time (curve c in figure A.15). At first, the load is principally a constant impedance and follows the d curve. With time, the load recovers (figure A.1) and becomes more like a constant power load. The voltage starts to decline as for curve a and b in figure A.15. Neither of the three static load models (a, b and d), could be used to emulate the behaviour of the field measured dynamic load model.

One can also see in figure A.16 that the transformer actions increase the speed of the voltage decline. All of the models chosen have an unstable voltage when the tap changer of the transformer starts to restore the voltage.

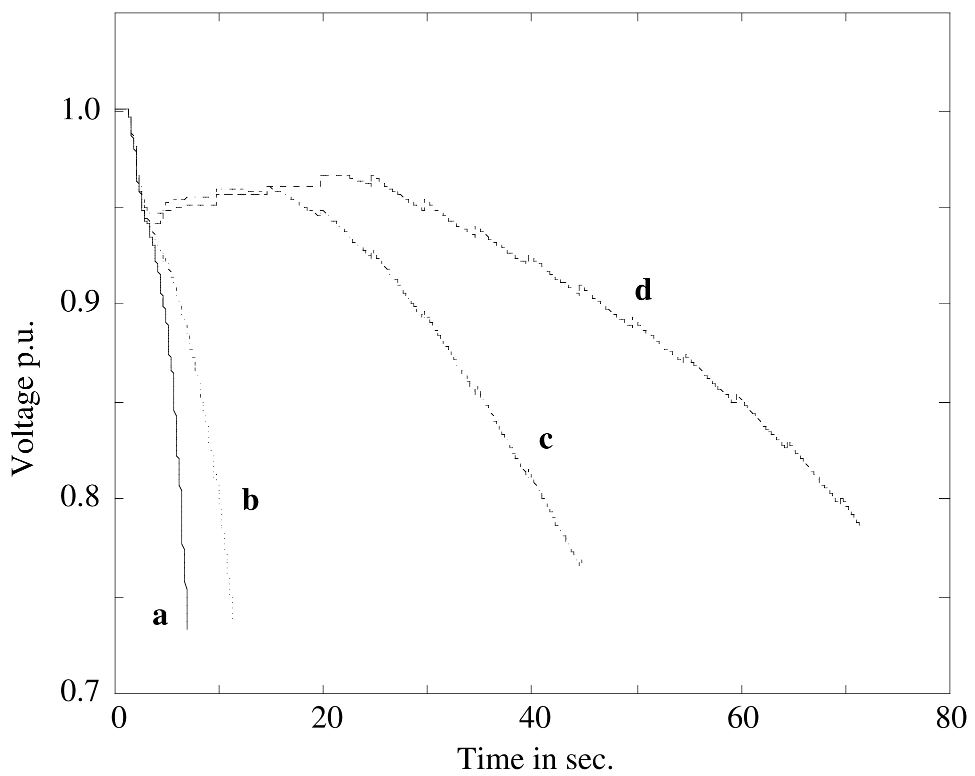

Figure A.16 The same load models as in figure A.15 but with one OLTC relay active. Note the shorter time scale. The tap changings accelerate the voltage decline.

If the transformer is omitted in order to decrease the computer simulation times and the constant power load is used with the motivation of restoring the voltage, the result could be a too pessimistic simulation (curve a). If a load model that is proportional to the voltage squared is used, a completely different response is possible (curve d). By choosing models that lie between a and d, a simulation of the voltage somewhere between these could be utilized.

A.3.4 Response of dynamic loads including OLTCs and current limiters: System 2

To demonstrate the long term voltage phenomenon in a large power system, a short-circuit causing two lines and one generator to trip was simulated (figure A.10). Two cases were studied: C and D. In case C all the tap changers in the system were locked and in case D they were active.

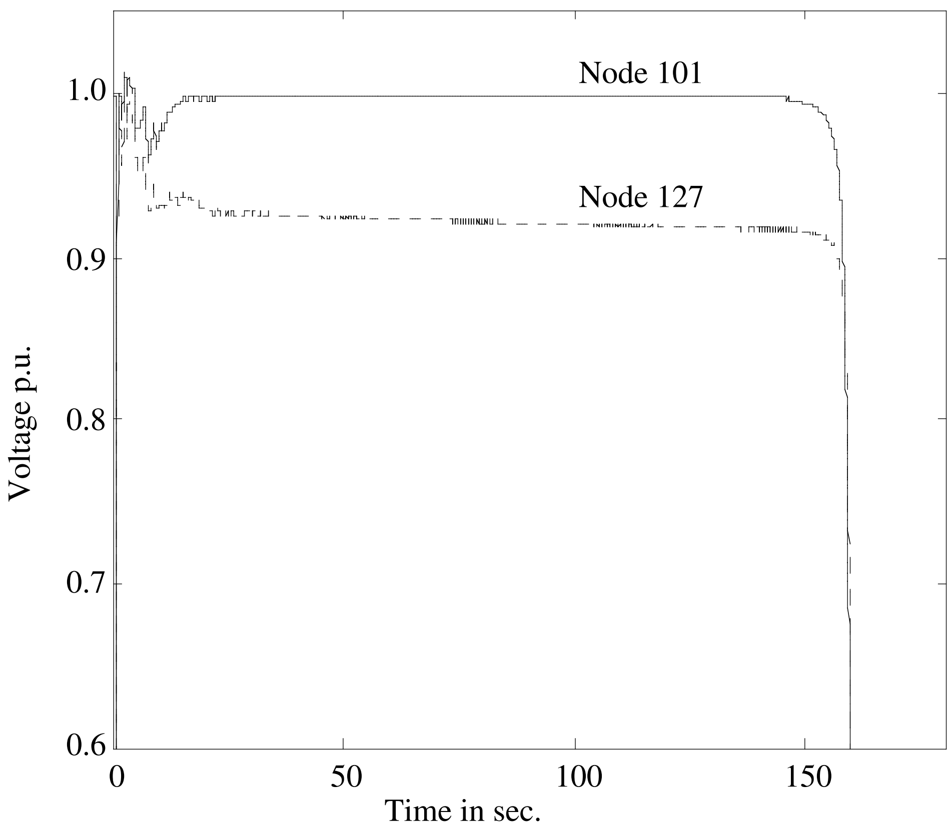

Figure A.17 Voltages in System 2. After the short-circuit the voltage is rather stable in node 101 but it slowly drops due to load recovery in node 127. After 160 seconds the voltage collapses.

Case C: When the short-circuit occurs, the generators with armature current limiters are activated and they continue to operate during the whole simulation. After the transient oscillations have died out, the delayed operation of the armature current limiters decrease the voltage. While the voltage level becomes acceptable in node 101, it is low in node 127 and slowly decreasing. After 160 seconds the load recovery in the nodes with depressed voltages pulls the voltages down, i.e. the dynamic in load characteristics causes the system to collapse. This simulation is analogoues to curve c in figure A.15.

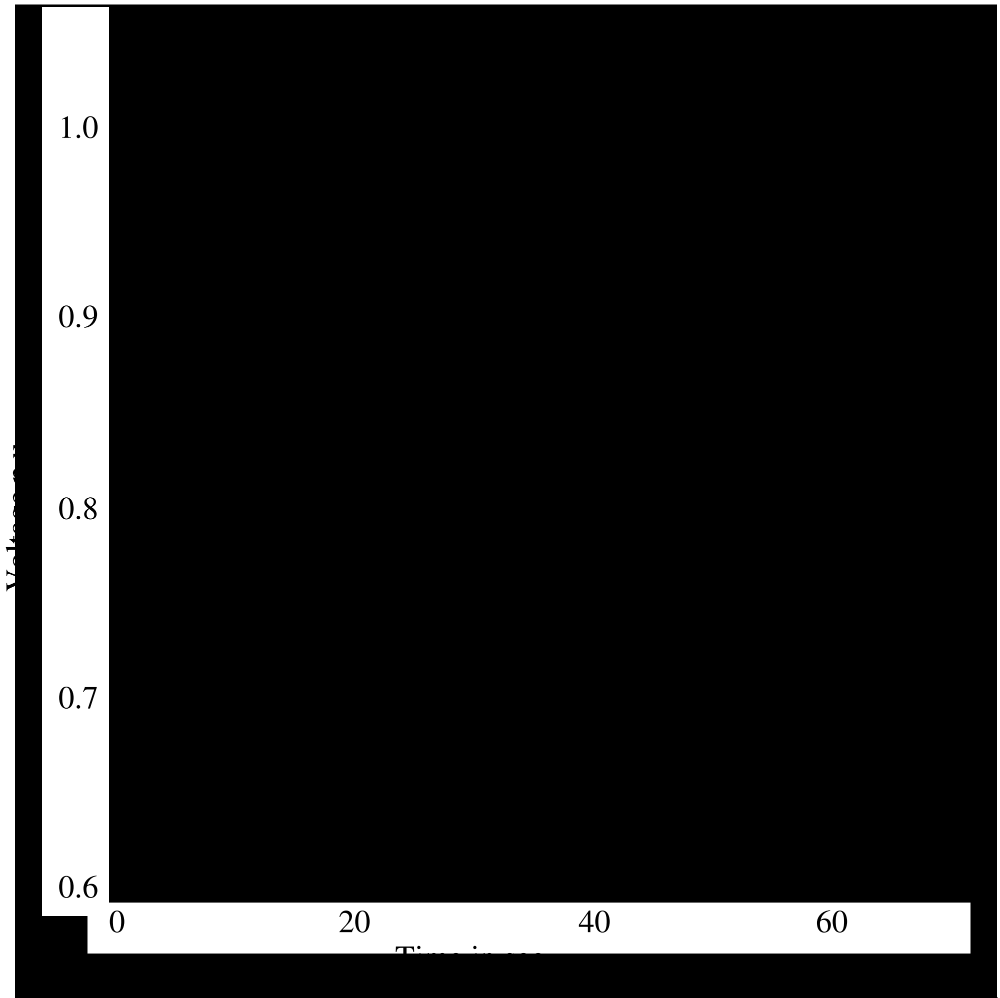

Figure A.18 Voltages in System 2. The same divergence of the voltage on the different sides of the transformers can be seen in figure A.11.

Case D: When one level of voltage regulating transformers is active the progression will go much faster. Up to the point when the first transformer changes tap position, the simulation is the same as above. After just a few tap movements of the transformers in the area, the voltage collapses. Note that the primary voltage at node 427 shows the same behaviour as the primary voltage in figure A.11. We have also seen that the transformer actions speed up the process in the simple system (figure A.16). A simulation with a similar behaviour could be found in [A.14].

A.3.5 Discussion of the simulations

In a weakened network with generators having limited voltage regulation capabilities, the regulating transformer behaviour is important when the generators become current limited. When a voltage level falls below the transformer dead band, the voltage will be restored by the OLTC. Every tap changing increases load voltage and thereby increases load demand. This also increases the current on the primary side, see figure A.12. The step up transformers near the generators can not cope with the load transformer tap changings due to the larger voltage drops in the network, which affect the load transformers more than the step up transformers. The current increase, therefore must be taken from a generator that is not current limited, probably far away from the critical area, since the mechanical power to the limited generators is virtually unchanged. If this is not possible or is very difficult due to line losses in the transmission system, the voltage starts to decrease, sometimes very fast (figure A.14, A.17 and A.18). In these simulations it appeared to us that the OLTC-regulation speeded up the voltage decline when the armature current limiters came into action (figure A.16 and A.18). In several French regions an automatic OLTC blocking system has been installed to prevent voltage collapse [A.2].

The system operator should be presented with the actions of the current limiters, due to their influence on the system. Therefore, this presentation is going to be implemented at the Sydkraft utility company.

A.4 Conclusions

The authors believe that it is important to model components with a high degree of accuracy. Many phenomena that were not expected to have an effect on voltage stability simulations turn out to be important when included. One thing that was found important was the blocking of the activated current limiter when there was a risk that the generator would become under-excited.

Accurate simulation can be a complement to more theoretical/mathematical treatment of voltage stability phenomena. These simulations can also be used to verify general theories developed on small, easier-to-understand networks.

However, it must kept in mind that the simulation results depend on the quality of the input data. Several parameters in the load model used here are difficult to extract from a real network. The simulations reported here show clearly how different load models affect the outcome of a simulation. The lack of information in this area should be remedied.

The simulations highlight the importance of the generator current limiter and its interaction with the on-load tap changer and the type of load model chosen.

A.5 Acknowledgements

The authors would like to thank Sydkraft company and Sydkraft Research Foundation for their engagement in this research area and for their financial support.

A.6 References

[A.1] Altsjö K., "Modelling of voltage regulator for on-load tap-changers", graduation thesis report No. 92/93:02, Department of Electrical Power Systems, Chalmers University of Technology, Göteborg, Sweden, (In Swedish only), 1993.

[A.2] Bourgin F., Testud G., Heilbronn B. and Verseille J., "Present Practices and Trends on the French Power System to Prevent Voltage Collapse", IEEE Transactions on Power Systems, Vol. 8, No. 3, 1993.

[A.3] CIGRÉ, TF 38-02-10, "Modelling of Voltage Collapse Including Dynamic Phenomena", 1993.

[A.4] Concordia C., "Voltage Instability", Electrical Power & Energy Systems, Vol. 13, No. 1, pp. 14-20, 1991.

[A.5] Graf K.-M., "Dynamic Simulation of Voltage Collapse Processes in EHV Power Systems", EPRI EL-6183, Research Project 2473-21, 1989.

[A.6] Gustafsson M., “Generator armature and rotor current limiters effect on the reactive power generating capability”, graduation thesis report No. 92/93:06, Department of Electrical Power Systems, Chalmers University of Technology, Göteborg, Sweden (In Swedish only), 1993.

[A.7] Harmand Y., Trotignon M., Lesigne J.F., Tesseron J.M., Lemaitre C. and Bourgin F., “Analysis of a Voltage Collapse-Incident and Proposal for a Time-Based Hierarchical Containment Scheme”, Cigré report 38/39-02, Paris, 1990.

[A.8] Hill D.J., “Nonlinear Dynamic Load Models with Recovery for Voltage Stability Studies”, IEEE/PES 1992 Winter Meeting, New York, 1992.

[A.9] IEEE Publication 90TH0358-2-PWR, “Voltage Stability of Power Systems: Concepts, Analytical Tools, and Industry Experience”, New York, 1990.

[A.10] Karlsson D., “Voltage Stability Simulations Using Detailed Models Based on Field Measurements”, Ph. D. Thesis, ISBN 91-7032-725-4, Göteborg, Sweden, 1992.

[A.11] Karlsson D., Lindén K., Segerqvist I. and Stenborg B., “Temporary load-voltage characteristics for voltage stability studies- Field and Laboratory measurements”, Cigré report 38-204, 1992.

[A.12] Kwatny H.G., Pasrija A.K. and Bahar L.Y., “Static Bifurcations in Electric Power Network; Loss of Steady-State Stability and Voltage Collapse”, IEEE Transactions on Circuits and Systems, Vol. 33, No. 10, pp. 981-991, 1986.

[A.13] Löf P.-A., Andersson G. and Hill D.J., “Voltage Stability Indices for Stressed Power Systems”, IEEE/PES 1992 Winter Meeting, New York, 1992.

[A.14] Stubbe M., Bihain A. and Deuse J., “Simulations of voltage collapse”, Electrical Power & Energy Systems, Vol. 15, No. 4, pp. 239-243, 1993.

[A.15] Van Cutsem T., “Dynamic and Static Aspects of Voltage Collapse”, Engineering Foundation Conferences, Bulk Power System Voltage Phenomena: Voltage Stability and Security, Santa Barbara, California, 1988.

[A.16] Vu K.T. and Liu C.-C., “Dynamic Mechanism of Voltage Collapse”, System & Control Letters, Vol. 15, No. 4, pp. 329-338, 1990.

A.7 Appendix

Primary data for the simple test system:

The dynamic load model:

$\alpha_s = 0.38$
$\alpha_t = 2.26$
$\beta_s = 2.68$
$\beta_t = 5.22$
$P_0 = 0.10$ p.u.
$Q_0 = 0.04$ p.u.
$T_{pr} = 127.6$ s
$T_{qr} = 75.3$ s.

Line parameters:

The short line: x = 0.75 p.u.

The long line: x = 1.5 p.u.

The transformers:

$x_k = 0.1$ p.u.
voltage set-point = 1.0 p.u.
deadband = 0.02 p.u.
tap step = 0.015 p.u.

Paper B Behaviour of generator current limiters near the point of voltage collapse

Paper presented at "Stockholm Power Tech, International Symposium on Electric Power Engineering", 1995.

Abstract

Voltage instability and system collapse could be ascribed to the inability of a power system to sustain the load. Analysis of the problem over the years has strongly focused on the significance of reactive power and its repercussions on voltage. This paper has a different approach where the collapse phenomenon is treated as a current problem and is related to the current limiter behaviour of generators. The effect on the system differs drastically depending on whether the field or the armature current limiter becomes active. An illustration of how a field current limited generator exposed to a voltage drop will reach the armature current limit is made. It will also be shown that the relation between changes in current and voltage (ΔI/ΔU) as a function of different disturbances gives valuable information on the onset of voltage collapse.

Keywords

Voltage instability, voltage collapse, armature current limiter, field current limiter, current-voltage trajectory.

B.1 Introduction

There are several approaches to voltage stability problems. One approach might be to divide the power system into three parts: the transmission system, the distribution system which includes the electrical load demand, and the generation system. These three sub-systems interact with each other and voltage stability problems can originate in any of these sub-systems. For transmission systems, increased reactive power demand can cause a voltage stability problem.

In distribution networks, stalling asynchronous motors, air-conditioning systems and electrical heating appliances are examples of dynamic loads that can give rise to voltage stability problems. Voltage problems can also be due to generators. A well known example is the field current limiter (over-excitation limiter) [B.7]. However, the armature current limiter affects the power system in an even more drastic way. The armature current limiter is quite often neglected in the analysis because it is not commonly used. However, there are reasons to include it as an overcurrent protection system. This paper analyses current limiter behaviour and its significance for system stability.

B.2 Generator current limiters

The interaction between the current limiters and the network is studied using the following model of the synchronous generator (figure B.1):

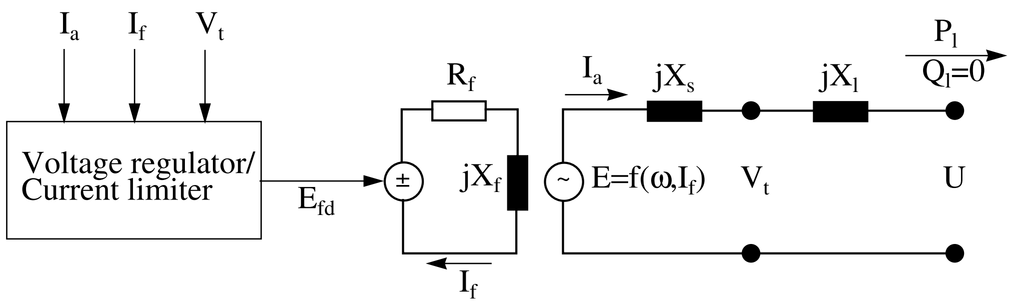

Figure B.1 The synchronous round rotor generator with a transmission link and an active load demand.

The Voltage regulator/Current limiter[1] (see chapter A.2.2) may operate in one of three regulating modes:

- Regulating terminal voltage V_t at a given set-point. This is the normal operating condition.
- The field current I_f may be limited to avoid overheating of the field winding. This corresponds to a constant voltage E and the voltage regulation point V_t disappears. The “synchronous reactance” X_s can now be considered as a part of the transmission system. The value of X_s is not trivial. It depends on armature reaction, self-inductance (and resistance) of armature coils and the pole shapes of the rotor and

1. FREA manufactured by ABB.

stator. The value of X_s is therefore difficult to predict quantitatively (see ref. [B.5]).

Note that the relation between E and I_f is nonlinear due to saturation, which is evident when the machine is light loaded. For a machine connected to a lagging load, the armature reaction will decrease the field and makes the relation more linear.

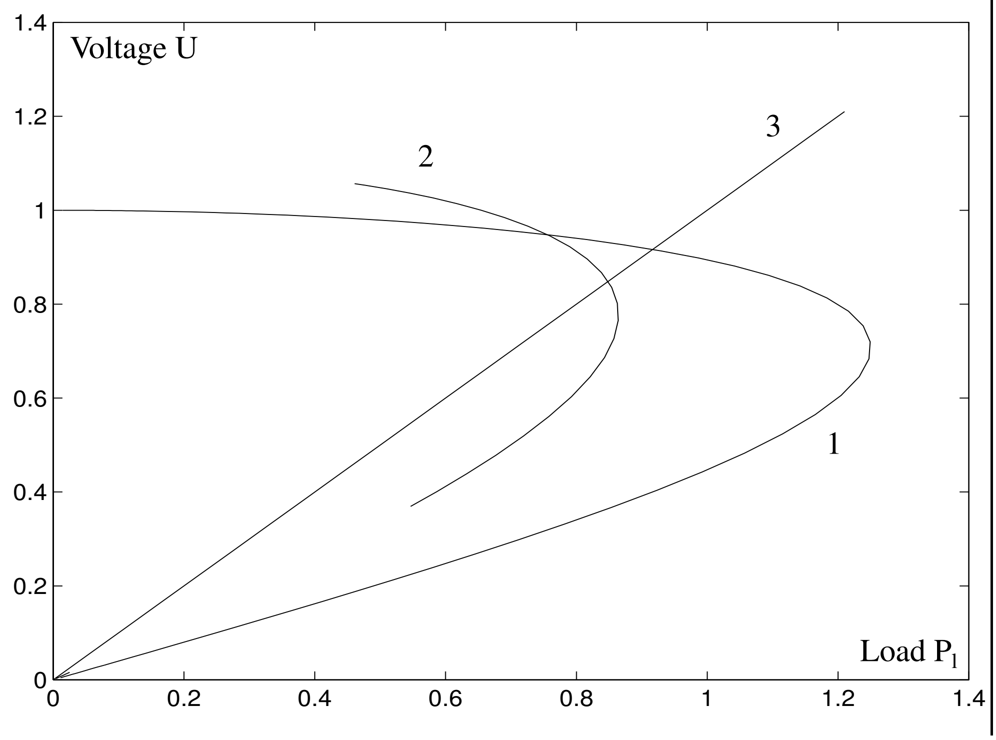

Figure B.2 Possible system characteristics as seen by the load (constant power factor), depending on which mode the generator is working in. The shapes and slopes will vary with the power factor of the load (Symbols from figure B.1).
1: Voltage regulating mode (V_t constant)
2: Field current limited mode (E constant)
3: Armature current limited mode (I_a constant)

- The armature current I_a is limited if it exceeds a specified level. This protection system avoids overheating of the armature windings. In that case the generator loses all voltage regulating capabilities and becomes a constant current source. The only way the protection system now can decrease a too high I_a is by decreasing E. This certainly stresses the voltages in a system.

If the generator is not equipped with an armature current limiter, the generator is usually tripped by an overcurrent relay and all production is lost from that source, i.e. an even worse situation for the system. Some large hydro-power stations in Sweden use this configuration whereas nuclear power plants use armature current limiters.

If the regulator is working in a limiting mode, the most severe limitation is valid. The system characteristics as seen by the load are shown in figure B.2 for the three modes.

B.2.1 The capability diagram for the generator

A capability diagram displays possible operating areas where the generator thermal limits are not violated [B.1]. The small circle in figure B.3 corresponds to the MVA-rating of the generator, and the circle-segment is the boundary due to field current limitation.

If the generator becomes field current limited and is exposed to a decreasing voltage V_t, it will end up as armature current limited. In the capability diagram this can be seen since the small circle "shrinks" and the large circle segment "moves" to the right.

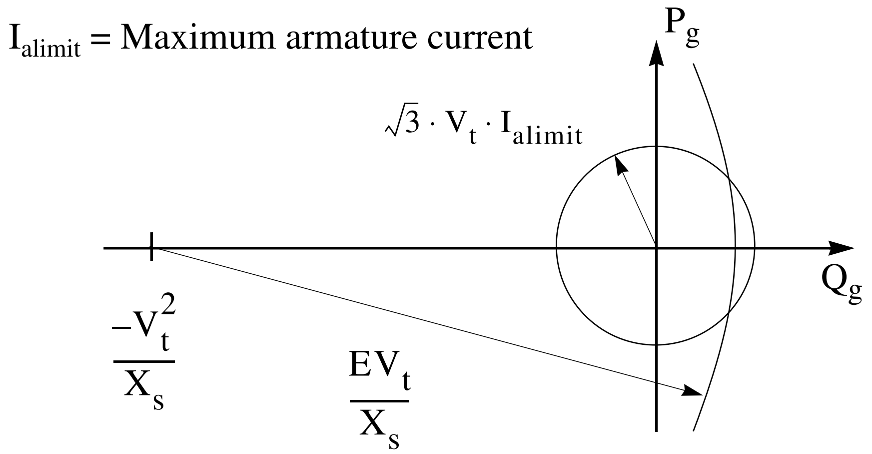

Figure B.3 The capability diagram for a generator. The working point must be inside both circles. Only the thermal constraints of the generator are indicated. Prime mover restrictions may be added to the capability diagram. (For symbols: see figure B.1).

B.2.2 The interaction between the current limited generator and the load characteristics

If the load P_l in figure B.1 is increased from zero, one of the following sequences will occur:

- The voltage V_t is kept at the given set-point until the transmission system will be unable to transmit the power over X_l at a viable voltage U and comes into voltage stability problems due to lack of transmission capacity.
- The field current limiter is activated after further load increase. The reactance in the system increases and this might cause a voltage collapse in the same way as the tripping of a line in the network can cause a collapse. The system may also survive with this increased reactance but at a lower voltage U. The load increase causes a lower voltage V_t at the terminal. This may activate the armature current limiter (figure B.5) or causes an non-viable voltage U.
- The armature current limiter becomes activated before the field current limiter. At this point the outcome depends only on the load characteristics (see chapter B.2.4).

Usually, generators are designed such that they are field current limited before they reach maximum armature current. However, efficiency improvements on the turbine side may increase the active power output and thereby move the generator working point closer to the armature current limit. This is valid for several of the Swedish nuclear power plants.

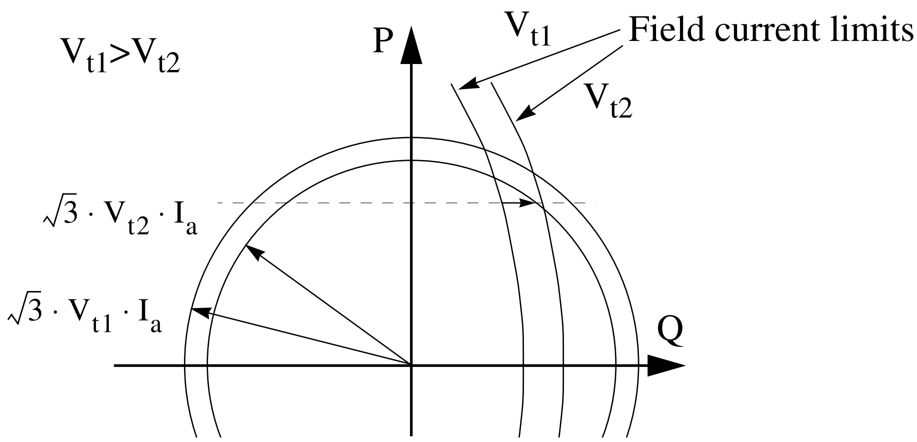

Figure B.4 The capability diagram for two different voltages $V_{t1}>V_{t2}$ for a field current limited generator. The dotted line is active power delivered from the turbine to the generator. The small arrow indicates how the working point can become armature current limited when the terminal voltage decreases. Note that the reactive power out from the generator increases for a field current limited generator exposed for a voltage drop.

B.2.3 The influence of the field current limiter

It is interesting to consider a real field current limiter (see chapter A.2.2) with delayed operation and to study how it is interacting with a dynamic load. By including delayed operation the transient load characteristics appear when the limiter drastically changes its operating mode (figure B.5).

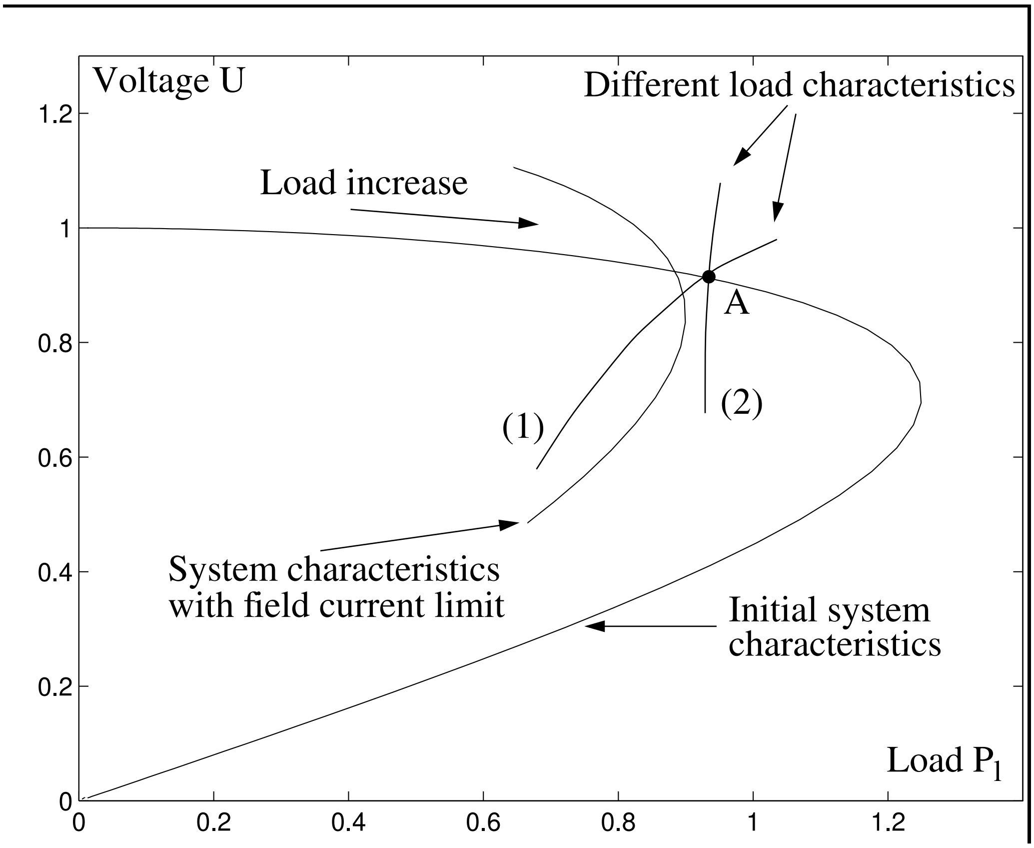

Figure B.5 A load increase with a delayed field current limiter. In point A the limiter comes into action and a continuous transition to the new system characteristics will occur. It then depends on the load characteristics if the system will find a stable operating point (1) or become unstable (2).

Depending on the values of the systems components, it is possible for the system to be unstable due to the fact that the working point is on the lower side of the UP-curve. Certain types of loads can be unstable on the lower side of the UP-curve (See ref. [B.2] and [B.6]).

B.2.4 The influence of the armature current limiter

When the armature current limiter becomes activated, the load behaviour is important and is going to decide if the small system will be stable or not. In figure B.6, two possible load characteristics, I and II are shown.

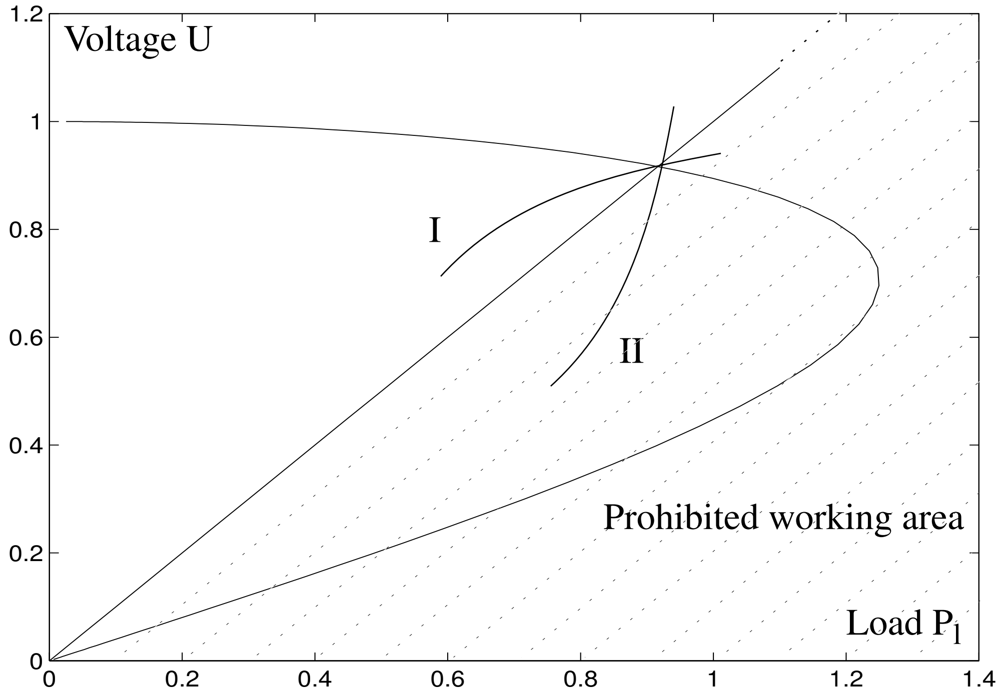

Figure B.6 Armature current limiter and load interaction. Two possible load characteristics I and II are indicated.

A general expression for the load can be given by:

$$P = P_0 \left(\frac{U}{U_0}\right)^{\alpha} \tag{B.1}$$

Here the value of α is of particular significance in case of armature current limitation and will be analysed further on. The armature current limiter divides the UP-plane in two zones, where the right one is not a possible stable operating area with regard to thermal heating of the generator. The output power from the generator into the load follows the relation $P_l = \sqrt{3} \cdot U \cdot I_s$ i.e. a straight line in the UP-plane (in case of no reactive load as in figure B.1). If the operating point enters the unstable half, the only possible protection action of the current limiter to decrease I_a is to decrease E (i.e. decrease the field current I_f).

Case A: An increase of load demand and α>1:

We will have the following situation:

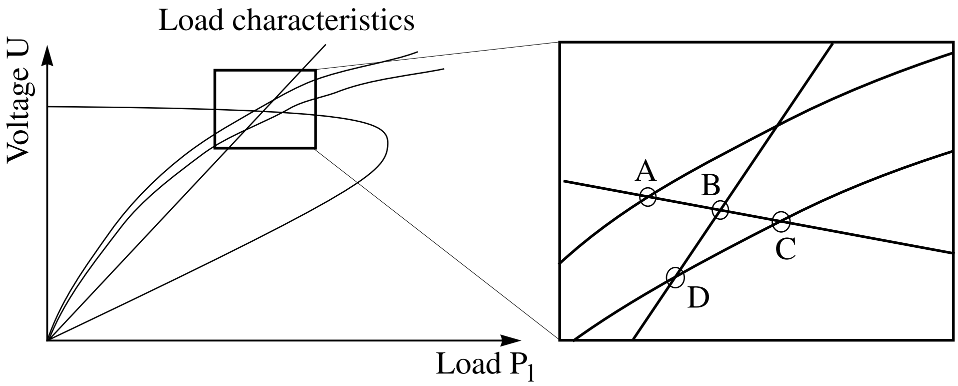

Figure B.7 Armature current limiter and load interaction when α>1.

A load increase where the character of the load does not change (same α) can be expressed as an increase of P_0 in equation (B.1). At the beginning the system is located at point A in figure B.7. After the load increase the system moves to C. The stator current limiter either prohibits that movement in B or starts its timer for a delayed operation (see chapter A.2.2). The armature limiter then forces the system operating point to D, which is a stable operating point.

Case B: An increase of load demand and α<1:

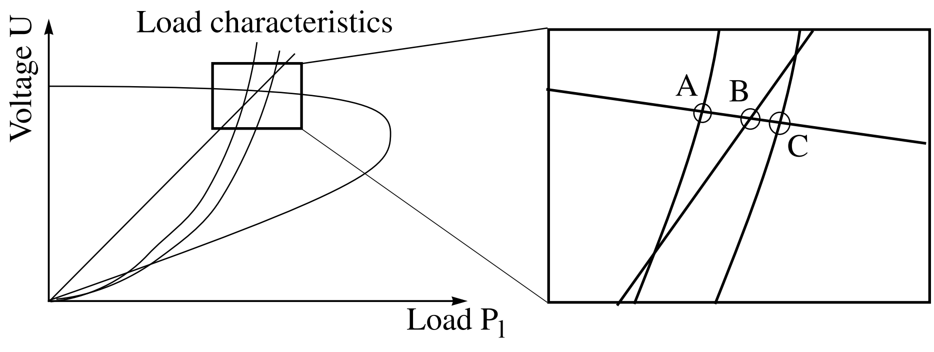

Figure B.8 Armature current limiter and load interaction when α<1.

The system is located in A in figure B.8 (stable operating point between the UP-curve and the load characteristic). We increase P_0. The system wants to move to C. When it passes B the current limiter either stops the armature current increase or starts its timer for a delayed action (see chapter A.2.2). The only possible direction for the system is to decrease the voltage but this means an even larger violation of the armature current and an even lower voltage E. The voltage collapses since there is no intersection between the system characteristic and the load characteristic. This also indicates that the voltage decline during a collapse can be very fast in the final phase.

The condition for returning to a stable situation is that the load current ($=I_a$) decreases below I_{alimit}. For the load end we can calculate the current in figure B.1:

$$I_a = \frac{P_l}{U} \qquad \text{and using equation (B.1)} \tag{B.2}$$

$$\frac{\partial I_a}{\partial U} = \frac{P_0}{U_0^{\alpha}} \cdot (\alpha - 1) \cdot U^{\alpha - 2} \tag{B.3}$$

The system will find a stable operating point at I_{alimit} when $\alpha>1$ and it will be unstable for $\alpha<1$. This should be compared with the cases A and B, respectively. It can be seen that the combination of an armature current limiter and a negative $\partial I_a/\partial U$ can be interpreted as a stability criterion for the simplified system in figure B.1. A $\partial I_a/\partial U>0$ gives a stable situation while $\partial I_a/\partial U<0$ leads to an unstable situation.

Since the property of $\partial I/\partial U$ seems to contain valuable information on an impending voltage collapse in a small system, a simulation study has been made to analyse the $\partial I/\partial U$ relation in a more general sense. The simulated quantity in this paper is

$$\frac{\partial I}{\partial U} \approx \frac{\frac{\Delta I}{\Delta t}}{\frac{\Delta U}{\Delta t}} = \frac{\Delta I}{\Delta U} \tag{B.4}$$

A similar study has been made using the CIGRÉ Swedish test system [B.4].

B.3 Simulations

The simulations are made on a simple power system consisting of one dynamic load, two generators, and four transmission lines connected as shown in figure B.9, (see appendix for network data). Generator G1 is to be regarded as an infinitely strong power source, while G2 is a small generator. The dynamic load is based on parameters taken from field measurements [B.3].

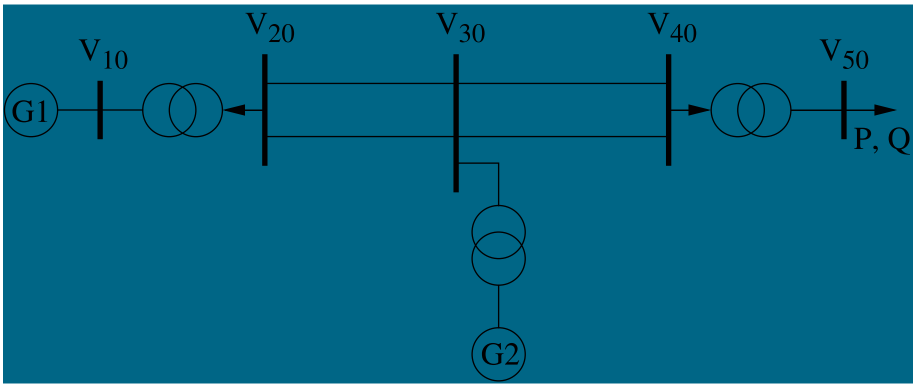

Figure B.9 A simple power system

The model used to analyse the ΔI/ΔU signal is implemented as a "user-written" model in the PSS/E[1] program. As shown in figure B.10 there are two possible outputs: one continuous output named ΔI/ΔU value, and a discrete one named ΔI/ΔU signal. The latter is used in these studies. The values of ΔI/ΔU are calculated for each current flow at each node.

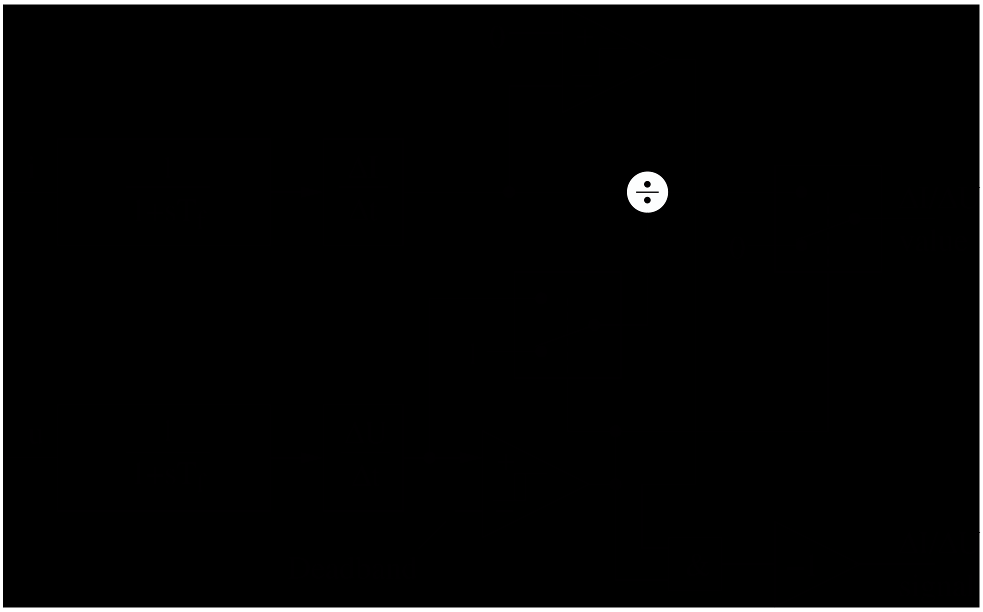

Figure B.10 The ΔI/ΔU model. There are two possible outputs: A continuous one named ΔI/ΔU value, and a discrete one named ΔI/ΔU signal.

1. Power System Simulator for Engineers, by PTI (U.S.A)

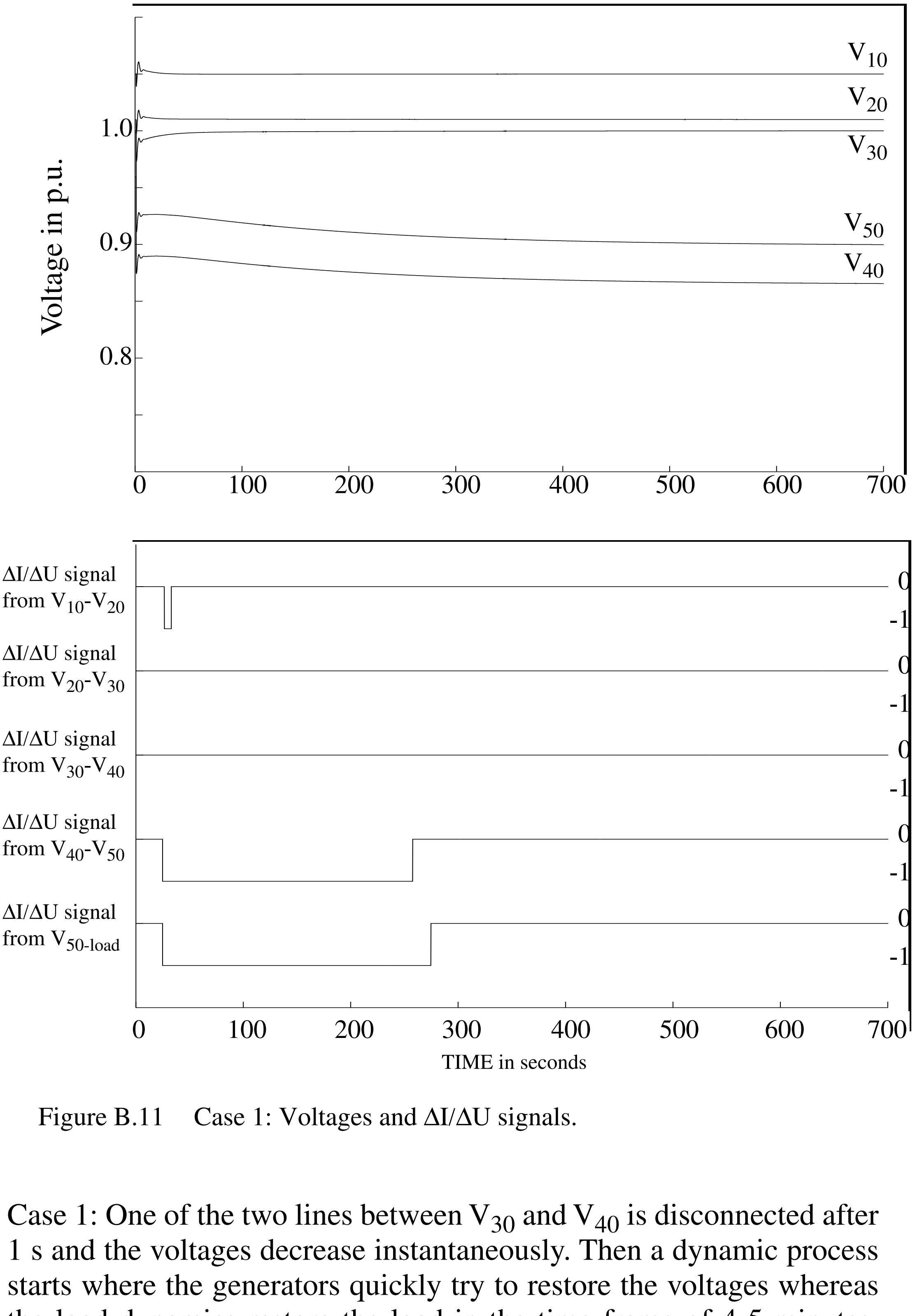

Figure B.11 Case 1: Voltages and ΔI/ΔU signals.

Case 1: One of the two lines between V_{30} and V_{40} is disconnected after 1 s and the voltages decrease instantaneously. Then a dynamic process starts where the generators quickly try to restore the voltages whereas the load dynamics restore the load in the time frame of 4-5 minutes. After about 6 minutes the system has found a new stable operating point. The course of events can be studied in figure B.11 where the discrete ΔI/ΔU signals in combination with the node voltages are shown. The current limiters and the dynamics in the OLTCs are not activated. In this case the ΔI/ΔU signals give a warning at three nodes after about 25 s. At the V_{10} node there is just a short dip depending on the voltage oscillations in combination with the load recovery. But at the other two nodes, V_{40} and V_{50}, there are negative ΔI/ΔU signals as long as the dynamic load is in the recovering phase. This means that these two nodes are weakened but the system survives and the ΔI/ΔU signals return to their original zero level.

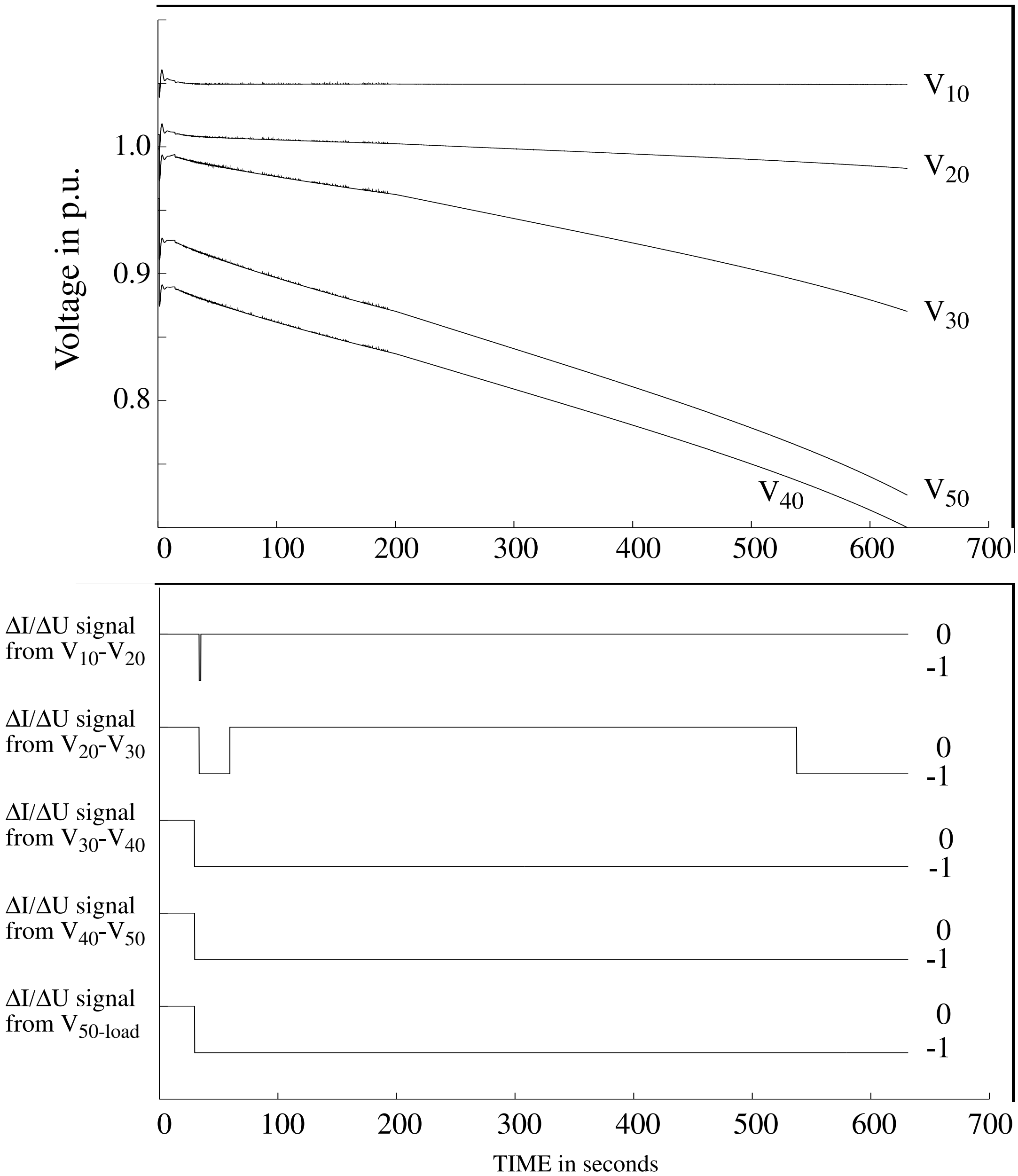

Figure B.12 Case 2: Voltages and ΔI/ΔU signals.

Case 2: This case has exactly the same conditions as the first case except that the field current limiter of G2 is activated after 14 s. After 200 s the armature current limiter becomes activated. In this case, the system will not find a stable operating point and the ΔI/ΔU signals become negative at every node. A close look at figure B.12 shows a spreading in time in which the ΔI/ΔU signals become negative. The nodes close to the load are ‘voltage weak’ which means that here the ΔI/ΔU signals become negative there first. The ΔI/ΔU signals near the strong generator become negative a few seconds later, but they will return to the original zero level since generator G1 sustains the voltages. After 200 s the armature current limiter at G2 becomes activated and the voltages at the weak nodes V_{30}, V_{40}, and V_{50} decline even more until the simulation is stopped at 0.7 p.u.

B.4 Discussion about the IU-trajectory

It is generally agreed that the frequency is stable to a point very close to the occurrence of a voltage collapse. Therefore we can assume that the load is satisfied with respect to the active power demand. Hence the limiting parameter will be the load current which is supplied from the generators and the reactive sources in the system. There are two scenarios that limit the current in an impending collapse situation: a) The transmission lines are not able to sustain the load and relays will trip the current overloaded lines and a voltage collapse may occur. b) Generators reach their thermal limits and become current limited. It is obvious in these cases that, as long as the currents increase and the voltages decrease, the system will run into trouble sooner or later. By following the direction of the trajectory of I and U it is possible to gain more information about the systems state. In other words, a continuously negative sign of ΔI/ΔU predicts that we are moving towards a voltage collapse.

A power system which load are increased will naturally have a decreasing voltage. In order to avoid ΔI/ΔU signals during normal load conditions there is a voltage deadband in time. The voltage must decrease faster than a certain amount or in other words ΔU/Δt must exceed the deadband as shown in figure B.13, indicating a stressed system. If this is valid, the current change is studied. If the current has decreased this might indicate a voltage fluctuation and should not be dangerous for the system. But if the current has increased this indicates a load increase or some sort of limitation in the system which is dangerous, especially as the voltage support is weak already.

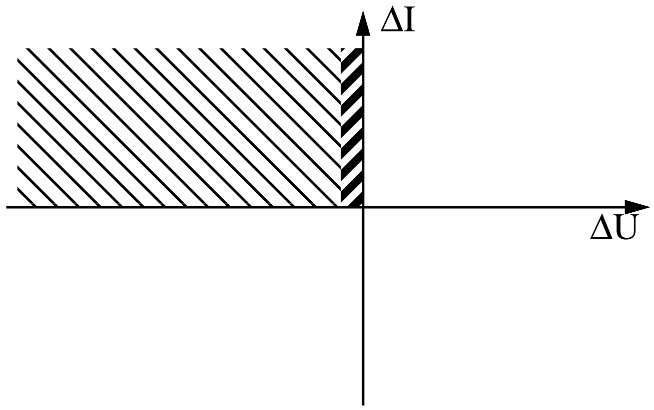

Figure B.13 The marked area symbolizes a dangerous direction for the system and the marked line symbolizes the dead band used in the simulations.

Another interesting observation is the geographical spreading of the negative $\Delta I/\Delta U$ signal. Simulations show how an increased number of nodes receive negative signs of $\Delta I/\Delta U$ after an initial disturbance which ends up with a collapse. These observations indicate where the network has been weakened and where reactive support is needed.

In combination with other indicators, the $\Delta I/\Delta U$ signal could be a valuable indicator of an emerging voltage collapse. A suitable application would be in a system emergency protection scheme. In addition, currents and voltages are easy to measure in a power system.

Issues that have to be studied more are appropriate dead bands and time constants for the filters to avoid that transients from generator swings causing too much signals. No attention is given to the $\Delta I/\Delta U$-value (i.e. the amplitude). This will be an objective for future work.

B.5 Conclusions

When studying voltage collapse phenomena it is important to notice how generator current limiters may affect the characteristics of the system. It is worth to notice that a field current limited generator becomes armature current limited if the terminal voltage declines. This implies that it is necessary to model the armature current limiter, since this limitation is more severe for the system. Current limiters can, in combination with load dynamics, explain why the voltages have decreased so fast in several collapse situations. Another current limiting aspect of the collapse problem is the decreasing transmission ability in the case of declining voltages in combination with recovering loads. This situation can lead to erroneous trippings of lines and in that way cause a voltage collapse. In combination with other criteria the sign of $\Delta I/\Delta U$ might be a valuable indicator of an imminent voltage collapse.

B.6 Acknowledgements

The authors would like to thank the Sydkraft company and the Sydkraft Research Foundation for their engagement in this research area and for their financial support.

B.7 References

[B.1] S. J. Chapman, “Electric Machinery Fundamentals”, McGraw-Hill, ISBN 0-07-010914-1, 1991.

[B.2] M. K. Pal, “Voltage stability conditions considering load characteristics”, Transactions on Power Systems, Vol. 7, No. 1, February 1992.

[B.3] D. Karlsson, “Voltage Stability Simulations Using Detailed Models Based on Field Measurements”, Ph.D. thesis, ISBN 91-7032-725-4, 1992

[B.4] Cigré TF 38-02-08, “Long Term Dynamics Phase II-Final Report”, 1995.

[B.5] P. Borremans, A. Calvaer, J. P. de Reuck, J. Goossens, E. Van Geert, J. Van Hecke, A. Van Ranst, “Voltage Stability- Fundamental concepts and comparison of practical criteria”, Cigré 38-11/1-8, 1984.

[B.6] N. U. Krantz, M. N. Gustafsson, J. E. Daalder, “Voltage Collapse with a Laboratory Power System Model”, Stockholm Power Tech, Proc. Power Systems, pp. 191-196, 1995.

[B.7] Cigré TF 38-02-10, “Modelling of Voltage Collapse Including Dynamic Phenomena”, 1993.

B.8 Appendix

Network data

Dynamic load data [B.3]:	α_s=0.38, α_t=2.26, β_s=5.22, β_t=2.68, P_0=0.8 p.u., Q_0=0.03 p.u., T_{pr}=127.6 s, T_{qr}=75.3 s.
Line data:	$R_{10\text{-}20}$=0.08 p.u., $X_{10\text{-}20}$=0.8 p.u., $B_{10\text{-}20}$=0.1 p.u., $R_{20\text{-}30}$=0.04 p.u., $X_{20\text{-}30}$=0.4 p.u., $B_{20\text{-}30}$=0.05 p.u.
Transformer data:	$X_{10\text{-}20}$=0.1 p.u., $X_{40\text{-}50}$=0.1 p.u., X_{G2} included in generator G2
ΔI/ΔU-Data	Filter time constant 5s, Deadband -0.00004 pu/s, Δt=1s

Paper C Avoiding Voltage Collapse by fast Active Power Rescheduling

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Abstract

Basic ideas for a method where the active power production is rescheduled in an automatic (fast) way to increase the loadability of the power system during a voltage instability are presented. Active power production is a parameter that is controllable during this instability phase and it may have a positive influence on the system vulnerability to collapse, especially when current limitations of the generators are involved. Depending on the strength of the system, two major objectives can be distinguished: to strengthen a local area from collapsing or to avoid an increase of the voltage depressed area.

Keywords

Voltage instability, voltage collapse, generator current limiters, active power rescheduling, active power dispatch

C.1 Nomenclature

ACL	armature current limiter
E	voltage at the large generator
FCL	field current limiter
I_l	current limit value for the small generator
n	tap step
P_0	nominal (pre-disturbance) active load power
P_d	active load demand (p.u.)
P_g	active power production in the small generator
P_l	active load capacity (p.u.)
Q_g	reactive power production in the small generator
T	time constant for tap changer control
T_p	active load recovery time
V	load voltage

V^0	set-point voltage for the tap changing control
V_0	pre-disturbance load voltage (usually equal to V^0)
V_t	terminal voltage at the small generator
X	reactance for one transmission line
E_g	internal voltage during field current limitation
X_g	internal reactance during field current limitation
Q_{max}	maximum reactive power output from the large generator
T_r	controller time constant

All values are in p.u. X=0.6 or 1.4, P_0=0.66 or 0.43, I_l=0.08, V_t=0.98, V^0=1, T=40s, T_p=40s, T_i=10s, E_g=1.08, X_g=1, Q_{max}=0.189, T_r=10 s.

C.2 Introduction

There are different methods to arrest or avoid an imminent voltage collapse. Among the most studied so far are load shedding [C.1], control (blocking) of on-load tap changers (OLTC) [C.2], [C.3] and [C.4] and capacitor switching (including SVC) [C.5]. This paper will study another approach to voltage collapse alleviation based on the rescheduling of active and reactive power during the voltage instability phase. In particular, the effect of rescheduling of generator current limiters' influence, which is one of the key factors contributing to voltage collapse will be demonstrated/investigated.

The main focus of this paper is on the action of armature current limiters and how active power rescheduling can alleviate the situation but field current limiters will also be treated. Armature current limiters are common in large power plants in Sweden (i.e. nuclear power plants) and are therefore of a main concern in the Swedish network. Usually generators are designed in such a way that they are field current limited rather than armature current limited. However, efficiency improvement on the steam turbine side may push the generator operating point closer to the maximum armature current. Also, the capability diagram for the generator shows that a field current limited generator will eventually become armature current limited if it is exposed to a decreasing voltage [C.6]. In power systems without armature current limiters one may regard tripping of a generator due to armature overcurrent as a more limited case since an armature current limiter in place of an overcurrent protection would have kept the generator connected to the system for a longer time. Benefits can then be gained by remedial actions which takes some time to implement, such as the starting of gas turbines, if the system can withstand a voltage collapse a little bit longer by this active power rescheduling.

The aim here is to study voltage instability in a time-frame where automatic protection systems such as generator current limiters operate, i.e. a time-scale of a couple of seconds up to a minute. Other phenomena in the power system such as on-load tap changer controls and certain load dynamics work in the same time-frame and have therefore been included. The possibility for operators to intervene during this time-frame is very limited, yet there will be enough time to allow for actions of automatic control equipment.

In this paper, the definitions of voltage stability, voltage instability and voltage collapse comply with the definitions made by CIGRÉ [C.7]:

- A power system at a given operating state and subject to a given disturbance is *voltage stable* if voltages near loads approach post-disturbance equilibrium values. The disturbed state is within the region of attraction of the stable post-disturbance equilibrium.
- Following voltage instability, a power system undergoes *voltage collapse* if the post-disturbance equilibrium voltages are below acceptable limits. Voltage collapse may be *total* (blackout) or *partial*.
- Voltage instability is the absence of voltage stability, and results in progressive voltage decrease (or increase). Destabilizing controls reaching limits, or other control actions (e.g., load disconnection), however, may establish global stability.

Assuming that the system is controllable during the voltage instability phase by means of fast active power rescheduling, this paper will demonstrate how that control action can lead to a voltage stable system in certain situations. Note however, that there are other aspects of active power rescheduling not considered here when the system is operated in such a way that voltage instability is avoided.

The paper describes used models together with their equations. System operation is divided into different modes depending on the state of the generators current limiters. In Section C.4 the capability of the system is discussed in relation to these different modes. The next section discusses the possibilities to change the system capability by means of active power rescheduling. This is further demonstrated through simulations in Section C.6. Used symbols are explained at the beginning of the paper together with data for the system.

C.3 The system and its models

A small system model is used for this study (see Figure C.1). The system contains two generators, where the small generator represents local production close to the load and the large generator represents a strong, remote production area where the main part of active load demand is produced. The dynamic load is supplied through an ideal tap-changing transformer; both are described in section C.3.1.

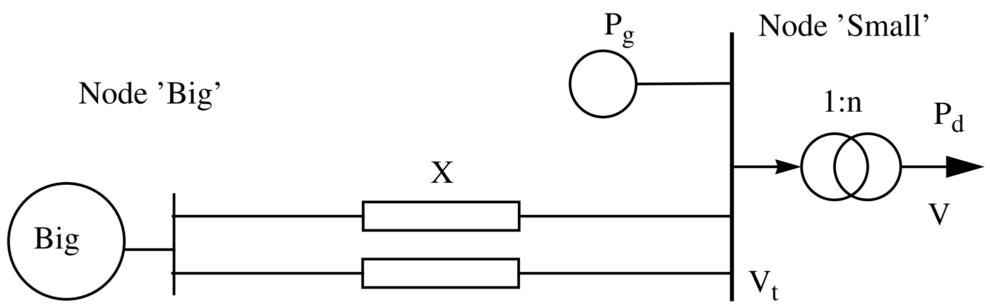

Figure C.1 The studied system. The contingency used in this paper is a tripping of one of the parallel lines

Both generators are assumed to be equipped with ideal (i.e. no time delays, etc.) field and armature current limiters. The Field Current Limiter (FCL) is modelled for both generators by taking in an extra, synchronous reactance X_g between the generator terminal voltage and generator internal voltage and "freezing" this voltage to E_g (Figure C.2a).

The Armature Current Limiter (ACL) is implemented as an actual current limiter for the small generator (Figure C.2b) whereas the current limiter for the big generator is represented as a reactive power limitation i.e. $Q_b \leq Q_{max}$ (Figure C.2c). This is done to allow the calculation of the stationary behaviour of the system since it avoids the voltages to become solely dependent on load and tap changer dynamics in certain cases.

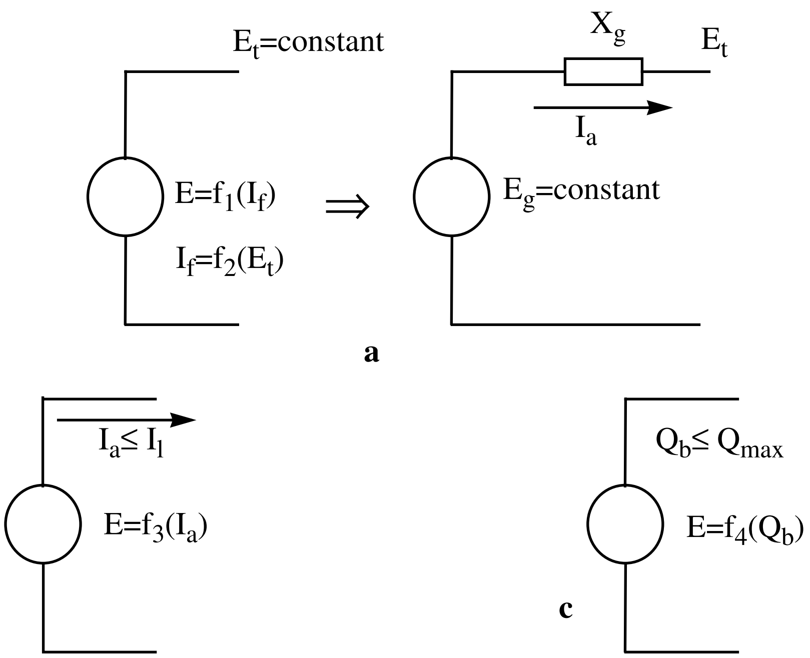

Figure C.2 Different implementations of current limiters: (a) Field current limiter, (b) Armature current limiter for the small generator, (c) Armature current limiter for the large generator

C.3.1 Load model and OLTC-model

A voltage dependent dynamic load model is used to model load recovery in the time-frame of a minute. Following Hill and Karlsson [C.8, C.9], we define static and transient load characteristics $P_s(V)$ and $P_t(V)$ respectively and a recovery time T_p.

A load state x_p is introduced according to

$$x_p = T_p(P_d - P_t(V)) \tag{C.1}$$

The variable x_p can be seen as a measure of the energy deficit in the load. According to [C.9], the exponential load recovery is given by

$$\dot{x}_p = -\frac{1}{T_p}x_p - P_t(V) + P_s(V) = -P_d + P_s(V) \tag{C.2}$$

The stationary and transient voltage behaviour can be described by the voltage dependent static load characteristics

$$P_s(V) = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} \text{ and } P_t(V) = P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{C.3}$$

Values used in this paper are α_s=0 and α_t=2. The reactive power load demand is considered to be zero at all time.

The real power balance corresponds to

$$P_d = P_l(V, n) \tag{C.4}$$

where P_d is the load demand and P_l is the system capability at the load point whose function will vary depending on activated current limiters (called “modes” henceforth), the actual voltage and the tap step. The system capacity $P_l(V,n)$ will be evaluated for different modes in Section C.4.

The transformer tap-changing relay is modelled as:

$$\dot{n} = \frac{1}{T}(V^0 - V) \tag{C.5}$$

where V^0 is the set-point voltage for the transformer. It is ideal in that sense that it has no reactance and assumes a continuous tap control.

Equations (C.2), (C.4) and (C.5) give a differential-algebraic state space system representation which depends on the current limiting mode the generators are working in (see Section C.3.2). In each mode k, the system can be described in a general form:

$$\begin{aligned} \dot{\mathbf{x}} &= f_k(\mathbf{x}, \mathbf{y}, u) \\ \mathbf{0} &= g_k(\mathbf{x}, \mathbf{y}, u) \end{aligned} \tag{C.6}$$

The control variable ’u’ suggested here is P_g, the active power production of the small generator.

C.3.2 Different operating modes of the generators

Depending on the limiter(s) activated in the generators the system can be in one of several distinct operating modes. For every distinct mode, the system will have a different capability curve (PV-curve) at the load point (see Section C.4). The normal condition for a generator is that it is voltage controlled (VC) i.e. it can keep its terminal voltage at a prescribed set-point value without violating any capability limits. Of all possible operating modes existing in the system, eight of them as listed in Table C.1, have been implemented during these simulations. Modes where the large generator becomes current limited before the small one, are excluded in this paper since the purpose is to study the behaviour of the generator close to the load demand (i.e. the small generator). As can be seen in Table C.1, a Mode 4, in which the active production of the small generator is controlled, is introduced. This mode represents control actions on the local production (P_g in Figure C.1) to enhance the system capability during any generator current limitation in the system. Different strategies for this control will be studied in the sequel. Figure C.3 indicates some of the possible transitions which can occur during system operation.

Mode	Small generator	Big generator
1	VC	VC
2	fcl	VC
3	acl	VC
4	P_g=f(...)	VC
5	fcl	FCL
6	acl	FCL
7	fcl	Q_{max}
8	acl	Q_{max}

Table C.1 Different operating modes used in this paper for the system in Figure C.1. VC Voltage Controlled, fcl/FCL field current limited, acl armature current limited, Q_{max} maximum reactive power output.

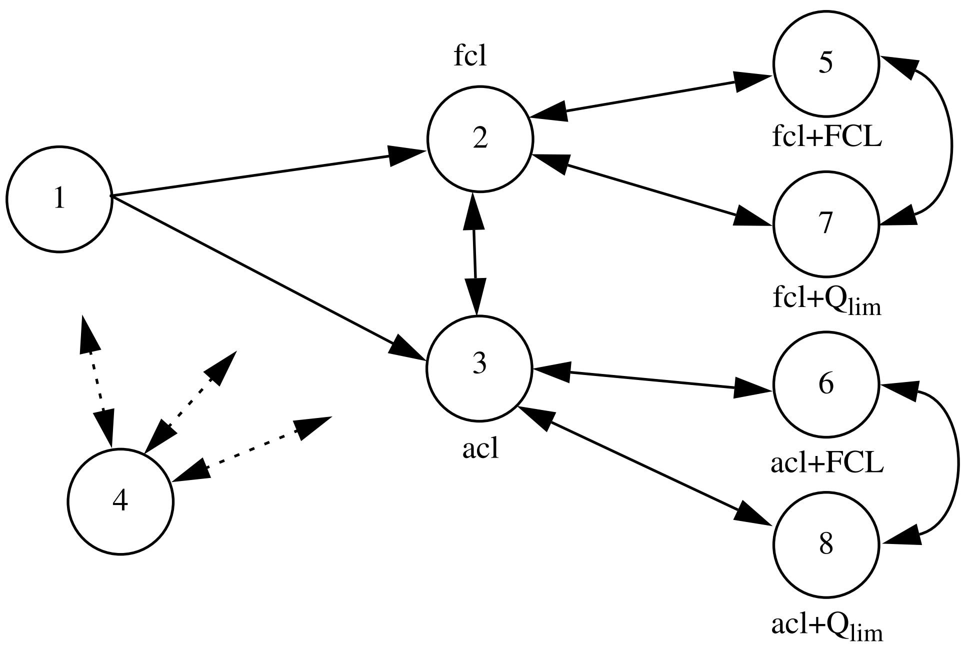

Figure C.3 The operating modes can change in a number of different ways. Those implemented here are indicated by arrows.

C.4 System capability curves for different modes

In this section the system capacity $P_l(V,n)$ is calculated for a few modes which are of interest further on in the paper.

C.4.1 Mode 2, field current limitation

For Mode 2 the capacity in the load point can be written based on Figure C.4 where the small generator is represented as in Figure C.2a.

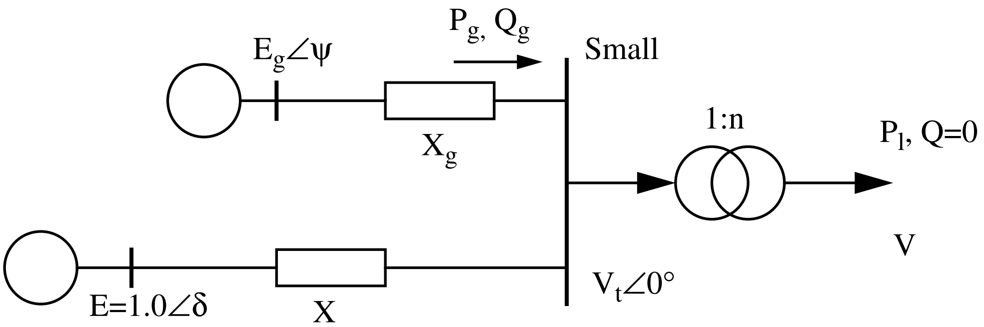

Figure C.4 The system for Mode 2. δ is the voltage angle over X and ψ the angle over X_g.

The reactive power balance at the node Small gives

$$Q = \frac{EV}{nX}\cos\delta - \frac{V^2}{n^2X} + Q_g = 0 \tag{C.7}$$

The active and reactive power output from the limited generator can be written as

$$P_g = \frac{VE_g}{nX_g}\sin\psi \tag{C.8}$$

$$Q_g = -\frac{V^2}{n^2X_g} + \frac{E_gV}{nX_g}\sqrt{1-\left(\frac{P_gnX_g}{VE_g}\right)^2} \tag{C.9}$$

The capacity at the load point can be written according to

$$P_l(V, n) = P_g + \frac{EV}{nX}\sqrt{1-\cos^2\delta} \tag{C.10}$$

where

$$\cos\delta = \frac{VX}{En}\left(\frac{1}{X_g} + \frac{1}{X}\right) - \frac{E_g X}{EX_g}\sqrt{1 - \left(\frac{P_g n X_g}{VE_g}\right)^2} \qquad \text{(C.11)}$$

C.4.2 Mode 3, armature current limitation

The capacity for Mode 3 can be calculated using Figure C.5. The reactive power balance equation at the small generator terminal is in this case identical to equation (C.7) and the reactive power output from the small generator can be written as

$$Q_g = \sqrt{\left(\frac{VI_l}{n}\right)^2 - P_g^2} \qquad \text{(C.12)}$$

The system capability P_l becomes

$$P_l(V, n) = P_g + \frac{EV}{nX}\sqrt{1 - \cos^2\delta} \qquad \text{(C.13)}$$

where

$$\cos\delta = \frac{V}{En} - \frac{nX}{EV}\sqrt{\left(\frac{VI_l}{n}\right)^2 - P_g^2} \qquad \text{(C.14)}$$

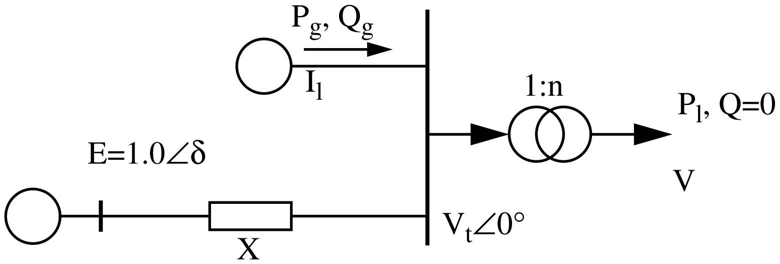

Figure C.5 The system for Mode 3. δ is the voltage angle over the line reactance X.

In order to find a relationship for maximum loadability during Mode 3 we assume that the variables E, X, I_l and n are constant. The voltage dependence of the load is also neglected in this subsection to allow straightforward calculations. However, a voltage independent load may be used to show qualitative relationships in this first step. Taking the derivative of equation (C.13) with respect to P_g we find

$$\frac{\partial P_l}{\partial P_g} = 1 - \frac{P_g\left(\frac{V}{nE} - \frac{nX}{EV}\sqrt{\left(\frac{VI_l}{n}\right)^2 - P_g^2}\right)}{\sqrt{\left(\frac{VI_l}{n}\right)^2 - P_g^2}\sqrt{1 - \left(\frac{V}{nE} - \frac{nX}{EV}\sqrt{\left(\frac{VI_l}{n}\right)^2 - P_g^2}\right)^2}} \qquad \text{(C.15)}$$

Combining with (C.12) and (C.14), (C.15) gives

$$\frac{\partial P_l}{\partial P_g} = 1 - \frac{P_g \cos\delta}{Q_g\sqrt{1 - (\cos\delta)^2}} \qquad \text{(C.16)}$$

By taking the zero value of equation (C.16) we find

$$\frac{Q_g}{P_g} = \frac{1}{\tan\delta} = \tan\phi \qquad \text{(C.17)}$$

which is the maximum loadability point (the second differential is negative). Equation (C.17) can be used as a control law for the small generator active power rescheduling in modes 3 and 4 when we have a radial voltage instability (For discussion about radial voltage instability see section C.6). Observe the difference between ϕ and δ. ϕ is associated with the angle between voltage and current produced by the small generator and δ is the voltage angle between the small and large generators. A simulation using this relation is shown in Section C.6.2.

C.4.3 Mode 8, armature current limit and reactive power limit

For Mode 8 the system capacity P_l can be written as

$$P_l(V, n) = P_g + \sqrt{\frac{V^2}{n^2X}(Q_g + Q_{max}) - Q_g^2} \qquad \text{(C.18)}$$

where Q_g is given by equation (C.12). The equation (C.18) may be derived by expressing the current I from the big generator as

$$I = \frac{\sqrt{(P_l - P_g)^2 + Q_g^2}}{V/n} \qquad \text{(C.19)}$$

and using

$$Q_{max} - XI^2 = -Q_g \tag{C.20}$$

Combining (C.19) and (C.20) gives

$$P_l^2 - 2P_lP_g + P_g^2 + Q_g^2 - \frac{V^2}{n^2X}(Q_g + Q_{max}) = 0 \tag{C.21}$$

resulting in P_l expressed by equation (C.18).

The capability for the other modes can be established correspondingly.

C.5 Change of system capability by active power rescheduling

The possibilities to change active production may seem limited. Difficulties are probably not so much associated with changing the production as such but rather with such questions as when to make a change and how much to change. A power plant must be able to lose all its active load in case of an contingency. It must therefore be possible, even for a short while, to make smaller changes if this can help the system.

It is also possible to imagine situations where a power increase is available. Many power plants have the possibility to be overloaded for a short time which can be useful to save the system. Also, Kaplan-turbines have its maximum efficiency point below the maximum power output. Hydro power plants may therefore have the possibility of an extra increase in active power production. This could be useful during a field current limitation of the generator which will be discussed in Section C.5.2.

C.5.1 Capability changes in mode 3

As can be seen in Figure C.6, the small generator is able to influence the capability of the system at the load point despite being armature current limited. The plot shows how much active power the system can deliver at the load point for a certain tap step n and load voltage V with the small generator being armature current limited. The capability will vary with voltage V and tap step n as can bee seen in equation (C.13). Since the most likely operating point in practice (generators working with power factors above 0.6) is to the right of the maximum transfer point in Figure C.6, it is clear that a *decrease* of the local active power production P_g will *increase* the system capability P_l at the load point.

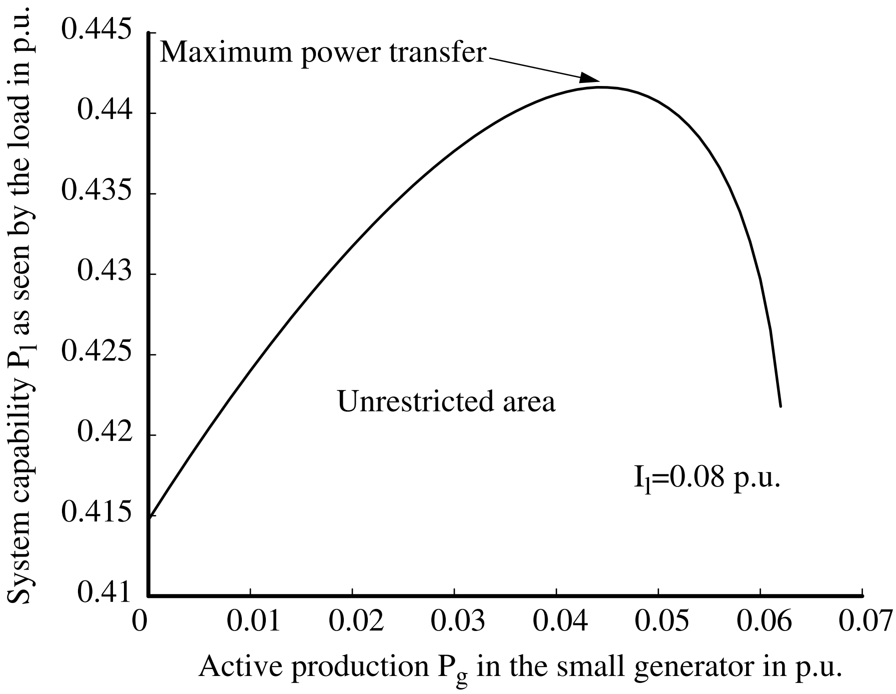

Figure C.6 The curve shows the system capability P_l (equation C.13) in Mode 3 at the load point as a function of active production P_g

The shape of the system capability P_l will vary with the activated mode. Some of them, such as modes 3, 6 and 8, will have a shape quite similar to Figure C.6 indicating therefore that a small change of the produced active power may have a significant impact on the system capability. Note however that not all modes exhibit such a characteristic.

A very similar network as the one shown in Figure C.1 was used in a laboratory experiment [C.10] carried out on an accurate three-phase model of a transmission network equipped with the same control equipment as used in real power systems. The system was exposed to a load increase until the armature current limiter became activated which without taking remedial actions would have caused a voltage collapse. A decrease of active power production recaptured voltage control on the current limited generator and prevented the collapse.

C.5.2 Capability changes in mode 2

In case of a mode 2 operation, i.e. an activation of the field current limiter in the small generator, the change of system capacity will be nearly proportional to the active production of the small generator. This can be seen from equations (C.9) and (C.10). Note that the second term in equation (C.10) does not alter much when P_g changes since the power angle between the large and the small generator does not alter considerably when the major part of active production comes from the large generator. Assuming that the voltage V is fairly constant this gives $P_l(V,n) \sim P_g$. Figure C.7 illustrates such a characteristic. It is clear that from the systems point of view the small generator should produce as much active power as possible. Note however, that an increase of active production P_g moves the generator operating point closer to the armature current limitation (which can be seen in Figure C.7 where the dash-dotted line indicates the operation of armature current limit). Therefore, assuming that an increase in active power P_g is available, care must be taken not to activate armature current limitation (or overcurrent armature tripping of the generator).

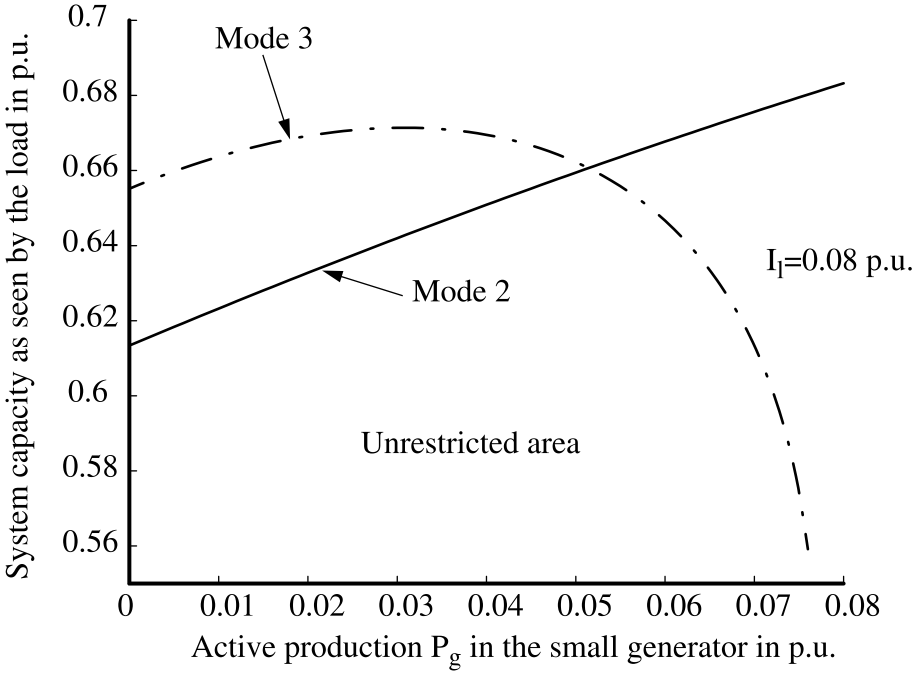

Figure C.7 The curve shows the system capacity P_l (equation C.10) at the load point in Mode 2 as a function of active production P_g. A principal shape of a Mode 3 capability limit is also indicated.

The same observation, that active power ought to be increased during a field current limited generation operation is also made on the laboratory model mentioned earlier [C.10].

C.6 Simulations

The geographical area affected by a voltage collapse depends on several aspects. The system may be exposed to a deficit of local generation or shortage of transmission capacity causing a collapse. These two mechanisms is exposed in these simulations. In terms of the line reactance X and load level P_d, it is possible to distinguish between two voltage collapse scenarios:

- *A weak system with high reactance X and low power transfer.* In this case the load end voltage can collapse with only the small generator operating in field or armature current limiting mode (see Refs. [C.10], Chapter 7, [C.11]). This can be described as a ***radial voltage collapse.*** Apart from the radial connection feeding the load end whose voltage collapses, the reminder of the system is intact without causing any violation of the generator capability in the large, remote generation area.

- *A strong system with low reactance X and high power transfer.* We can now endanger the whole system considering that also the large, remote generation area can also become limited owing to voltage stability problems at the load end. This can be described as a ***system voltage collapse,*** i.e. all load in a system (not only the load connected to the radial line) may endanger a voltage collapse.

As can be seen further on it is possible in the latter case to ‘‘support’’ the large generator using the small one to try to prevent a system collapse. In the first case though, there is no such option and all countermeasures must be done at the load end.

The significance of changing the active power in the small generator and its effect on the system voltage behaviour will be shown via different simulations Both radial and system voltage collapses will be demonstrated where the initial disturbance is a tripping of one of the parallel lines in Figure C.1.

C.6.1 Radial voltage collapse caused by armature current limiter

Two different simulations are demonstrated in this particular case. The system of Figure C.1 is exposed to the line tripping at t=0. Without rescheduling of the active power P_g, the voltages on both sides of the transformer collapse as illustrated by solid lines in Figure C.8.Voltage behaviour denoted by dashed lines illustrates however the alleviation of voltage collapse achieved by rescheduling of the active power P_g.

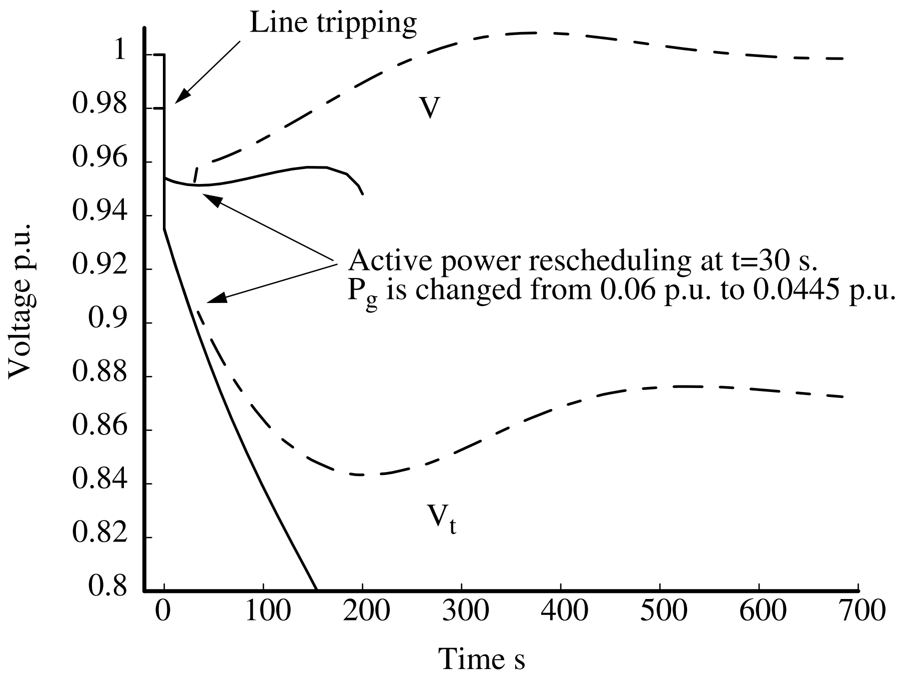

Figure C.8 Voltages on both sides of the transformer for two different production levels P_g in the small generator

After disconnection of one of the parallel lines in Figure C.1, the system enters mode 3 which causes a reactive power deficit. A monotonically decreasing voltage V_t results which further reduces reactive power output from the small generator since it is armature current limited. The state space trajectory for this unstable case is shown in Figure C.9. The trajectory starts at t=0 s. Since the load voltage is below V^0, the transformer starts to increase its tap ratio. The load experience a power deficit (transient load demand is less than steady state load demand). Referring to equation (C.2), an increase in the load state x_p occurs. There are two equilibrium points marked b and c which are stable and unstable respectively. The system will become stable if the system trajectory returns to the stable point b. At point d in Figure C.9 the trajectory leaves the $\dot{x}_p<0$ region, i.e. the so called excess load region (where the load demand P_d is (transiently) greater than the steady-state load requirement [C.2]). Since the load demand P_d is now less than the steady state value, the energy deficit x_p cannot be restored to zero and the system will not be able to reach the stable operating point b. The system undergoes a voltage collapse.

The model of the armature current limiter does not allow for the generator to become underexcited and the system will therefore have a fixed limit at Q_g=0. Real current limiters may prohibit this transition from overexcitation to underexcitation mode by changing back to voltage control which will most likely violate the armature current limit again and activate the current limiter [C.12]. Here the simulation is ended when Q_g=0 point is reached. As seen in the state space in Figure C.9, it corresponds to the system trajectory hitting the dotted line Q_g=0.

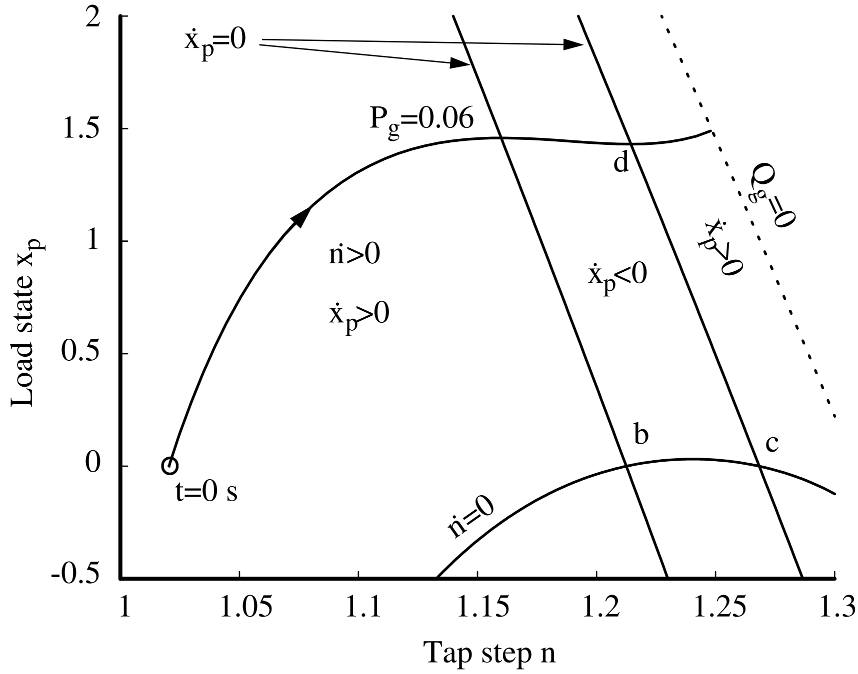

Figure C.9 The state space trajectory for a radial voltage collapse without active power rescheduling. Point b is the stable steady state operating point to which the trajectory fails to proceed to

For the stable case an active power rescheduling is performed at t=30 s. The load voltage increases transitionally as seen in Figure C.8. As viewed in the x_p-n plane in Figure C.10, the excess load region is expanded by the power rescheduling. As a result the system has a possibility to restore the energy deficit x_p to zero and to settle at a new steady-state operating point labelled a in Figure C.10. The oscillatory behaviour of the voltage can easily be seen in the state-space. For discussion about similar behaviour observed with tap locking as a control action, see Refs. [C.2, C.3]. The amount of P_g to reschedule is in this example taken from Figure C.6. At the beginning the active production is P_g=0.06 p.u. and it is decreased to 0.0445 p.u. which is the numerically computed value which corresponds to the maximum of the P_l-P_g curve plotted in Figure C.6.

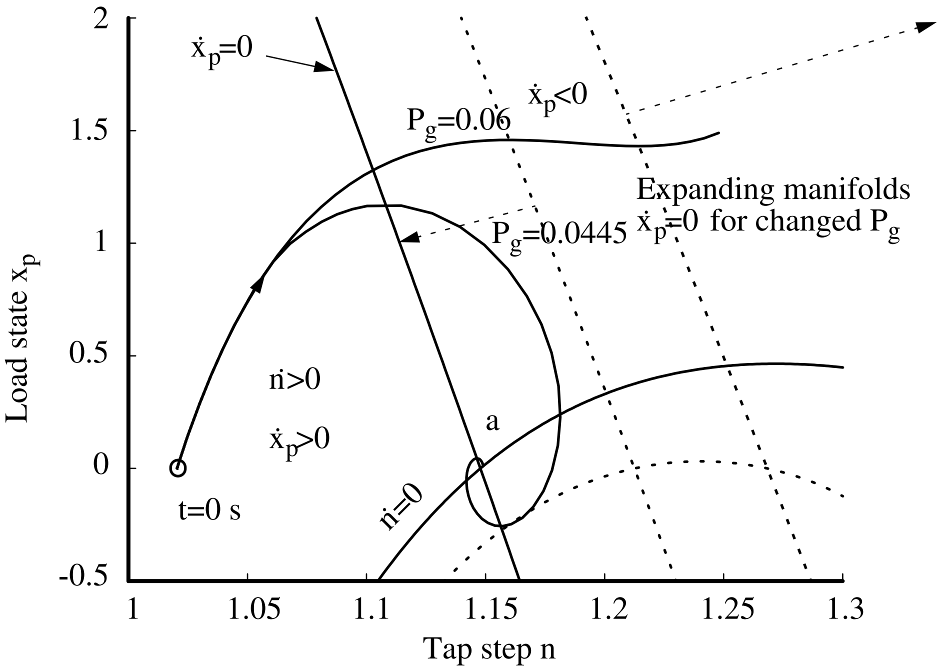

Figure C.10 The state space trajectory for the radial voltage collapse (P_g=0.06) and with active power rescheduling (P_g=0.0445). The dotted lines are valid for the unstable case presented in Figure C.9

C.6.2 Simulation of mode 4 operation

The proposed control rule in Section C.4.2 for a radial voltage collapse caused by armature current limitation is here demonstrated for several different cases. The objective is to compare the control strategy of an armature current limiter used today with a strategy which can influence active power production P_g continuously. A control scheme used here is based on equation (C.17). Firstly, the set-point active power production P_{gc} is calculated as

$$P_{gc}^2 + \frac{P_{gc}^2}{\tan^2\delta} = (V_t I_l)^2 \tag{C.22}$$

$$P_{gc} = V_t I_l \sin\delta \tag{C.23}$$

which gives, for the present values of V_t and δ, the active power P_{gc} that the generator should produce to achieve maximum P_l according to equation (C.17). Secondly, a proportional regulator with a time constant T_r is implemented to control the active power production P_g as

$$\dot{P}_g = \frac{1}{T_r}(P_{gc} - P_g) \tag{C.24}$$

The outcome in this case is very sensitive to the pre-disturbance active load level of the generator. Two different starting points P_{g0}=0.06 p.u. and P_{g0}=0.07 p.u. are therefore shown in Figure C.11. The amount of active power production compared to the rated power of the generator roughly reflects the situation in real generators. The second working point, P_{g0}=0.07 p.u., will not be able to support as large load P_0 as the former, as can be seen in Table C.2. This can also be observed in Figure C.6. The higher the active power production P_g, the lower the system capacity P_l is.

	Mode 3 operation	Mode 4 control after 10 seconds
P_{g0}=0.06 p.u. P_0=0.43 p.u.	Collapse after 168 seconds (Trajectory a)	Stable (Trajectory c)
P_{g0}=0.07 p.u. P_0=0.43 p.u.	Collapse after 12 seconds	Stable
P_{g0}=0.07 p.u. P_0=0.40 p.u.	Collapse after 45 seconds (Trajectory b)	Stable (Trajectory d)

Table C.2 Trajectories, refer to Figure C.11.

As an attempt to prevent voltage collapse, the system operation is switched to mode 4 operation 10 seconds after the initial disturbance (i.e. control by means of equation (C.24)). Figure C.11 shows the ‘δ-cos ϕ’-plane with equation (C.17) indicated as a dashed line. The post-disturbance starting points of the trajectories are marked with small circles for two of the three cases indicated in Table C.2. Two trajectories marked a and b in Figure C.11, are leading towards a collapse while two trajectories, c and d, alter to Mode 4 operation and become stable.

From equation (C.17) it is possible to see that local active power production should be lowered on the right side of the dashed line whereas it should be raised to the left of the line to increase the loadability. Observe that a reduction of active power will release more reactive power (see equation (C.12)) and thereby rise the voltage V_t whereas the voltage will decrease for an increase in active production. The direction of the voltage change after rescheduling will therefore not indicate if the control action has alleviated the situation or not when the generator is armature current limited.

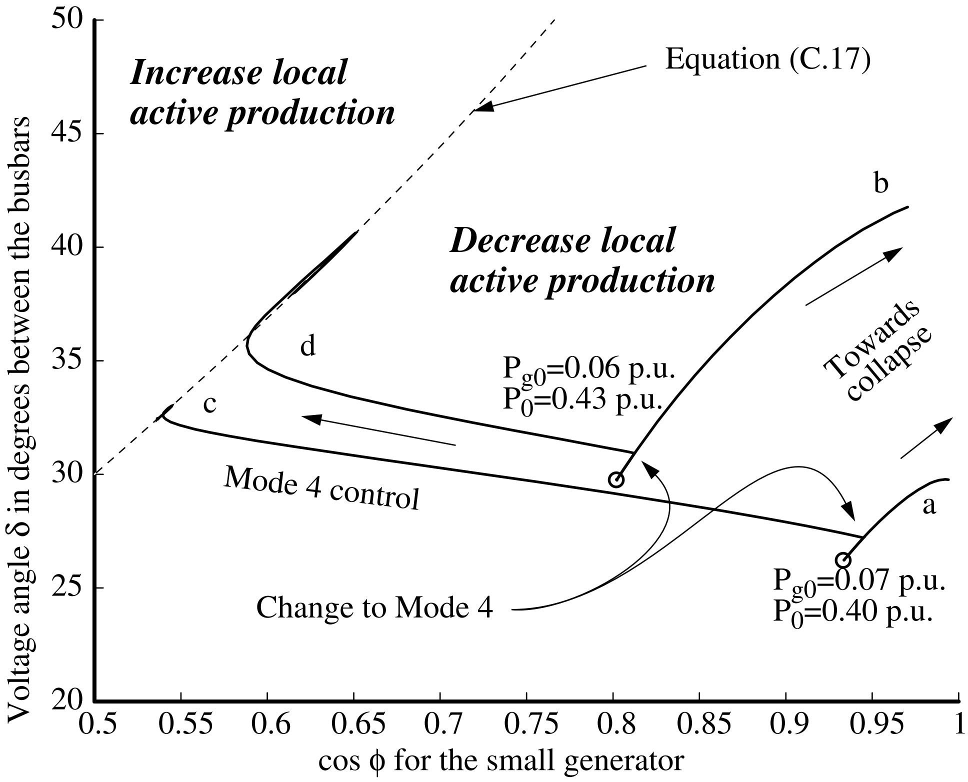

Figure C.11 The angle-power production plane for the small generator for four different simulations. I_l=0.08 p.u.

C.6.3 System Voltage Collapse

An example of how the control of active production in the small generator can be used to avoid system voltage collapse will be shown here. The system parameters have changed from earlier subsections to higher load P_0 and lower impedance X. The tap changer is blocked in this example to enlighten the effect of rescheduling. Otherwise the system is the same as before. Two different starting levels of active power production with and without active power rescheduling are shown (Figures C.12 and C.14).

One of the parallel lines in Figure C.1 is disconnected at t=0 as the initial disturbance. This immediately activates the armature current limiter at the small generator and voltage drops transitionally from its pre-disturbance value of 1.0 p.u. shown in Figure C.12. Dynamic load recovery then tries to restore power demand until around 80 s when both cases violates the reactive power limit in the large generator and mode 8 is activated. Figure C.14a shows the trajectories in the PV plane and how mode 8 causes the voltage to collapse.

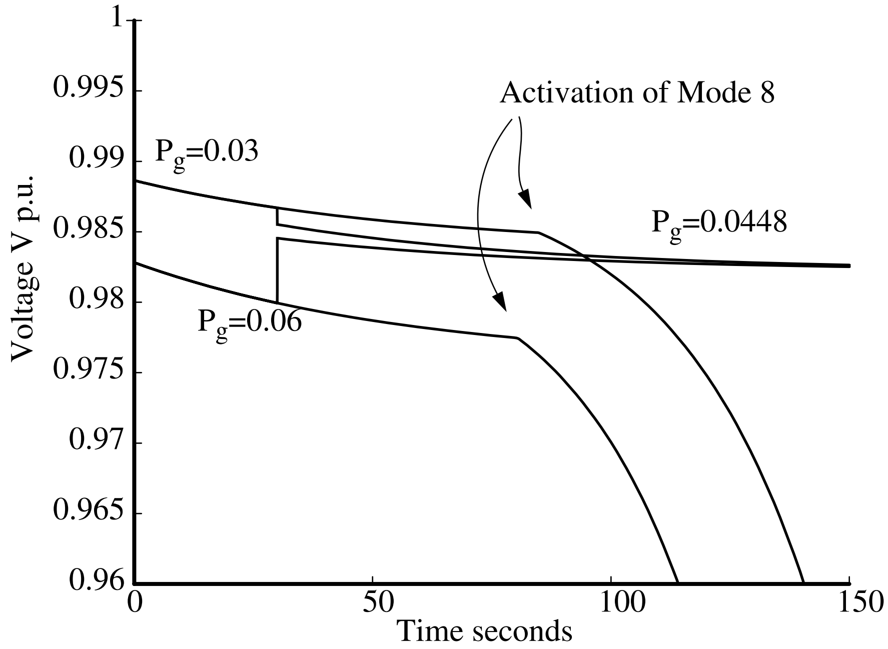

Figure C.12 The active production P_g is rescheduled at t_{sw}=30 s to the value that increases the load capability and avoids activation of Mode 8 and a collapse.

To alleviate the collapse in this case is to change P_g to achieve as high a loadability as possible without violating the Q_{max} limit at the large generator. This constraint will modify the shape of the P_l-P_g curve in Figure C.6 but it will still have a similar shape as can be seen in Figure C.13 by the dash-dotted line. The figure shows the capabilities when the voltage V_t is at its set-point value for mode 3 and mode 8 and the combined constraint.

Since the system capacity is not sufficient to deliver the load demand after the line trip, an instant voltage drop occurs as seen in Figure C.12. This decreases the load demand transitionally and increases the capability of Mode 3 operation until an equilibrium is achieved. However, the voltage drop also decreases the system capability for mode 8 operation. Dynamic load recovery will slowly decrease the voltage and move the working point towards the dash-dotted line in Figure C.13 which shows the line where the capabilities of mode 3 and 8 are equal. A further voltage drop will activate mode 8 and the system will collapse.

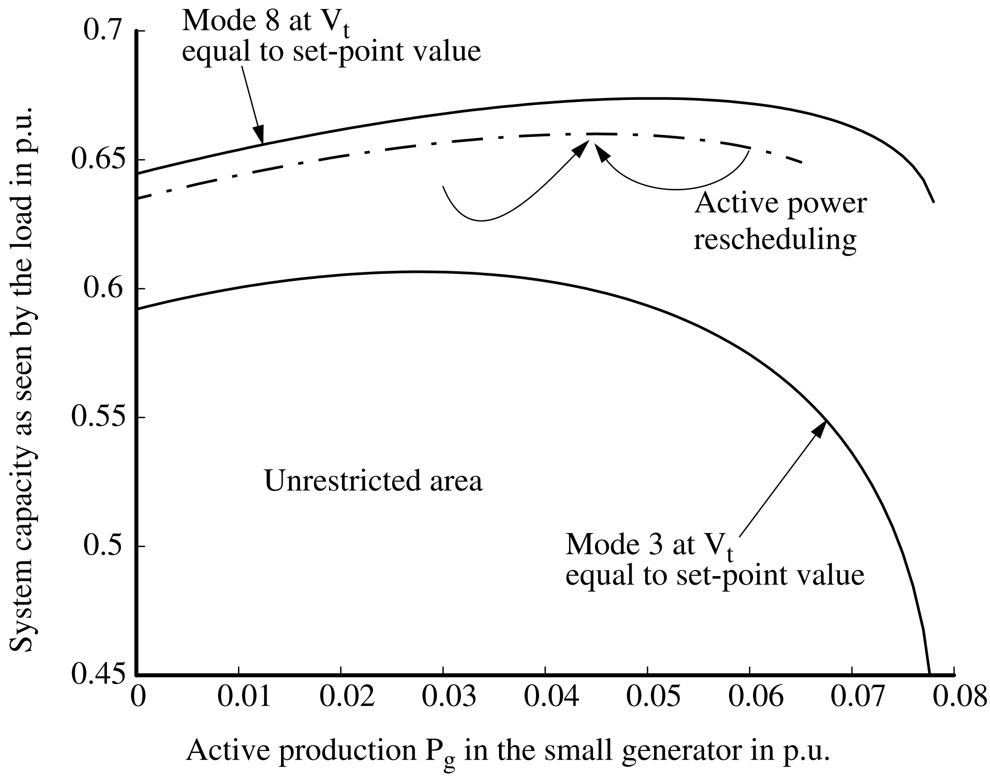

Figure C.13 The capability curve for Mode 3 and Mode 8

Figure C.14 illustrates the influence of the rescheduling of P_g in the VP-plane. The severe characteristic of mode 8 is shifted to the right in Figure C.14b) when the scheduling is performed. The two cases shown in Figure C.14a) illustrate the unstable system behaviour caused by activation of mode 8. At the two points denoted by small circles in Figure C.14b) the active production P_g is changed to the new value which gives higher load capability for mode 3 without violating Q_{max} and the trajectory transitionally jumps to the new capability curve. The dash-dotted line indicates, for all possible values of P_g, the activation point from mode 3 to mode 8. It is the same line as the dash-dotted line in Figure C.13 but now seen in a different plane.

The new P_g is found by solving the equation system described by equation (C.12) and equation (C.18) and from these the maximum loadability point is calculated. The chosen load characteristic has a transient characteristic of α_t=2 and a constant power load characteristic of α_s=0. This makes the system unstable in Mode 8 [C.12]. The time t_{sw} is in this example chosen without any deeper analysis.

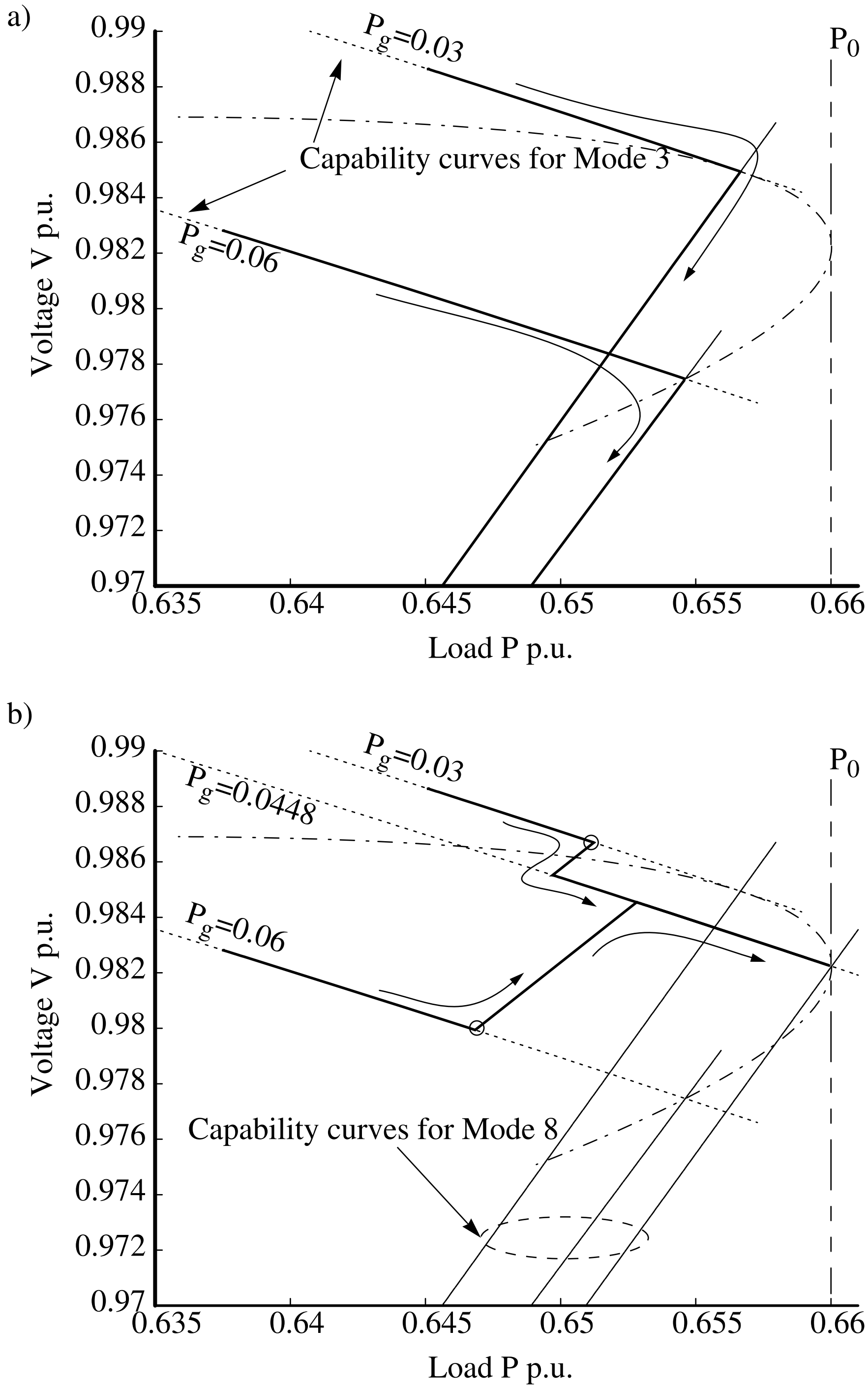

Figure C.14 Post-disturbance trajectories in the VP-plane for four different cases. P_0 is the nominal (pre-disturbance) active load power

It is interesting to note that for the two cases where a switching occurs the load voltage changes in opposite directions when the power rescheduling is executed. The condition used by Arnborg [C.1] for load shedding is that voltage should always increase at the 'switching' time in order to save the system. Figure C.12 illustrate that voltage behaviour immediately after the switching cannot be used as a criterion for a successful active power rescheduling. One can view the problem in the following way. In the case of a high active production in the small generator, the system benefits from a decrease in its production which releases more reactive power. When it has a low active production though, the load capability is increased by producing more active power locally. For the more simple case presented in Section C.6.2 it is easier to see that the system could make use of either an increase or a decrease of active power production.

The analysis of modes 5 and 6, i.e. modes with the large generator field current limited can be assignable to a case similar to a radial voltage collapse presented in section C.6.1. The field current limiter will increase the reactance between the generators and by this make the connection weaker.

C.7 Conclusions

This paper demonstrates in a number of ways how field and armature current limiters can interact with the power system and may cause voltage instability even for a simple system. The time period studied is the first minute or so after a contingency which will cause violation of the current limiters and by this threaten system stability. The different current limiters divide the system operation into different ‘modes’. Some voltage collapse scenarios associated with these modes are discussed and remedy actions by means of active power rescheduling is introduced. Carefully selected small changes of active power production increase the static system loadability for these operating modes. Dynamic simulations show that the system can make use of this increased static capability at least by prolonging the time until the voltage collapse occurs. It has been demonstrated that the power system during certain conditions can make better use of reactive power than active power and that a local *decrease* of active power may *increase* the maximum load capability in that area. Armature current limitation shows this characteristics during certain cases. A quantitative ‘rule’ describing a favourable relation between local active and reactive power production during armature current limitation is determined. Field current limitation request a local increase of active power production to increase the maximum load capability in that area.

It is also shown that local active power rescheduling can alleviate voltage instabilities in remote areas. By including control signals (alarms) from generators remote to the controlled one, it might be possible to avoid that the geographical area of voltage instability increases.

C.8 Acknowledgements

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C.9 References

[C.1] Arnborg S., ”On strategies for Undervoltage Load Shedding in Power Systems”, Stockholm Power Tech, Sweden, STP PS 06-03-0378, pp. 167-172, 1995.

[C.2] Popović D., Hiskens I. A. and Hill D. J., ”Investigations of load-tap changer interaction”, International Journal of of Electrical Power & Energy Systems, Vol. 18, No. 2, pp. 81-98, 1996.

[C.3] Vu K.T. and Liu C.-C., ”Dynamic mechanisms of Voltage Collapse”, Systems & Control letters 15, pp. 329-338, 1990.

[C.4] Vu K.T. and Liu C.-C., ”Shrinking stability regions and Voltage Collapse in Power Systems”, IEEE Transactions on Circuits and Systems-I: Fundamental Theory and Applications, Vol. 39, No. 4, pp. 271-289, 1992.

[C.5] Xu W., Mansour Y. and Harrington P. G., ”Planning methodologies for voltage stability limited power systems”, Int. Journ. of Electrical Power & Energy Systems, Vol. 15, No. 4, pp. 221-228, 1993.

[C.6] Sjögren F. G. A., Johansson S. G. and Daalder J. E., “Behaviour of generator current limiters near the point of voltage collapse”, Stockholm Power Tech, Sweden, STP PS 07-06-0492, pp. 221-226, 1995.

[C.7] Cigré, TF 38-02-10, ”Modelling of Voltage Collapse Including Dynamic Phenomena”, 1993.

[C.8] Hill, D. J. ”Nonlinear Dynamic load Models with Recovery for Voltage Stability Studies”, IEEE Transactions on Power Systems, Vol. 8, No. 1, pp. 166-176, 1993.

[C.9] Karlsson D. and Hill. D. J., ”Modelling and identification of Nonlinear Dynamic loads in Power systems”, IEEE Transactions on Power Systems, Vol. 9, No. 1, pp. 157-166, 1994.

[C.10] Gustafsson M. and Krantz N., ”Voltage Collapse in Power Systems-Analysis of Component Related Phenomena using a Power System Model”, Technical report No. 215L, ISBN 91-7197-221-8, Dept. of Electrical Power Engineering, Chalmers University of Technology, 1995.

[C.11] Lachs W. R., ”Control of Voltage Stability on EHV Power Systems”, The University of New South Wales, School of Electrical Engineering, May 1992.

[C.12] Johansson S. G., Sjögren F. G. A., Karlsson D. and Daalder J. E., “Voltage Stability Studies Using PSS/E”, Bulk Power System Phenomena III, Davos, Switzerland, pp. 651-661, 1994.

Paper D Mitigation of Voltage Collapse caused by Armature Current Protection

Accepted for publication in IEEE Power Engineering Society Transactions

Abstract

The importance of field current limiter behaviour during voltage instabilities is generally known. A field current limiter will weaken the system by introducing extra reactance. A tripping of the generator by an armature overcurrent relay or the activation of an armature current limiter will severely cripple the power system which often causes the breakdown of the system voltages. One way to alleviate the influence of the armature current protection during the instability is to make small changes in the active power production of the generator and thereby fully utilize the capability of the generator. Depending on the location of the overloaded generator different actions can be taken to support the critical area as long as sufficient transmission capacity and that active and reactive power reserves are available remotely. This active power rescheduling may also alleviate the influence of a field current limiter. Some simulations are shown for a power system with a radial structure.

Keywords

Long-term Power system dynamic stability, Armature Current Limiter, Field Current Limiter, Active Power Rescheduling

D.1 Introduction

Some contingencies in a power system may lead to a stressed situation where voltages appears to be stable. These ‘voltage instabilities’ may evolve in an unfavourable sequence of events consisting of different control- and protection actions which interacts with the physical behaviour of the transmission system. This causes a situation where voltages eventually becomes uncontrollable and non-viable. The system may experience a voltage collapse. The number of actions involved in such a sequence indicate that a broad spectrum of components and several time constants must be taken into account. By properly identifying the behaviour of the involved components and the interactions in this sequence one might be able to suggest remedial actions alleviating the voltage instability. One major contribution to the final phase before collapse is the limitation of currents in the generator to avoid overheating. This paper investigates this aspect in particular.

Field windings are protected by field current limiters whereas armature windings may be protected either by overcurrent relays or current limiters. Nuclear power plant generators in Sweden are protected by both field and armature current limiters where the field current is reduced in order to avoid overloading. An implementation of these limiters is described in reference [D.10]. An overcurrent relay can be used for thermal protection of the stator [D.7, Section 4.1.1.2] or as a backup protection and effectively limit the available armature current.

The field and armature current limiters have a completely different impact on generator behaviour during an instability [D.15]. A too high armature current will in many cases cause a relatively fast voltage collapse once the current is limited. The goal here is to avoid limitation or to alleviate the impact of this protection equipment by changing active power production in the generator. The same method may be used to avoid an overcurrent tripping of the generator which is an even more severe case since all production from the generator will then be lost instantaneously. References [D.4] and [D.16] also discuss other generation based countermeasures to avoid long term voltage collapse.

D.2 General idea and background

Power systems as the Nordel system (the interconnected transmission system of Norway, Finland, Sweden and Zealand in Denmark) have a radial structure where power is transferred over long distances to load areas. A general outline for such a system can be seen in Fig. D.1. Most of the load power demand P_d comes in this case from the remote generation area which is responsible for the frequency control. The relatively small generator P_g influences the voltage level in the load area. Since the current limiters of the small generator affects the production of reactive power, the limiters will decide the maximum load demand P_d that the system can supply, or in other words the system capability in the load point. Normally, the capability of the generator is given as in Fig. D.2.

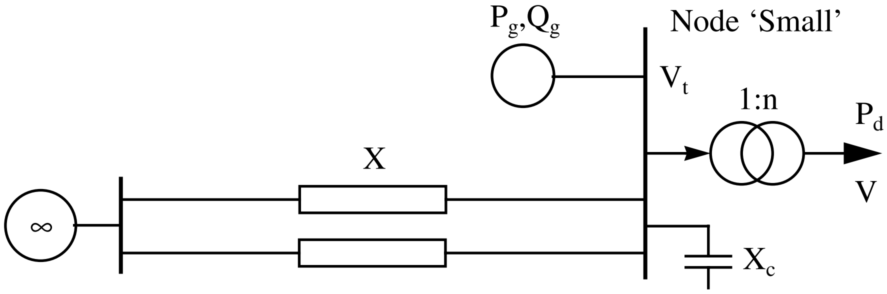
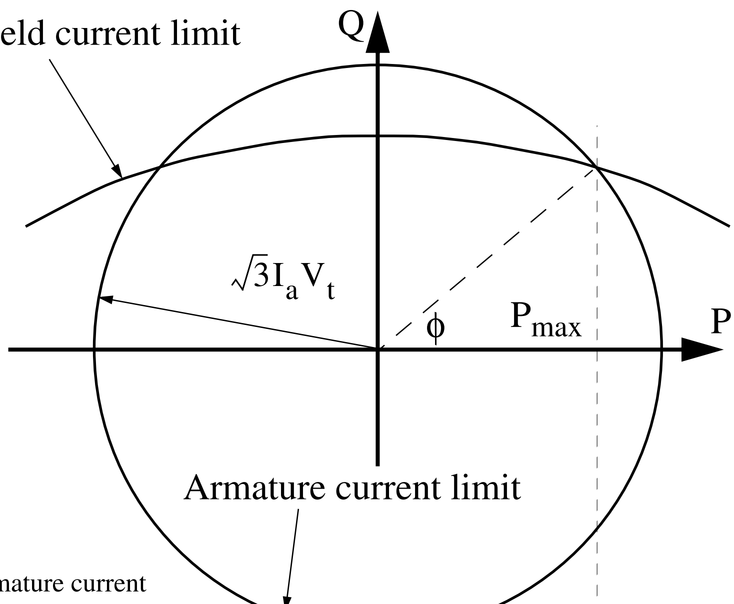


Figure D.1 A representative model of a radial system.

The armature current limit is represented as a circle whereas the field current limit follows an arc in the PQ-plane. Several other restrictions may influence this capability [D.1]. If the power plant increases its efficiency on the turbine side and hence increases P_{max} (without an increase of the rating of the generator) the armature current limit will be the critical one. Also, a decreasing terminal voltage V_t will shrink the armature current circle and threaten the generator of an armature current violation. Here the analysis is taken from the systems point of view. In references [D.8] and [D.9] the *system capabilities* for different operating 'modes' of the involved current limiters are calculated. Appendix I gives a summary.

As an example, Fig. D.3 shows the quantitative shape of the system capability for two modes. The capability is plotted as a function of the active power production P_g in the small generator either when the small generator becomes field current limited (Mode 2) or armature



I_a is the maximum armature current
$\cos\phi$ is the power factor of the generator

Figure D.2 The capability curve for a single generator.

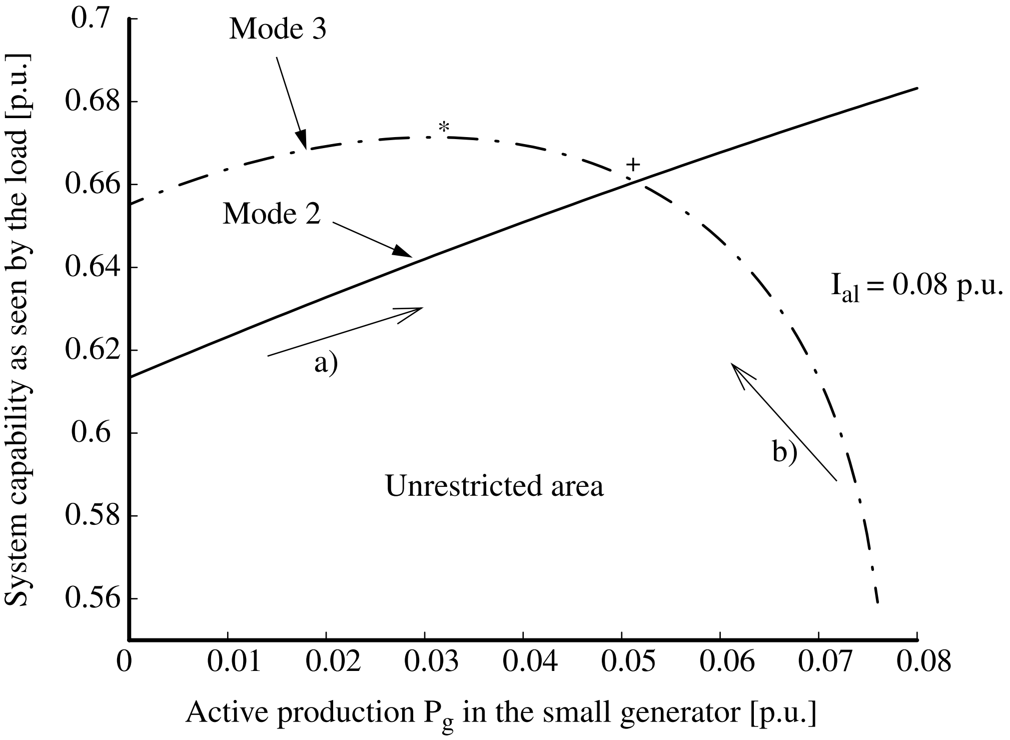


Figure D.3 The curves show the system capability as a function of active production in the small generator for 2 different modes.

current limited (Mode 3). The relative position between the two curves will vary with the system parameters.

If the load demand becomes higher than the system capability one of the limiters in the small generator will be activated (assuming the remote production source to be infinite). This will change the performance of the power system and a voltage instability process may emerge. As can be seen in Fig. D.3 it can be possible to avoid a limitation and increase the system capability in the load point by changing active power production. The basic idea is then to try to 'tune' or modify both active and reactive power production in the small generator to increase the amount of load demand the system can support in that local area. Present current limiters are only controlling (decreasing) reactive power output.

When the small generator becomes field current limited an *increase* of active power production should be made (arrow a in Fig. D.3) until the generator reaches armature current limitation (or maximum active power production) indicated with + in the figure. Note the possibility to temporarily 'boost' a field current limit above its steady state level until the field winding reaches its maximum temperature [D.8, D.12]. This may remove the field current limit restriction completely for a while and make the system capability solely dependent on the armature current limit (indicated by the dash-dotted line in Fig. D.3). The system capability curve has then a maximum point indicated with * in Fig. D.3. A *decrease* of active power production during armature current limitation (arrow b) must take this point into account.

Reference [D.9] gives an expression for this maximum point under the assumption of voltage independent load demand (the combination of load and tap changer control may be seen as a voltage independent load for longer times). The relation is shown in (D.1) below. It can also be identified in the power circle plane of the transmission line [D.6, D.16]. The dotted vectors in Fig. D.4 indicate a situation where the small generator is becoming armature current limited. This implies that vector a) has its maximum length (assuming constant voltage). A decrease of reactive power output, Q_g, from the small generator in this situation decreases the amount of power P that can be transmitted over the line i.e. decreases the system capability in the load point. If on the other hand the available apparent power from the small generator is used in such a way that it aligns itself with the vector describing the line capacity, the system capability will be maximized as shown with

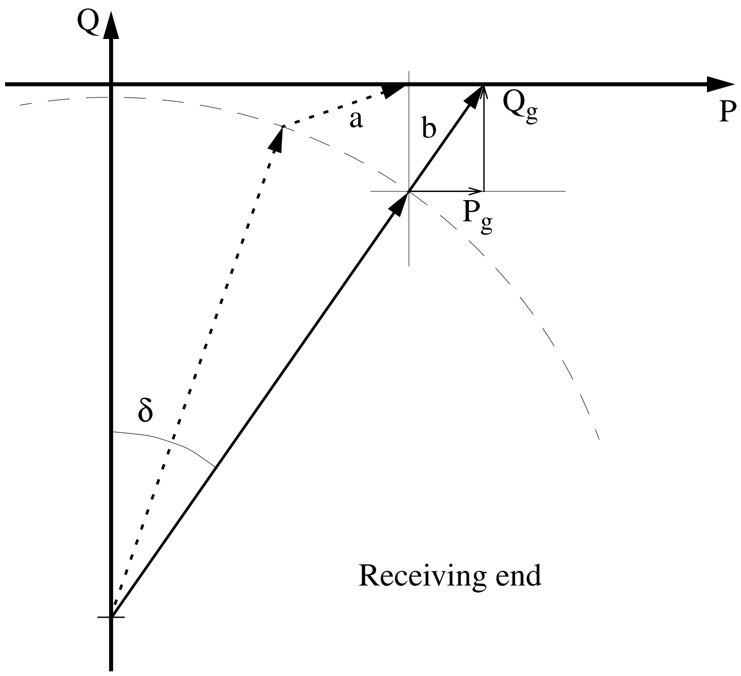


Figure D.4 The power circle plane for the transmission system in Fig. D.1. Vectors a) and b) have the same length representing $|V_t \cdot I_{al}|$.

solid vectors in Fig. D.4. If δ represents the voltage angle between the infinite bus and the load bus one can write (from Fig. D.4)

$$\frac{Q_g}{P_g} = \frac{1}{\tan\delta} = \tan\phi \tag{D.1}$$

where cos ϕ is the power factor of the small generator. This relation indicates the power factor for the small generator at the peak of the system capability in Mode 3 operation assuming an *infinite remote bus* and that the *transmission system* is *unaffected*. If the rescheduling of active power activate any current limitation at the 'infinite' bus or initiate distance relay protection, further analysis must be done (see [D.9]) to estimate the optimum P_g. A common value of δ in a tie line section may be 30°. The power factor giving maximum load capability for an armature current limited generator in the receiving end is then 0.5 i.e. a rather low value.

The discussion so far assumes zero reactive power load, Q_d, and voltage independent load. Graphical construction in the circle plane indicates for different kinds of reactive power loads how the small generator should be used for a load with reactive power demand. Some are indicated in Fig. D.5.

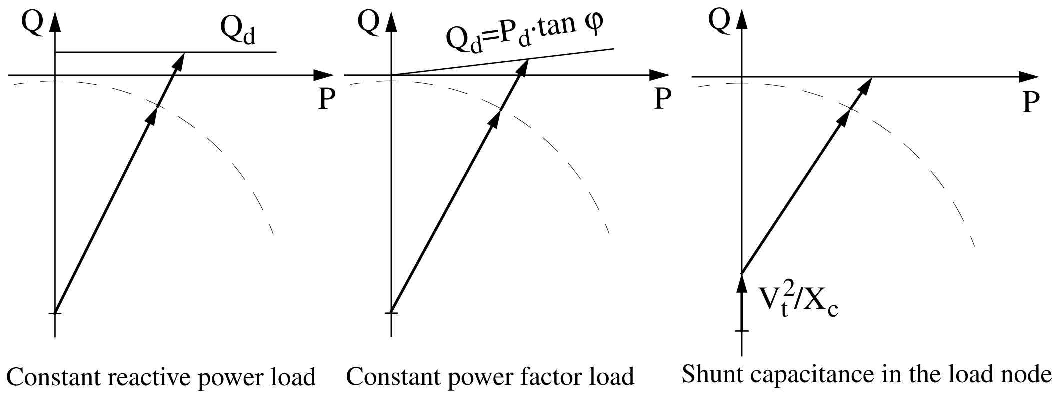


Figure D.5 Examples of reactive power demand and the maximum system capability point in the power circle plane

This paper will not discuss any questions on powerplant technology investigating the ability to change active power production or how to implement this into the existing governor system [D.16, D.17]. It is assumed that active power production is controllable and that it can be adjusted in moderate steps at a time scale of a couple of seconds and thereby operate in the same time scale as the current limiters.

Simulations in a small network that confirm these relations have to some extent been performed in [D.9]. Here we will analyse a more complex and larger network. The network used is the CIGRE Nordic 32 described in [D.3] which aims at having properties similar to the Nordel power system. A fairly simple Active Power Rescheduler (APR) has been designed which controls the mechanical input to the generator shaft when it becomes armature current overloaded. Fig. D.6 shows the function of the APR. If the armature current limit, I_{al}, is

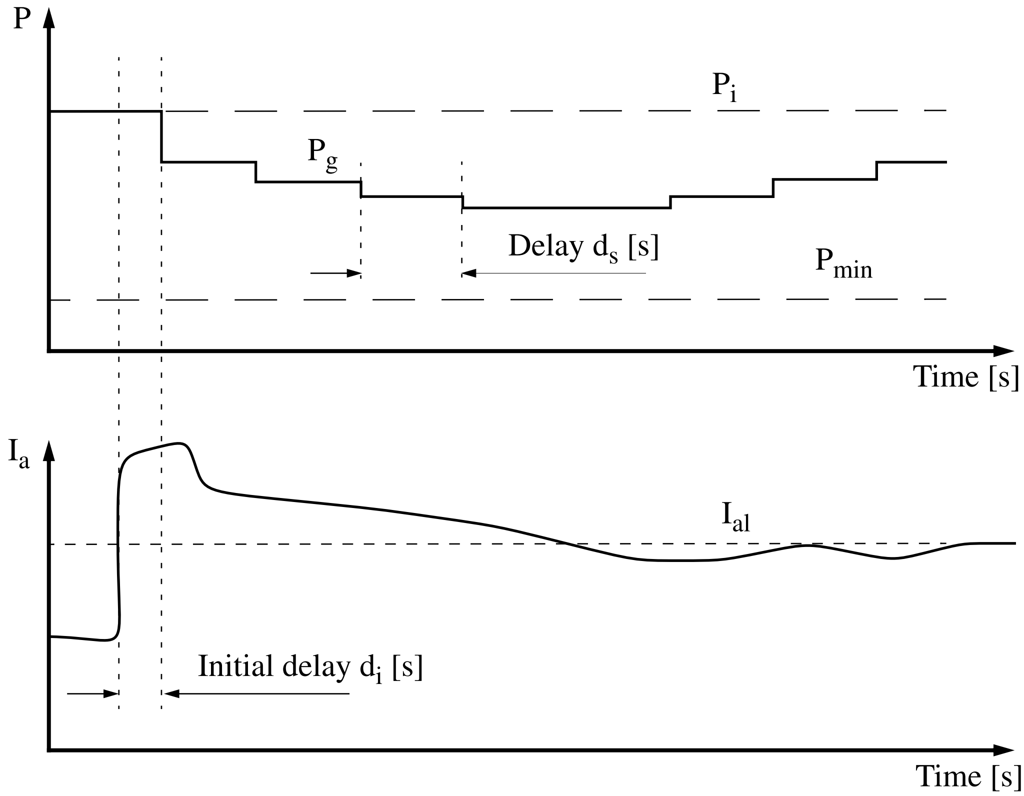


Figure D.6 Schematic behaviour of the active power rescheduler.

violated, the mechanical power set point P_g is lowered proportionally to the violation after an initial delay d_i. This stepping is continued every d_s second. P_g is stepped down when I_a is above its limit and stepped up when I_a falls below I_{al}. P_g is limited upwards by its pre-disturbance value P_i and downwards by a minimum value P_{min} which is an estimation of power production at the peak of the system capability. As will be seen further on the deviation from P_i will be rather small in the simulations. The stepping of P_g will also be blocked if the field current limit becomes violated which indicates that the system operates at the crossing marked with + in Fig. D.3. The value of P_g is then filtered with a time constant T_f to remove the steps in P_g

according to (D.2). The value P_m is used as the input to the generator shaft.

$$\frac{P_m}{P_g} = \frac{1}{1 + T_f s} \qquad (D.2)$$

None of the generators equipped with an APR in this analysis belongs to those responsible for frequency control so there will be no conflict with the governor. The ordinary current limiters which are a part of the parameters of the Nordic 32 network are still operable. The APR comes into action as a slower secondary control outside the original AVR/armature current limiter control loop trying to increase the capability for the system locally. To achieve selectivity between the different control systems the set point of the APR is chosen 0.01 p.u. below the setpoint value of the armature current limiter. The parameter values used for all simulations in this paper are d_i=1 s, d_s=10 s and T_f=1 s. The initial delay d_i is taken to be 1 second in order to study the exclusive influence of the APR (cf. end of Section D.3); the other parameters have been found empirically. The chosen delay d_s gives a rather slow response from the APR and where the AVR/armature current limiter control will dominate. An active power increase (when available) during field current limitation is not implemented into the APR and has not been considered so far.

D.3 The Nordic 32 test case

Several presentations of the used network showing different properties are available [D.2, D.13 and D.14] apart from the CIGRE-report itself [D.3]. The ideas presented in Section D.2 will be used here to try to protect a tie line cross section, indicated in Fig. D.7 by a dashed line, from a voltage collapse. The pre-disturbance situation is a highly loaded network where several different single contingencies will lead to a voltage collapse. The transmission of active power over the tie line section is heavy and an increase due to loss of production in the south or loss of transmission capacity will be severe for the system.

The simulations are performed with the PSS/E[1]-software and the same models are applied as used by Svenska Kraftnät when designing the network for CIGRE. Voltage drop compensation for most of the step-

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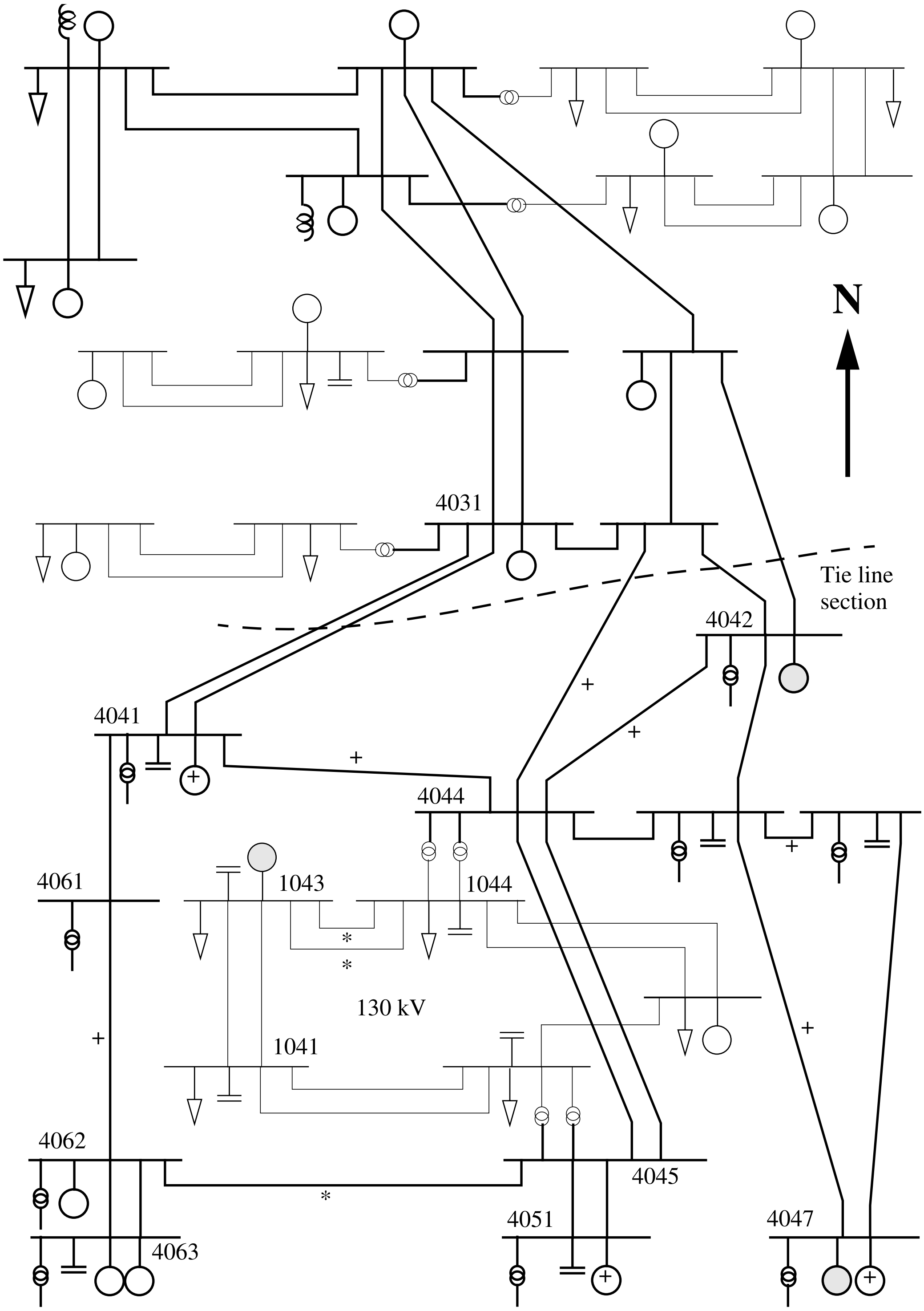


Figure D.7 The CIGRE Nordic 32 network. Shaded generators are equipped with an Active Power Rescheduler. Transmission lines of particular interest in this paper are indicated with * and components involved in section D.4.3 with +.

up transformers have been added to the original data set keeping voltages at the transformer nodes at their pre-disturbance level.

A comparison is made between the original data setup based on a static load model and simulations where load demand has a dynamic recovery as observed in field measurements in the Swedish network [D.5]. The load demand can then be represented by [D.11]

$$T_{pr}\frac{dP_r}{dt} + P_r = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{D.3}$$

$$P_m = P_r + P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{D.4}$$

where

V = supplying voltage [kV],

V_0 = pre-fault value of supplying voltage [kV],

P_0= active power consumption at pre-fault voltage [MW],

P_m = active power consumption model [MW],

P_r = active power recovery [MW],

α_s = steady state active load-voltage dependence,

α_t = transient active load-voltage dependence, and

T_{pr} = active load recovery time constant [s].

The parameters applied in this paper are α_s=0, α_t=1.3 and T_{pr}=60 s giving complete active power recovery. The reactive power load is represented as an inductance (quadratic voltage dependence) for all simulations.

Since the system responds differently to an active or reactive power change one must be careful about how to control the generator during the delay occurring after limiter *activation* (when the steady state level is exceeded) and prior to limiter *in operation* (when actions are taken). For the Nordic 32-network this delay is originally 20 seconds but has been decreased to 1 second for all armature current limiters in these simulations. The generator currents is then strictly limited to its steady state level within 1 second. The reason for this decrease in initial delay is to be able to calculate the exclusive influence that the active power rescheduling has on the system. The importance for the stability of this delayed operation can for instance be seen in [D.8] where a temporary overloading of the field current prolonged the time before the collapse.

Further studies are necessary to establish a satisfactory operation of the generator during this delay.

D.4 Simulations

D.4.1 Radial case in the sub-transmission part

The first simulation will excite the limiter of generator 1043 (Fig. D.7). This is one of several weak spots in the initial settings of the network. A double circuit tripping of the lines between 1043 and 1044 will initiate the armature current limitation of the generator which will cause a voltage collapse if no remedial actions are taken.

The outcome of this contingency depends on the chosen load model in the 130-kV part. For the static case i.e. the original data set, this contingency will be stable since the load demand will decrease approximately proportional to the voltage drop. However, one or more levels of regulating transformers below the 130-kV system (which are not included in this study network) and load behaviour will make the load demand voltage independent after a while [D.5]. Therefore, in the following example, all loads are dynamic as specified in Section D.3.

When the double-circuit trips, the 130 kV-system forms a radial structure with an armature current limited generator at the end, similar to the system in Fig. D.1. As can be seen in Fig. D.8 the voltage collapses without APR whereas the voltage becomes stable with APR-control. The reactive power output is decreased in the first unstable case until it reaches zero after 35 seconds without being able to keep armature current below its limit (Fig. D.9). The generator is tripped causing a total breakdown of the voltage in the radial part. Distance relays and/or undervoltage load shedding will then (most likely) isolate nodes 1043 and 1041 if such relays are included in the system.

Fig. D.9 also shows the reactive power output from the generator when the active power input has been decreased somewhat. The reduction of active power releases a significant amount of reactive power shown in Fig. D.9 as a shaded area which keeps up the voltage level until support is supplied by the tap changers of the transformers between node 4045 and node 1045. The armature currents are exactly the same for the two cases until just before the collapse when it is impossible to keep the current limited.

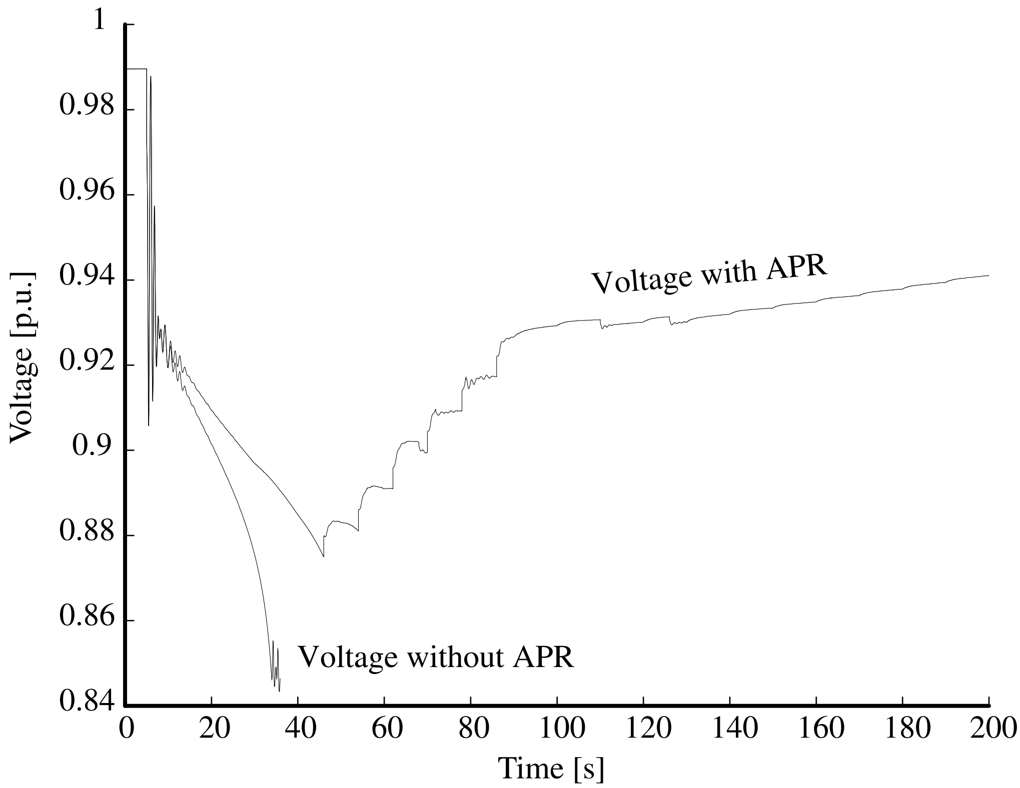


Figure D.8 Voltage in node 1043 for the two cases.

In Fig. D.10 the operation characteristics of the generator in node 1043 is summarized. Note especially the small decrease of mechanical

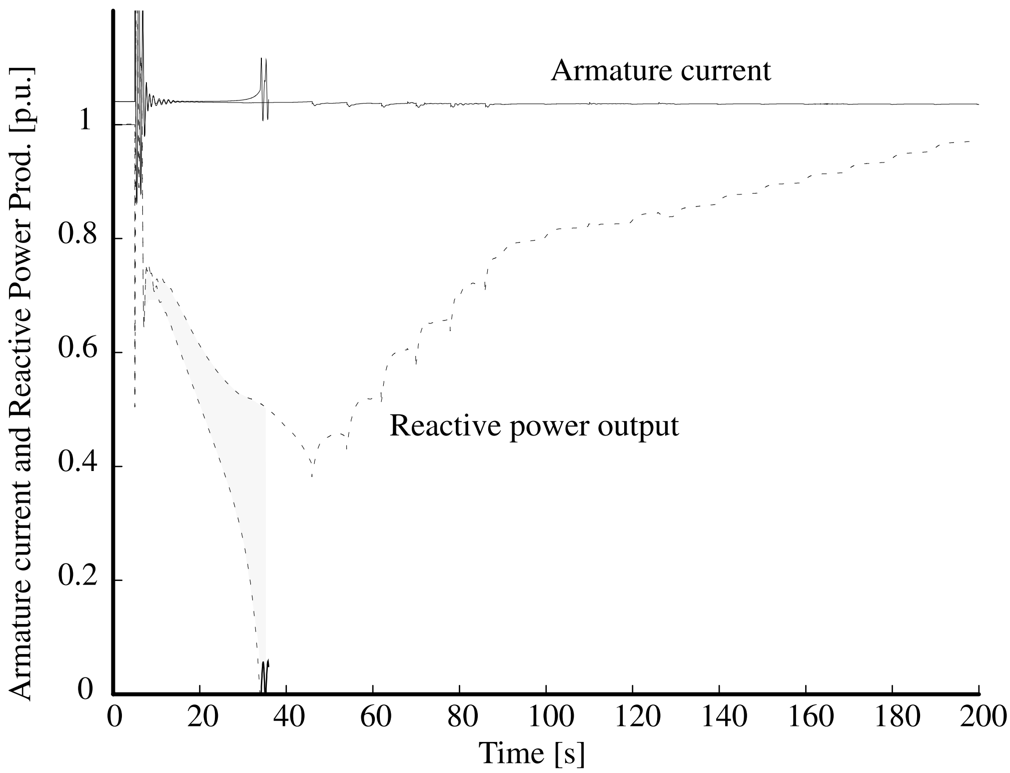


Figure D.9 The armature current (solid line) and reactive power production (dotted line) for generator 1043.

power input which starts after approximately 8 seconds. Compare the action with the capability of the system represented in Fig. D.3. If the operation of the radial part is far out to the right on the dash-dotted line (armature current limitation) a small decrease of mechanical power into the generator will increase system capability considerably.

The sensitivity to active power production can also be shown by starting the simulation with a smaller active power production in generator 1043. A decrease of less than 10 MW (of 180 MW) is sufficient to change the outcome of the unstable case to a stable one. The stable case with active power rescheduling has been simulated up to 800 s, a time which may be regarded as sufficiently long for the used models.

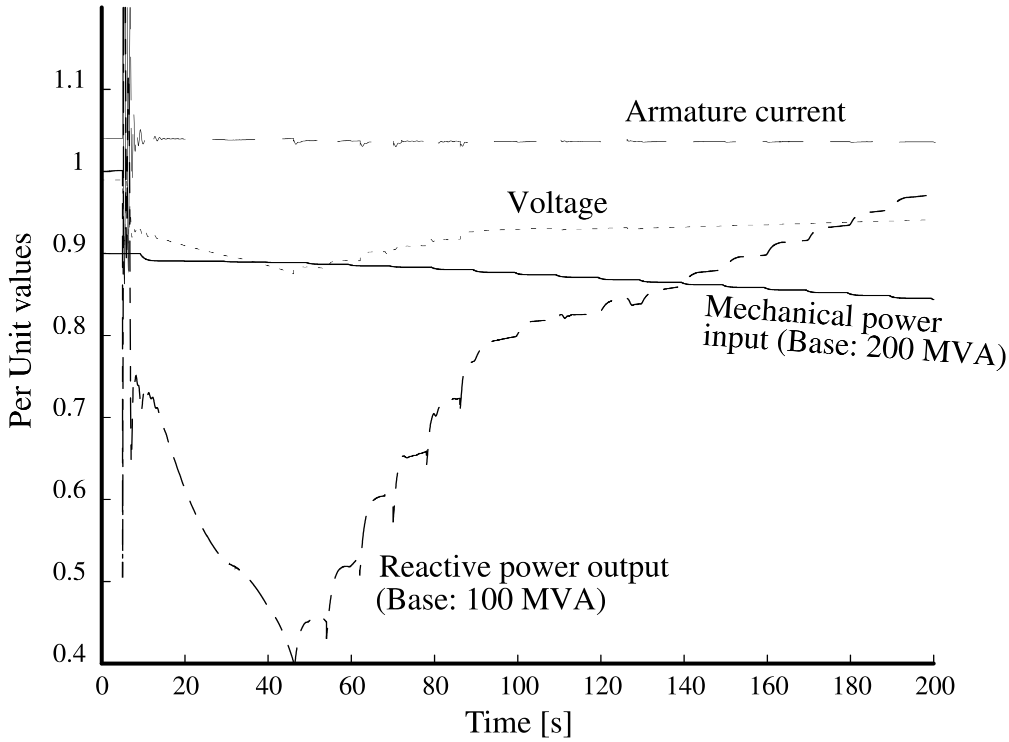


Figure D.10 The stable case. Note the small decrease of active power production (solid line) after 8 seconds.

D.4.2 Tripping of a 400 kV-line

A number of simulations were made when the line between node 4062 and node 4045 was tripped. The pre-disturbance active load demand in node 4063 was increased for every simulation raising the stress on the tie line cross section. The node 4063 was chosen due to the number of generators in the vicinity which can keep voltages in the system relatively constant between the simulations and thus keep the initial reactive power flows similar.

The line tripping will more or less divide the feeding of the southern part into three different radial structures. The general sequence of the most important events can be seen in Table D.1. The abbreviation ACL means that an Armature Current Limiter is *in operation* i.e. the delay of 1 s has already expired. A Field Current Limiter *in operation* is abbreviated with FCL and the time between *activation* and *in operation* is 20 seconds as in the CIGRE network specification. The active power rescheduling *in operation* is indicated with APR.

Since the setpoint value of the APR being lower than the one of the current limiter (-1%) the APR on generator 1043 is activated immediately but this has only a minor influence in the following. Table D.1 also reveals several other weak spots in the network. Generators 1043 and 4042 are initiated rather close to their armature current limits and generator 4031 close to its field current limit. Note that the field current limitation of 4031 can be dangerous for the APR-control operating in the south since the limitation weakens the transmission system in the transfer corridor. A fault closer to 4031 may stress that generator so much that the system endangers a rapid cascade of limitations of the generators up in the north i.e. a system voltage collapse discussed in [D.9].

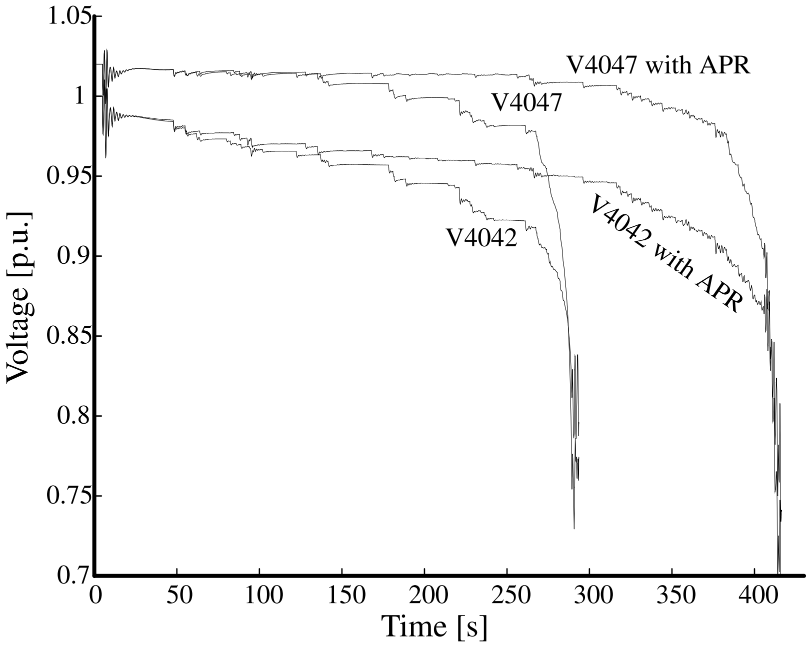


Figure D.11 Voltages with and without APR respectively for a line tripping in the south between node 4062 and node 4045.

Without APR		With APR	
Time [s]	Event	Time [s]	Event
		1	APR 1043
5	4062-4045 trips	5	4062-4045 trips
		6	APR 4042
6	ACL 1043	6	ACL 1043
6.3	ACL 4042	6.3	ACL 4042
95	FCL 4031	93	FCL 4031
138	ACL 4047	140	APR 4047_1
		263	ACL 4047_1
262	ACL 4051	357	ACL 4051
		384	ACL 4047_2
280	Collapse	410	Collapse

Table D.1: General sequence of events in Section D.4.2.

Figures D.11 to D.13 show some important aspects of the particular loading level described in Table D.1. Fig. D.11 displays the voltage levels for two different nodes in the system and Fig. D.12 shows the power flow through the tie line section. All frequency control is placed north of this tie line section, so when the APR comes into action and decreases local active production, more power must be transferred over the tie line section compared to the case without APR. Note however, that the reactive power demand is less due to the generally higher voltage level in the south which results in a lower demand of reactive power necessary in the transmission corridor despite the higher active power transfer.

Another way of showing the difference between these two cases is to plot the active load demand in the area south of the tie line section. Fig. D.13 shows that the load demand never reaches its pre-disturbance level without APR which is a requirement (α_s=0 in the dynamic load model). With the APR control the voltages are generally higher, the system succeeds in restoring the power demand above its steady state level but is not able to restore all of its energy deficit which has been added up in the load model during the first phase of the collapse. Eventually this case also collapses. The used load model ‘favours’ as small deviations as possible in voltage from its pre-disturbance value since it then lowers the energy deficit that arises until steady state power demand is achieved. This energy deficit must in this case be restored as an overshoot in power demand which stresses the system more.

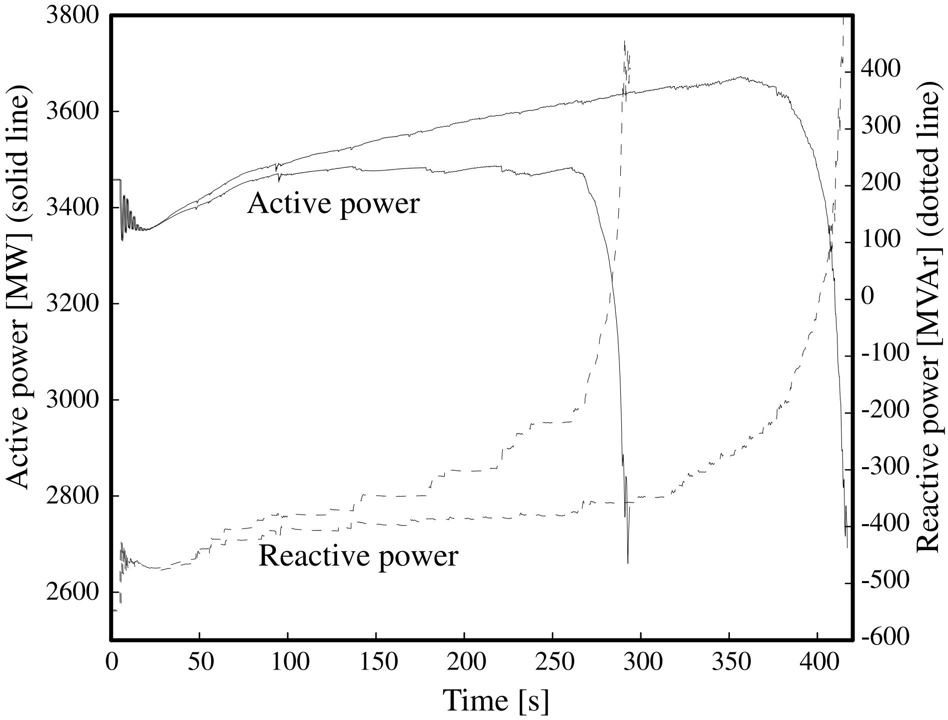


Figure D.12 Active and reactive power flows through the tie line section indicated in Fig. D.7. The loading is below Surge Impedance Loading and there is initially a northerly flow of reactive power.

The difference in time to collapse between the two control methods for all simulations is shown in Fig. D.14. The points indicate at which time

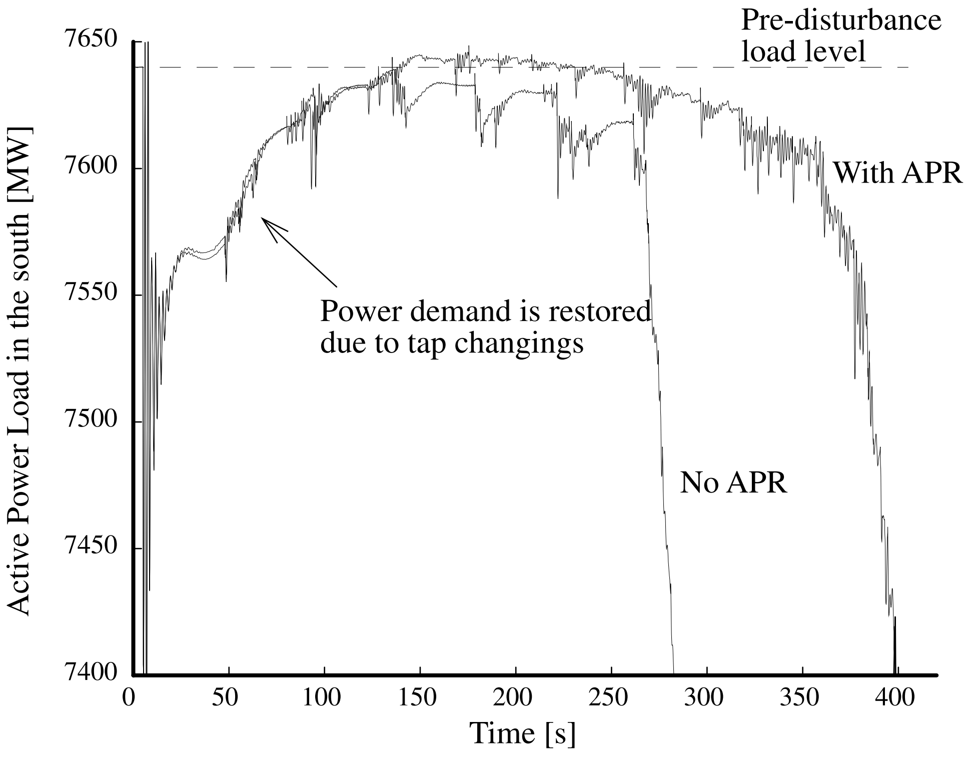


Figure D.13 The active power load demand in the south for the two cases. The dotted line indicate the pre-disturbance load demand.

the collapse occurs as a function of the transferred active power in the tie line section before the disturbance. The simulations have been executed up to 600 seconds so the points at 600 s are regarded as stable cases. The shadowed ‘window’ between the two curves indicate the gain in time or power that could be utilized with an APR. One can increase the power transfer with the same time to collapse, increase time before the collapse at the same level of power transfer or utilize a combination. At high transfers the curves merge. The control mechanism used has then less time to react. A faster control of active power may in such cases have been useful but it has been found that a faster control can cause situations where the advantage disappears for slow (other) collapses. The control becomes too fast. The goal here has been to find a rather robust (fixed) setting of the parameters of the APR, valid for all cases presented.

There are small variations from a monotone decrease in time as a function of power transfer shown in Fig. D.14. The origin of these are probably due to the tap changer deadband and the fact that the load model is initiated with its pre-disturbance value i.e. the voltage V_0 will vary between the simulations. These differences will appear in nodes without voltage control. As an example, the transformers between node 4044 and node 1044 and the load demand in node 1044 will interact in this way. It has not been possible to find a valid initial steady state power flow for a higher transfer through the tie line section than the highest one indicated in the figure (around 3750 MW). The highest feasible steady state load flow solution without the line (4062-4045) was just above 3644 MW. Note that the static load model is stable for all load levels despite that three generators work with the armature current limiter activated during the entire simulation. The reason is again that the static load model is ‘softer’ in this time range than the dynamic load model since the power demand decreases almost proportionally to the voltage.

D.4.3 ‘Monte Carlo’ simulations of single contingencies

To evaluate the performance of the APR, a broader spectrum of 9 different contingencies were applied to the system for a number of load levels. Components involved in these contingencies are marked with a small + in the network scheme (Fig. D.7).

In total 52 different network cases were analysed. Both the static load model defined in the CIGRE report [D.3] and the dynamic load model described in Section D.3 were used. Every simulation was executed

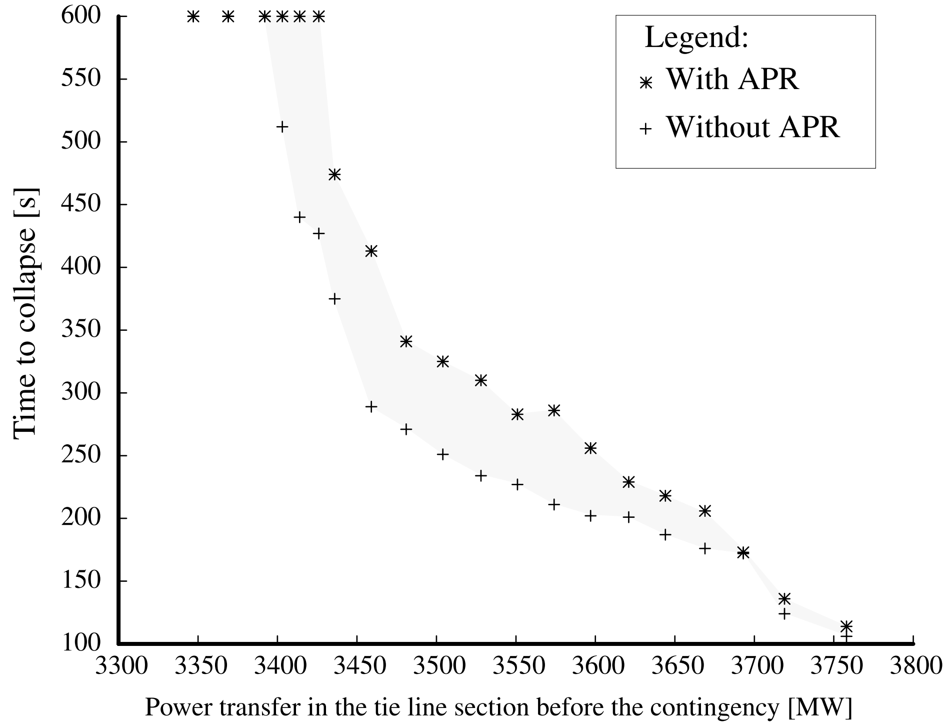


Figure D.14 A time-power window for the tripping of line 4062-4045.

with and without APR giving in total 208 cases. For those with a static load model 36% collapsed within 600 seconds whereas 54% collapsed with the dynamic load model. For the collapsing cases a plot was made indicating the time difference in seconds between the time for collapse with APR and without APR as a function of collapse time without APR. The plot is shown in Fig. D.15. One case was stable with APR

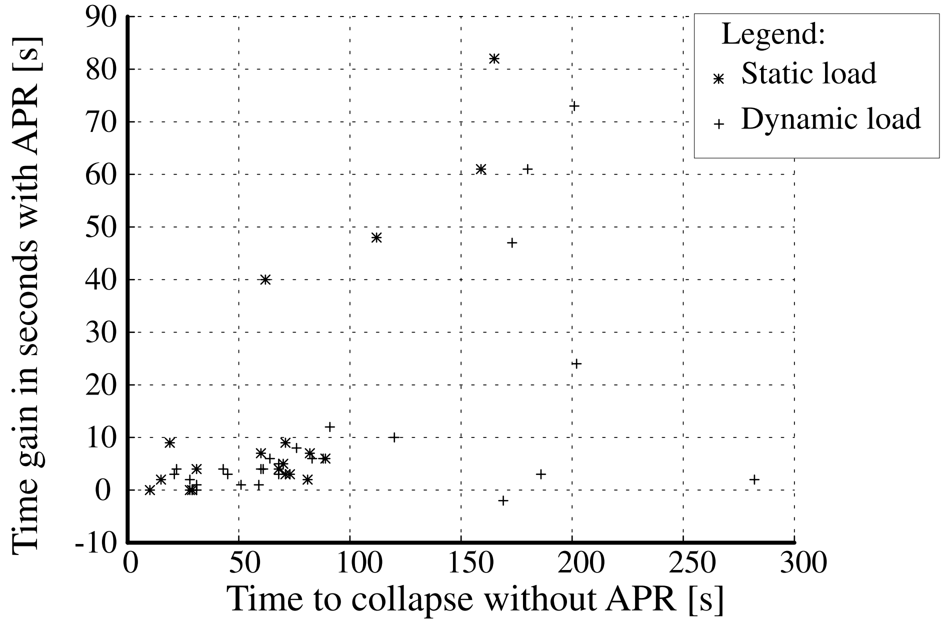


Figure D.15 A comparison between collapsing cases with and without APR

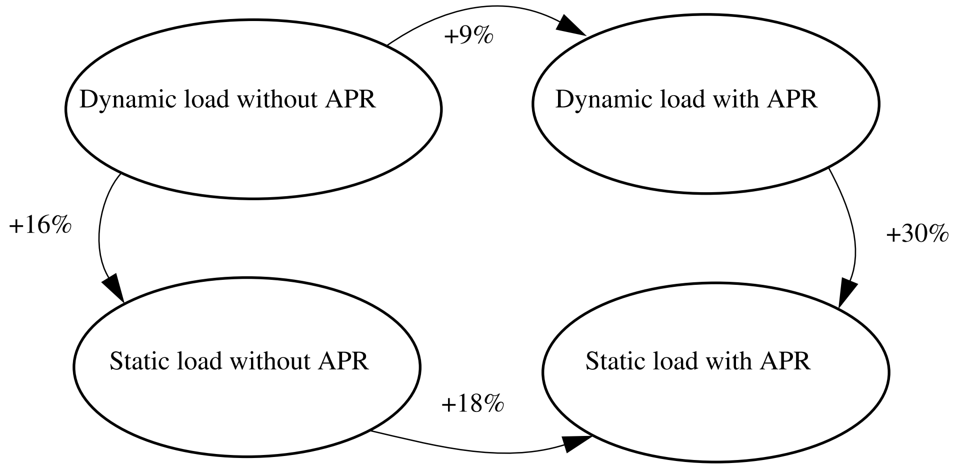


Figure D.16 The average gain in time for different modes of operation and load representation.

and unstable if not. The relative gain will vary between roughly zero and some 60% for these cases.

The average time gain before a collapse can be seen in Fig. D.16. Noteworthy is that the static load model gives longer times before collapse than the dynamic one except for fast collapses ($t<\sim 25$ s). The reason for this is that the dynamic model is initially a little bit softer ($\alpha_t=1.3$) than the static one ($\alpha=1$).

D.5 Conclusions

An active power rescheduling may during certain cases alleviate a voltage instability. The main requirement is that there is a strong remote generation area, which can be used to compensate the changed active power production. Also the changed power transfer must not initiate any relay protection trippings in the transmission grid. At least three advantages can be found by including active power rescheduling during armature current limitations:

- Higher voltages in the load area permits less reactive power losses in the transmission system (cf. Fig. D.12).
- Less energy[1] deficit in the dynamic load behaviour arises during the disturbed phase which alleviates any power overshoots (cf. Fig. D.13).

1. Originally wording: power

- Avoided or delayed tripping of an armature current limited generator approaching underexcited operation (cf. Section D.4.1).

It was found that a rather slow control of active power production was most beneficial in these simulations where the conventional armature current limiter were in action a considerably part of the time. Further studies are necessary to derive a proper design of this control system, especially with respect to the delay between activation and in operation of the armature current limiter and the requirements from the power plant operation. Also, the influence on power system oscillations must be investigated.

Acknowledgements

The author would like to thank Elforsk AB for their financial support through the Elektra-program.

References

[D.1] M. M. Adibi and D. P. Milanicz, “Reactive Capability Limitation of Synchronous Machines”, IEEE Transactions on Power Systems, Vol. 9, No. 1, pp. 29-40, 1994.

[D.2] S. Arnborg, ”Emergency Control of Power Systems in Voltage Unstable Conditions”, Ph. D.- Thesis, TRITA-EES-9701, ISSN 1100-1607, Royal Institute of Technology, Sweden 1997.

[D.3] Cigré TF 38-02-08 ”Long Term Dynamics Phase II”, 1995.

[D.4] Cigré TF 38-02-12 ”Criteria and Countermeasures for Voltage Collapse”, October 1995.

[D.5] G. leDous, J. Daalder and D. Karlsson, ”Dynamic Load Measurement in a Transmission System”, International Power Engineering Conference -97, Singapore, pp. 74-79, 1997.

[D.6] J. Grainger and W. Stevenson, *Power System Analysis*, ISBN 0-07-113338-0, McGraw-Hill, 1994

[D.7] IEEE Guide for AC Generator Protection, IEEE Std C37.102-1995.

[D.8] S. G. Johansson and J. E. Daalder, ”Maximum Thermal Utilization of generator rotors to avoid Voltage Collapse”, International Power Engineering Conference -97, Singapore, pp. 234-239, 1997.

[D.9] S. G. Johansson, D. Popović, D. J. Hill and J. E. Daalder, ”Avoiding Voltage Collapse by fast Active Power Rescheduling”, International Journal of Electric Power and Energy Systems, Vol. 19, No. 8, pp. 501-509, 1997.

[D.10] S. G. Johansson, F. G. A. Sjögren, D. Karlsson, J. E. Daalder, “Voltage Stability Studies Using PSS/E”, Bulk Power System Phenomena III, Davos, Switzerland, pp. 651-661, 1994.

[D.11] Karlsson D., ”Voltage Stability Simulations Using Detailed Models Based on Field Measurements” Ph. D. thesis, ISBN 91-7032-725-4, Göteborg, Sweden, 1992.

[D.12] W. R. Lachs and D. Sutanto. ”A Voltage Stability Indicator based on Rotor Heating”. IEE 2nd Int. Conf. on adv. in Power System Control, Operation and Management, Hong Kong, pp. 97-102, 1993.

[D.13] P.-A. Löf, ”On Static Analysis of Long-Term Voltage Stability in Electric Power Systems”, Ph. D.- Thesis, TRITA-EES-9501, ISSN 1100-1607, Royal Institute of Technology, Sweden, 1995.

[D.14] O. Samuelsson, ”Power System Damping - Structural Aspects of Controlling Active Power”, Ph. D.- Thesis, ISBN 91-88934-05-5, Lund University, Sweden, 1997.

[D.15] F. G. A Sjögren, S. G. Johansson and J. E. Daalder, ”Behaviour of generator current limiters near the point of voltage collapse”, Stockholm Power Tech 1995, STP PS 07-06-0492, pp. 221-226, 1995.

[D.16] C. Taylor, *Power System Voltage Stability,* ISBN 0-07-063184-0, McGraw-Hill, 1994.

[D.17] H. Termuehlen and G.Gartner, ”Sustained Fast Turbine-Generator Load Response in Fossil-Fueled Power Plants”, IEEE Transactions on Power Apparatus and Systems, Vol. 100, No. 5, pp. 2495-2503, 1981.

Biography

Stefan G. Johansson (S’ 94) received his M. Sc. from Chalmers University of Technology in 1992 and his Lic. Eng. in 1995 respectively.

He visited Sydney University for 7 months during 95-96. His interest lies in power system stability analysis on which he hopes to obtain his Ph.D. in ’98.

Appendix

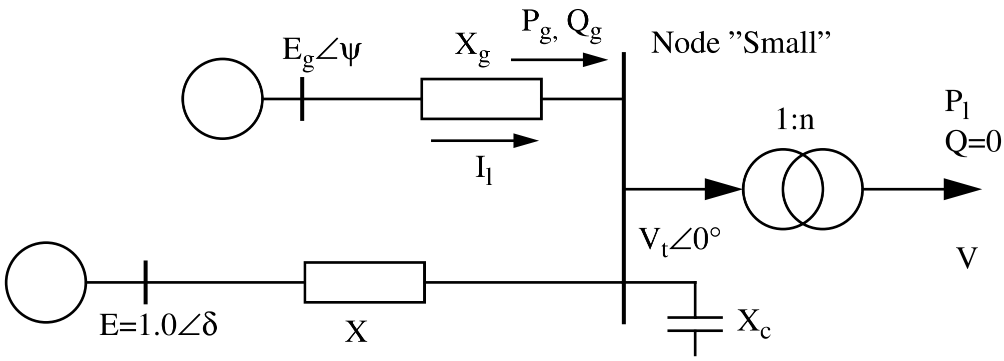


Figure D.17 The system for Mode 2 and Mode 3. δ is the voltage angle over X and ψ the angle over X_g.

For Mode 2, field current limitation in the small generator the capacity in the load point can be written based on Fig. D.17. The field current limiter is represented as a constant voltage source behind a reactance.

Reactive power balance at the node Small gives

$$Q = \frac{EV}{nX}\cos\delta - \frac{V^2}{n^2X} + \frac{V^2}{n^2X_c} + Q_g = 0 \tag{D.5}$$

The active and reactive power output from the limited generator are

$$P_g = \frac{VE_g}{nX_g}\sin\psi \tag{D.6}$$

$$Q_g = -\frac{V^2}{n^2X_g} + \frac{E_gV}{nX_g}\sqrt{1-\left(\frac{P_gnX_g}{VE_g}\right)^2} \tag{D.7}$$

The capacity at the load point can be written according to

$$P_l(V, n) = P_g + \frac{EV}{nX}\sqrt{1 - \cos^2\delta} \text{ where} \quad (D.8)$$

$$\cos\delta = \frac{VX}{En}\left(\frac{1}{X_g} + \frac{1}{X} - \frac{1}{X_c}\right) - \frac{E_g X}{E X_g}\sqrt{1 - \left(\frac{P_g n X_g}{V E_g}\right)^2} \quad (D.9)$$

The capacity for Mode 3 can be calculated using constant armature current in Fig. D.17. The reactive power balance equation at the small generator terminal is in this case identical to (D.5) and the reactive power output from the small generator is

$$Q_g = \sqrt{\left(\frac{VI_l}{n}\right)^2 - P_g^2} \quad (D.10)$$

The load capacity P_l becomes

$$P_l(V, n) = P_g + \frac{EV}{nX}\sqrt{1 - \cos^2\delta} \text{ where} \quad (D.11)$$

$$\cos\delta = \frac{VX}{En}\left(\frac{1}{X} - \frac{1}{X_c}\right) - \frac{nX}{EV}\sqrt{\left(\frac{VI_l}{n}\right)^2 - P_g^2} \quad (D.12)$$

Paper E Maximum thermal utilization of generator rotors to avoid voltage collapse

Paper presented at “International Power Engineering Conference -97”, Singapore, 1997

Abstract

The reactive power output from synchronous generators is strongly dependent on the behaviour of the field- and armature current limiters. These limiters therefore play a key role during a voltage instability. Field current limiters protects the generator from overheating the rotor winding. Based on the tracks of the field current, both constant and inverse time characteristics is used today for this protection. This paper investigates how a field current limiter which takes the actual temperature of the rotor into account, can be used to alleviate a voltage instability. If the rotor winding is not fully utilized from a thermal viewpoint before a disturbance it is possible to give the system extra support during an instability by temporarily increase the field current limit until maximum temperature is reached. Discussion on how this extra support can be managed together with limitations is shown with dynamical simulations on a small system.

Keywords

Voltage instability, Voltage collapse, Field Current Limiters, Thermal Overloading

E.1 Introduction

Different remedial actions to alleviate a voltage collapse have been proposed. Load shedding [E.2], blocking of transformer tap changers [E.11, E.13 & E.14] and switching of capacitors [E.15] are among the presented methods. Attention has also been given to the influence of dynamic load recovery [E.7] and the P-Q generation capability of generators [E.9] where the field and armature current limits play a major role.

The objective of this paper is to study the influence of field and armature current limiters during voltage instabilities. One possible action in case of an imminent voltage collapse is to increase the field current (temporarily) beyond its thermal steady state limit to keep voltage levels within viable limits. This may give other remedy actions, such as the starting of gas-turbines, a chance to save the system from a collapse.

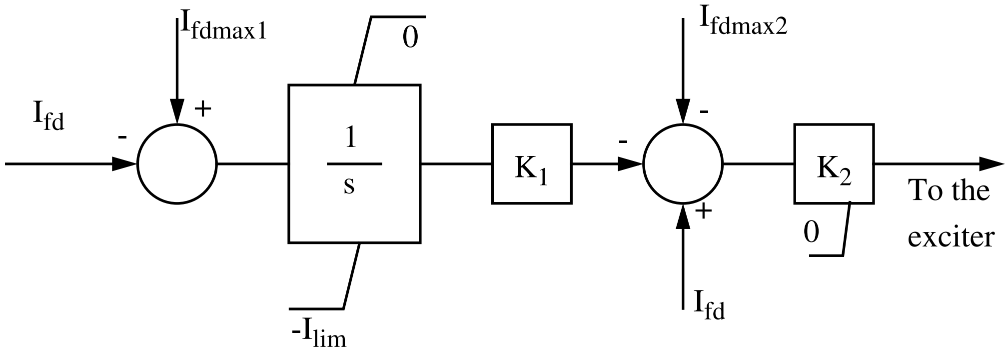
Cascaded action of On-Load Tap Changers at different voltage levels and/or recovering thermal load may cause a temporary overshoot in power demand after a voltage step [E.4, E.6 and E.8]. This in its turn may lead to current limiter activation and a voltage collapse. In such a case a temporary thermal overloading of the rotor is advantageous provided the overshoot is properly identified. Field measurements show that this power overshoot may be in the time-frame of a minute [E.4]. This may be short enough to allow a thermal overloading.

A small system has been analysed with the objective to study the heating of the rotor. Most parameters are based on data from field measurements. Different examples of the use of the thermal rotor capacity is shown.

E.2 Field current limiters

Several schemes of field current limiters are used. The one presented in [E.10] uses a block scheme according to Figure E.1. A field current I_{fd}, between I_{fdmax1} and I_{fdmax2} will be ramped down after a certain delay whereas a field current above I_{fdmax2} will be decreased immediately. This current limiter may be categorized as having an invert time characteristic for field currents between the two limiting levels.

Another type of over excitation limiter is presented in [E.6]. Here a switch-over occurs from the ordinary voltage control to constant field current delayed with a constant time from the field current violation. This current limiter uses two different levels of field current. The lower level is delayed and protects the rotor from overheating and corresponds to the I_{fdmax1} defined in Figure E.1. Usually the time delay of this lower level is in the range of 5 to 10 seconds. A higher level with instantaneous activation of the current limiter is used to protect static feeder equipment from overheating if the rotor is exposed to some kind of short-circuit. The semiconductors used in static feeders have much shorter thermal time constants than the rotor and must therefore be protected faster. This higher field current level may correspond to the I_{fdmax2} in Figure E.1. It is assumed henceforth that it is the heating of the rotor which is critical for the current limitation in the generator and not the temperature of the feeder equipment.



I_{fdmax1}=1.05·FLC (Full Load Current)

I_{fdmax2}=1.60·FLC

Figure E.1 Block scheme for the Maximum Excitation Limiter presented in [E.10].

An ANSI requirement [E.1] states that the field winding should withstand an overload of 125 percent of rated-load field voltage for at least one minute starting from stabilized temperatures at rated conditions. Table E.1 gives a survey of overload figures for the rotor field winding as specified in [E.1].

Time in seconds	10	30	60	120
Field Voltage in p.u.	2.08	1.46	1.25	1.12

Table E.1: Field-Winding Thermal Requirements [E.1]

E.2.1 Used models for the current limiters and thermal model for the rotor

The system used in this paper is shown in Figure E.2. It consists of a strong, remote generation area supplying a load node through two identical parallel transmission lines. The load at the remote node is supplied through a transformer equipped with an OLTC. A minor part of the load demand is supplied from local production in a generator close to the load. This generator is equipped with a field- and armature current limiter. The Field Current Limiter is modelled by the synchronous reactance X_g between the generator terminal voltage and generator internal voltage and ‘freezing’ the latter voltage to E_g (Figure E.3a). The Armature Current Limiter is implemented as an actual current limiter (Figure E.3b).

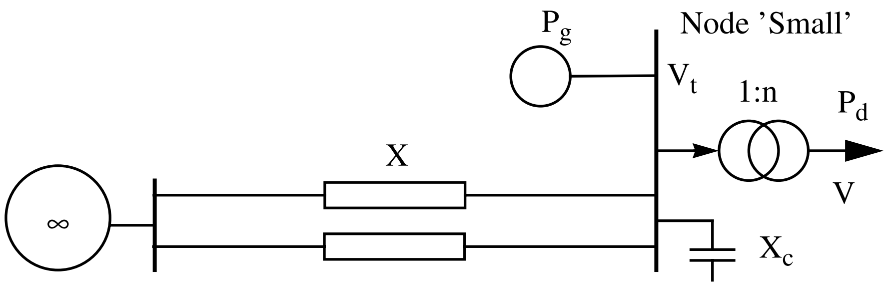


Figure E.2 The system studied. The used contingency in this paper is a tripping of one of the parallel lines.

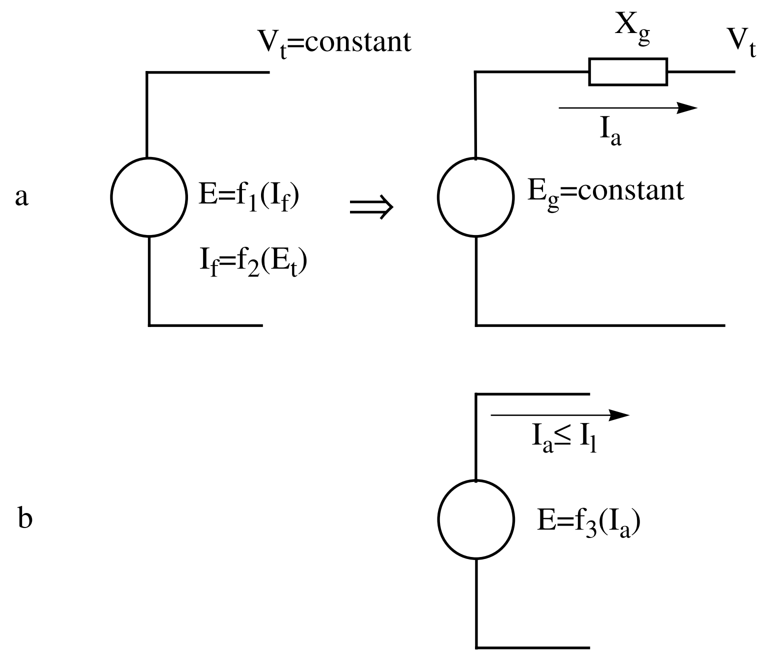


Figure E.3 Different implementations of current limiters; a) Field current limiter, b) Armature current limiter

The node ”Small” is also equipped with a capacitor corresponding to shunt capacitance of the lines and shunts connected to the node.

A straightforward model of the rotor heating is used. Lachs and Sutanto [E.9] propose a linear heat loss to the surroundings based on the field measurements they performed. A thermal model describing the temperature T_r of the rotor is chosen as

$$\dot{T}_r = k_1(E_g^2(t) - k_2 T_r) \tag{E.1}$$

where the constants are chosen to give a model with similar appearance as the field measurements presented in [E.9]. The step response in the temperature will be shown later.

E.2.2 Load Model and OLTC-model

A voltage dependent dynamic load model is used to model load recovery in the time-frame of a minute. Following Hill and Karlsson [E.5, E.7], we define static and transient load characteristics as $P_s(V)$ and $P_t(V)$ and a recovery time T_p. A load state x_p is introduced according to

$$x_p = T_p(P_d - P_t(V)) \tag{E.2}$$

The variable x_p can be seen as a measure of the energy deficit in the load. According to [E.7], the exponential load recovery is given by

$$\dot{x}_p = -\frac{1}{T_p}x_p - P_t(V) + P_s(V) = -P_d + P_s(V) \tag{E.3}$$

The stationary and transient voltage behaviour can be described by the voltage dependent static load characteristics

$$P_s(V) = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} \text{ and } P_t(V) = P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{E.4}$$

Values used in this paper are α_s=0 and α_t=2. The reactive power load demand is considered to be zero at all time. The capacitor at the load end is included as being a part of the system and not modelled as a load demand.

The real power balance corresponds to

$$P_d = P_l(V, n) \tag{E.5}$$

where P_d is the load demand and P_l is the system capacity at the load point whose function will vary depending on activated current limiter, the actual voltage and the tap step of the transformer. The system capacity $P_l(V,n)$ will be evaluated for different operating modes in Section E.3.

The transformer tap-changing relay is modelled as:

$$\dot{n} = \frac{1}{T}(V^0 - V) \tag{E.6}$$

where V^0 is the set-point voltage for the transformer. It is ideal in that sense that it has no reactance and assumes a continuous tap control.

Equations (E.1), (E.3), (E.5) and (E.6) give a differential-algebraic state space system representation which depends on the current limiting mode the generators are operating in. In each mode k, the system can be described in a general form

$$\begin{aligned} \dot{\mathbf{x}} &= f_k(\mathbf{x}, \mathbf{y}, u) \\ \mathbf{0} &= g_k(\mathbf{x}, \mathbf{y}, u) \end{aligned} \tag{E.7}$$

E.2.3 Operating Modes of the Generator

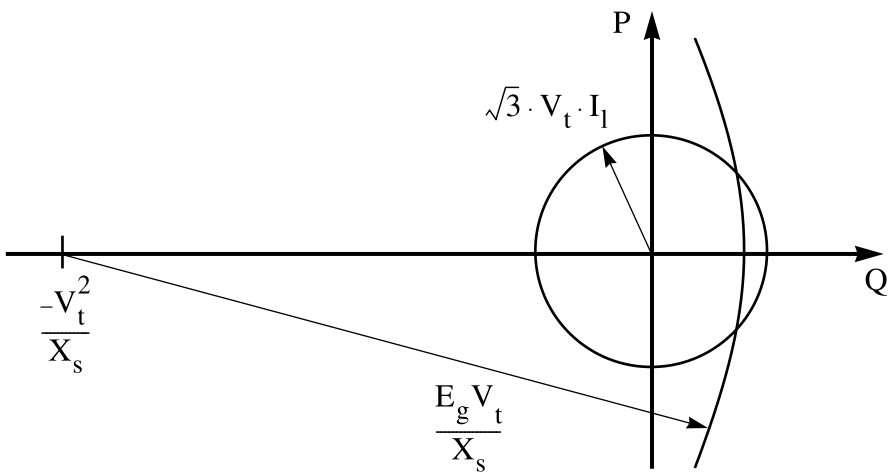


Figure E.4 The capability diagram of a generator for voltage stability studies.

The small generator in the load end is working in either one of the modes 'Voltage Controlled', 'Field Current Limited' or 'Armature Current limited'. These are called Mode 1, Mode 2 and Mode 3. The operation of the generator changes between these modes. The capability diagram of the generator [E.3] shows one way of transition between these modes. As can be seen in Figure E.4, the circle corresponding to constant armature current shrinks when voltage V_t decreases while the circle segment corresponding to constant field current will move to the right. Any operating point at the field current limit will eventually become armature current limited if the generator is exposed to a voltage decline.

It is not obvious from Figure E.4 to see how an increase of E_g will influence the capability of the generator. The increased voltage E_g will also increase V_t and the circle segment will move to the right. The circle corresponding to constant armature current will also increase in this case but since the increase in V_t is less than in E_g the generator will become armature current limited in this case if E_g is increased enough.

E.3 System capability curves

In this section the system capacity $P_l(V,n)$ is calculated for the modes 2 and 3.

E.3.1 Mode 2, Field Current Limitation

For Mode 2 the capacity in the load point can be written based on Figure E.5 where the small generator is represented as in Figure E.3a.

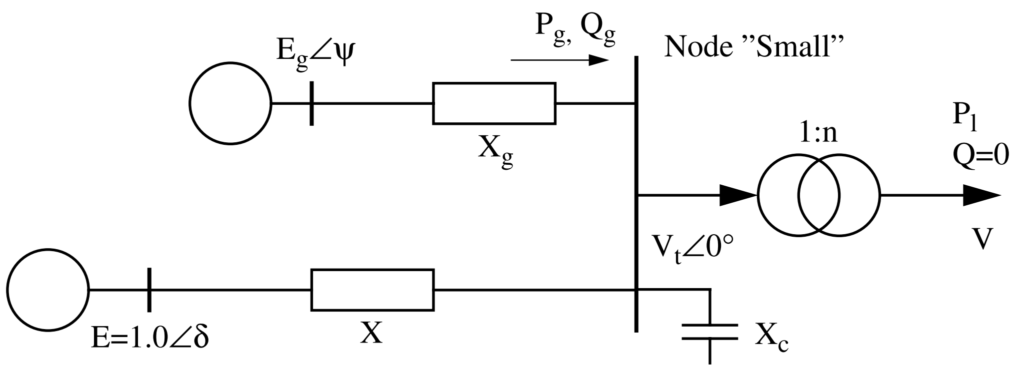


Figure E.5 The system for Mode 2. δ is the voltage angle over X and ψ the angle over X_g.

The reactive power balance at the node "Small" gives

$$Q = \frac{EV}{nX}\cos\delta - \frac{V^2}{n^2X} + \frac{V^2}{n^2X_c} + Q_g = 0 \tag{E.8}$$

The active and reactive power output from the limited generator can be written as

$$P_g = \frac{VE_g}{nX_g}\sin\psi \tag{E.9}$$

$$Q_g = -\frac{V^2}{n^2X_g} + \frac{E_gV}{nX_g}\sqrt{1-\left(\frac{P_gnX_g}{VE_g}\right)^2} \tag{E.10}$$

The capacity at the load point can be written according to

$$P_l(V, n) = P_g + \frac{EV}{nX}\sqrt{1-\cos^2\delta} \text{ where} \tag{E.11}$$

$$\cos\delta = \frac{VX}{En}\left(\frac{1}{X_g} + \frac{1}{X} - \frac{1}{X_c}\right) - \frac{E_gX}{EX_g}\sqrt{1-\left(\frac{P_gnX_g}{VE_g}\right)^2} \tag{E.12}$$

E.3.2 Mode 3, Armature Current Limitation

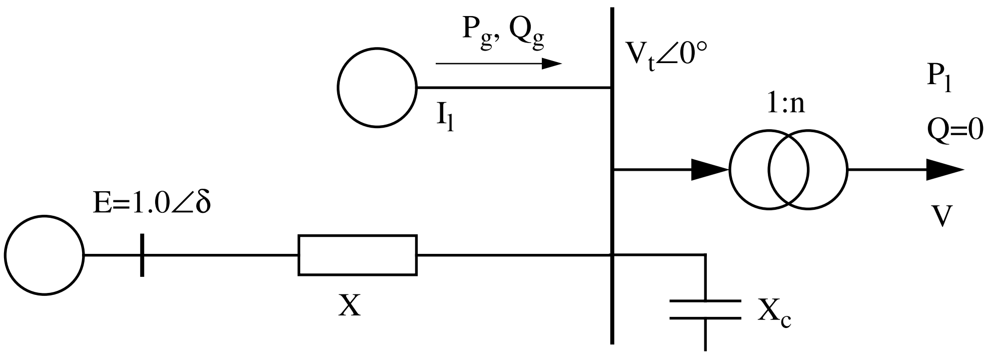


Figure E.6 The system for Mode 3. δ is the voltage angle over the line reactance X.

The capacity for Mode 3 can be calculated using Figure E.6. The reactive power balance equation at the small generator terminal is in this case identical to equation (E.8) and the reactive power output from the small generator can be written as

$$Q_g = \sqrt{\left(\frac{VI_1}{n}\right)^2 - P_g^2} \tag{E.13}$$

The load capacity P_l becomes

$$P_l(V, n) = P_g + \frac{EV}{nX}\sqrt{1 - \cos^2\delta} \text{ where} \tag{E.14}$$

$$\cos\delta = \frac{VX}{En}\left(\frac{1}{X} - \frac{1}{X_c}\right) - \frac{nX}{EV}\sqrt{\left(\frac{VI_1}{n}\right)^2 - P_g^2} \tag{E.15}$$

E.4 The use of maximum thermal rotor loading

Figure E.7 shows how the capability in the load point depends on the internal voltage E_g for the two modes. If the small generator can produce more reactive power it is clear that we can increase the transmitted power from the large generator and thereby increase the load capacity. The interesting point is that the system has an upper limit of the capacity which is decided by the armature current limit shown in Figure E.7 as a straight line marked ”Mode 3”. Even if the internal voltage E_g could be increased considerably, the system capacity will be determined by this armature current limit. The system operation will change from Mode 2 to Mode 3 (where E_g is not controlled by the field current limiter) when we try to cross this limit and the system capacity will be decided by equation (E.14). One must take this into account before boosting the internal voltage E_g.

One aspect of exploiting the thermal capacity of the rotor is the question how to handle or manage this limited resource. The problem could be viewed in the following way. A contingency may be the cause that the field current exceeds its limit. After a specified delay the field current is reduced to this limit and remains stationary. Dependent on the pre-disturbance loading of the generator the rotor temperature can be below its maximum level at this point. It will in such a case increase further until it levels off to its maximum allowable temperature given by the field current limit (see Figure E.9, dashed curve). In the mean time the situation in the network may deteriorate due to decreasing voltage and a collapse may happen faster than that the rotor reaches its maximum temperature. In such a case the choice of the field current limit was too conservative with respect to our goal of avoiding a voltage collapse.

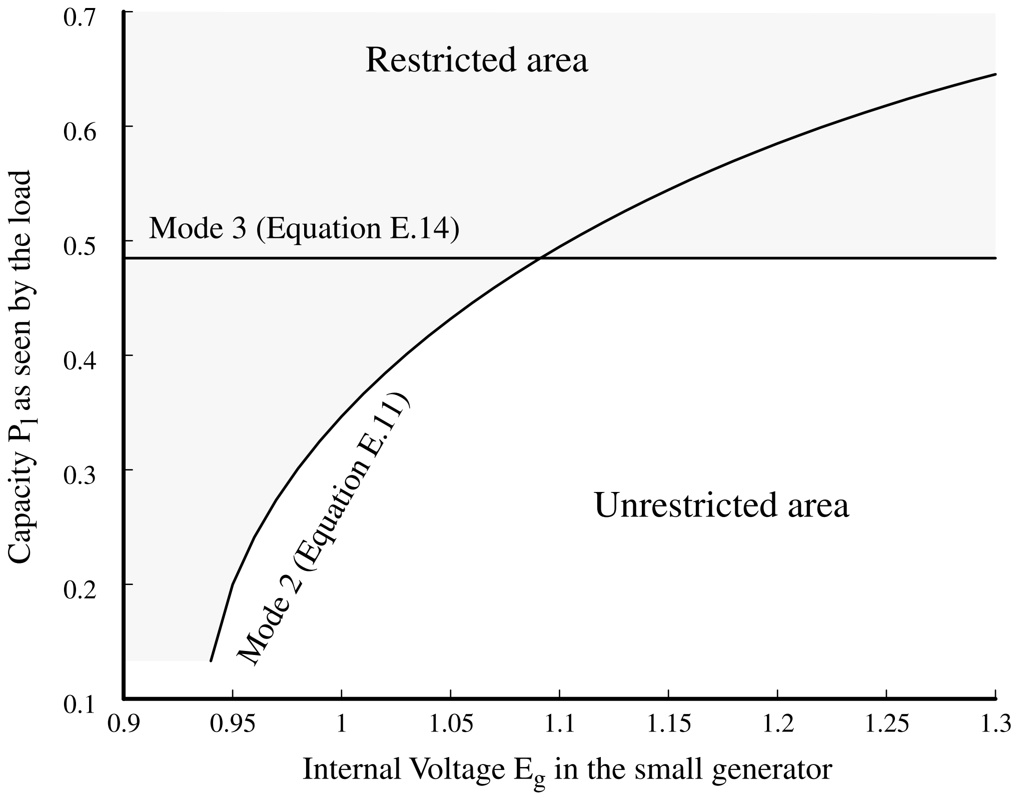


Figure E.7 The capacity as seen by the load as a function of internal voltage E_g for the different modes 2 and 3.

For that reason one could imagine the following scenario. Instead of a fixed current limit for the field current limiter, the voltage control system is now limited solely by maximum rotor temperature, which in its turn is decided by the pre-loading history and the heat generated by the field current. This allows (far) higher field currents (but for shorter times) thereby enabling the generator to keep its voltage controlled for a longer time than in the first scenario (c.f. Figure E.9, dotted curve). Managing the voltage at a higher level for a longer time increases the possibility to avoid a collapse, e.g. by activating other measures such as the starting of gas turbines, which will relieve the system.

As long as we have voltage control of the generator we are also able to control the temperature increase in the rotor to a certain extent. For example a choice could be that we are *decreasing* the terminal voltage somewhat below its set-point. The result is that the temperature increase will become less as compared with the previous scenario (Figure E.9, solid curve). At the same time the system will be notified about the stressed situation which may initiate other remedial actions as reactor disconnection etc. The discussed strategies will be shown by simulations in the following.

E.5 Simulations

The system in Figure E.2 is exposed to a tripping of one of the transmission lines. This activates the field current limiter in the small generator corresponding to a Mode 2 operation. Three different cases are shown in the following figures marked according to Table E.2.

Case	Curve
1: No over-current allowed	Dashed
2: Use up thermal capacity slowly	Solid
3: Use up thermal capacity fast	Dotted

Table E.2: Legends for the figures

Case 1: After a delay of two seconds the field current is decreased to its limited value. This will cause a voltage collapse as is shown by the dashed lines in Figure E.8. The corresponding temperature variation in the rotor is shown as a dashed line in Figure E.9, i.e. the step response of equation (E.1). Since the generator operates below rated conditions before the contingency, there is a margin in thermal loading which can be used. In this case of field current limitation, the rotor is not fully utilized from a thermal viewpoint until the very end of the simulation when the collapse occurs.

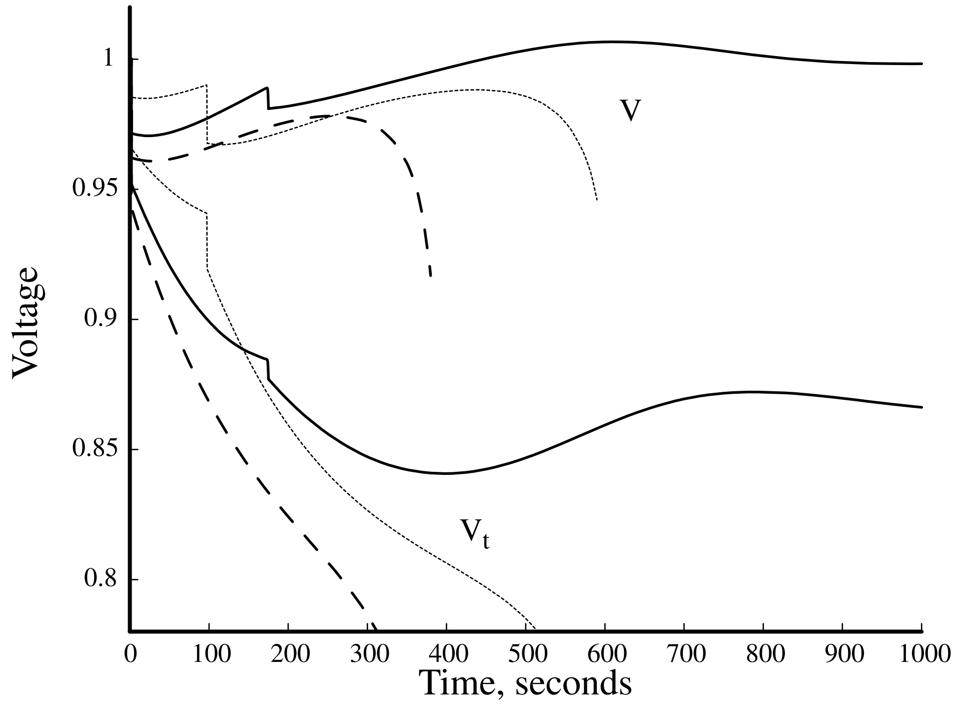


Figure E.8 Voltages on both sides of the transformer

Case 2: If the generator is excited with a field current somewhat higher than its limit until the rated temperature is reached, the system will in this case endure the voltage instability and the system is saved as indicated by the solid lines in Figures E.8 and E.9. The effect of the increased field current on voltage can be seen in Figure E.8 as a ”step” function on the voltage trace until the temperature reaches its limit after approximate 170 seconds as shown in Figure E.9. The effect of the voltage increase on the system is twofold: it decreases the power deficit in the load demand, and it decreases the reactive power losses caused by the transmission of active power from the remote generation.

Case 3: If the voltage E_g is increased even further the rotor temperature will go up so fast that the working point does not have time to move far in the state plane since the speed of the trajectory is decided by the time constants in the load and the transformer tap relay. The response of the system will be similar to the first case which collapsed as can be seen in the figures E.8 to E.10 on the dotted lines. Note however that the time between the contingency and the collapse now has increased.

The state space plane describing the trajectory of the load-state and the tap step is shown in Figure E.10 for the three cases. It consists of several regions which shapes are dependent on the parameters of the system. Two steady state operating points corresponding to points

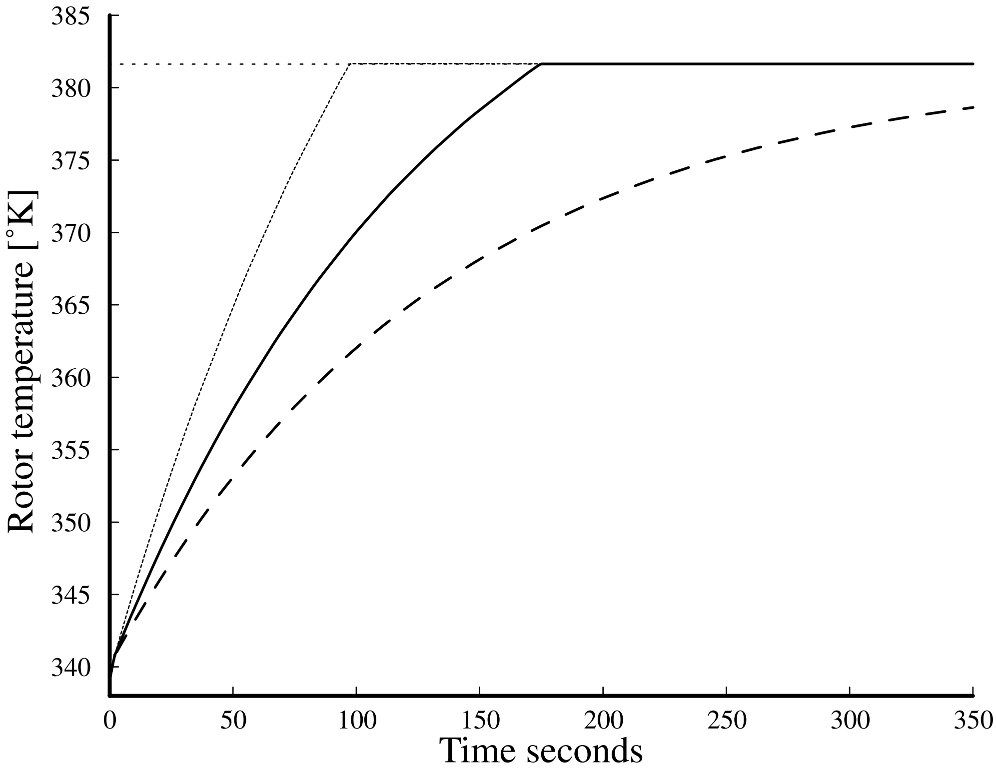


Figure E.9 Temperatures in the rotor (equation (E.1)).

where the derivatives of the system (equation E.7) is zero are labelled in the figure with a and b respectively. Point b is in this case an unstable point since a small perturbation from b not always returns the trajectory to b.

After the contingency the load experiences a power deficit due to the voltage drop and the load state x_p increases representing the energy deficit. Also, the tap changer starts to move the working point to the right in order to restore the voltage V to its set-point value of, in this case, 1.0 p.u. The direction of the trajectory is indicated by an arrow in Figure E.10. At the small +-symbol, the thermal limit is reached in case 2 (t=170 sec.) and the field current is decreased to its steady state value causing a considerable change in the trajectory. The effect on the system of using all of the available thermal capacity is a decrease of the peak of the energy deficit in the load since the maximum value of x_p is decreased.

When the trajectory crosses the $\dot{x}_p = 0$ line it enters the so called excess load region where the load demand P_d is (transiently) greater than the steady state load requirement [E.11]. The system can now restore the energy deficit and find a new steady state operating point a in Figure E.10 unless it leaves the excess load region to the right. If the trajectory

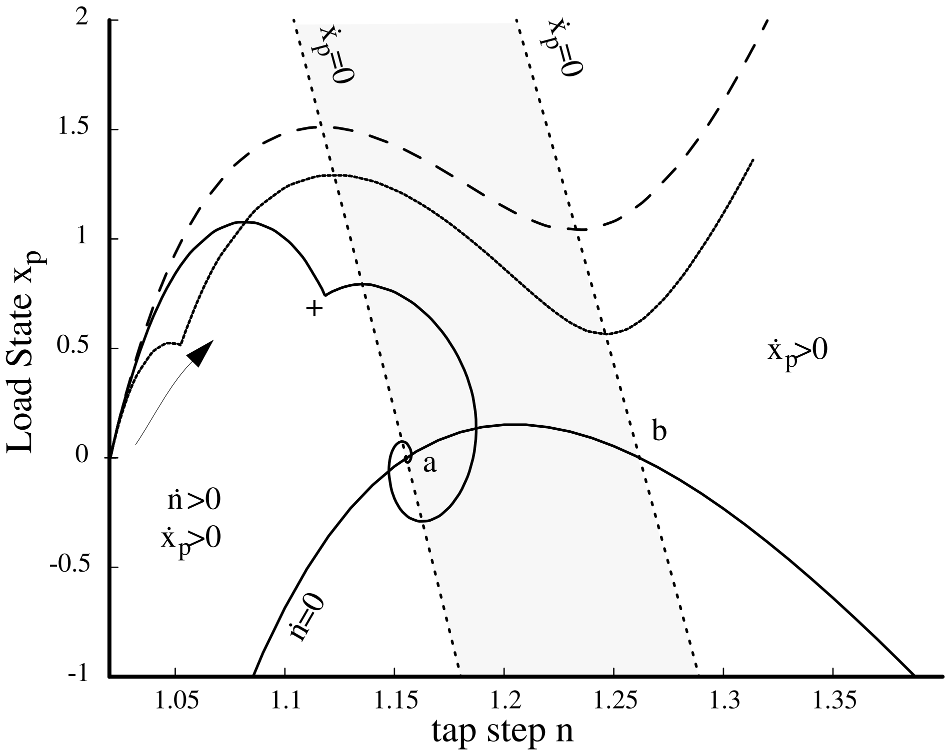


Figure E.10 The state plane with the trajectories and the load excess region (shaded).

enters that area, the system will collapse since it can not supply the steady state power demand $P_s(V)$[1] any longer. This will cause the power deficit to increase unrestricted.

The effect of an increase of E_g is visualized in Figure E.11. The first observation is that the load excess region increases when a higher value of E_g is allowed. This forces the system towards a lower energy deficit than given by the trajectory when the system collapses. Note however that the rotor temperature reaches its steady-state level before it reaches its stable point c in Figure E.11. If the system would have been able too keep E_g at its higher level all the time it would have ended up at point c. In case 2 the overloading is successful in that sense that the trajectory is within the region of attraction to point a at the +-sign in Figure E.10.

Finally, the influence of the static voltage dependent load demand will be shown. Figure E.12 shows how the load excess region will look like for different values of α_s (equation (E.4)). In all cases the load excess region will increase for an increase of E_g indicating that this action is beneficial for these cases for other load characteristics.

1. Originally wording: $P_s(v,n)$

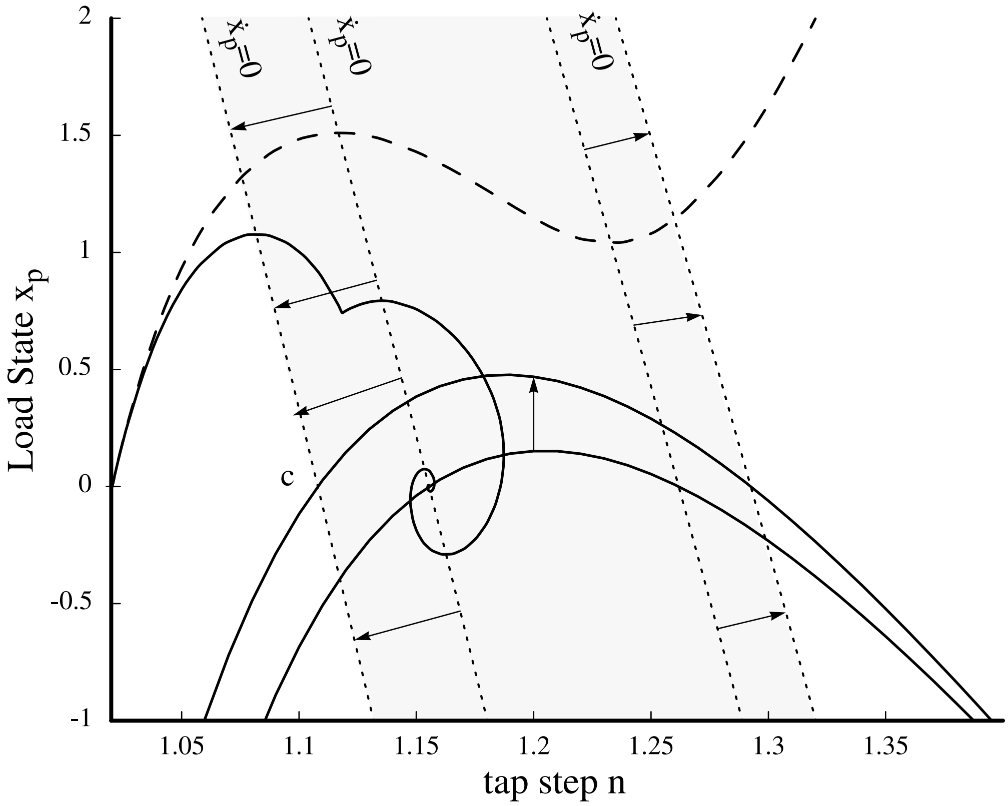


Figure E.11 The effect of an increased internal voltage E_g on the load excess region

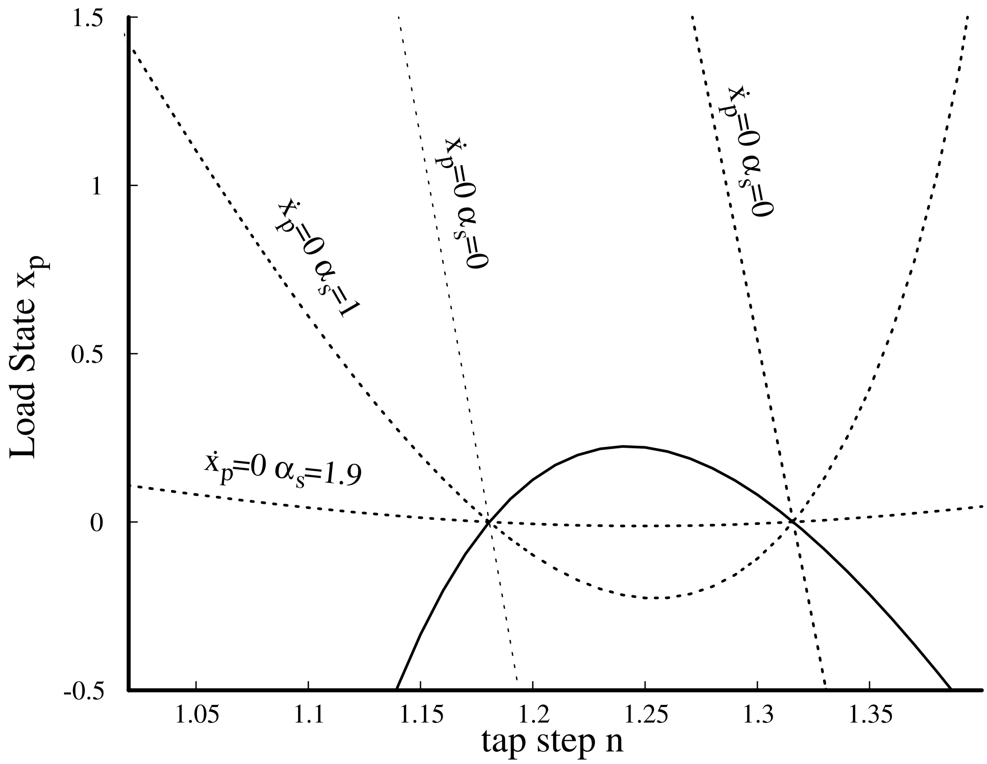


Figure E.12 The load excess region shapes for different static voltage dependencies for the load.

E.6 Conclusions

Under the assumptions made here a higher utilization of the rotor thermal capacity (when available) will at least prolong the time between an initial contingency and a voltage collapse. A proper use of this thermal capacity may lead to that the system is saved from a voltage collapse. Since this is a limited resource it must be treated wisely and an implementation on a real generator will require some kind of temperature measurement of the rotor winding.

Acknowledgements

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References

[E.1] American National Standard C50.13-1989 *Rotating Electrical Machinery-Cylindrical-Rotor Synchronous Generators*, American National Standards Institute, New York, USA 1989.

[E.2] S. Arnborg. and G. Andersson. On strategies for Undervoltage Load Shedding in Power Systems. *IEEE Stockholm Power Tech 1995*, STP PS 06-03-0378, pp. 167-172, 1995.

[E.3] S. J. Chapman. *Electric Machinery Fundamentals*. McGraw-Hill, ISBN 0-07-010914-1, 1991.

[E.4] G. leDous, J. Daalder and D. Karlsson. Dynamic Load Measurement in a Transmission System. *Int. Power Eng. Conf.*, Singapore, pp. 74-79, 1997.

[E.5] D. J. Hill. Nonlinear Dynamic load Models with Recovery for Voltage Stability Studies. *IEEE Transactions on Power Systems,* Vol. 8, No. 1, pp. 166-176, 1993.

[E.6] S. G. Johansson, F. G. A. Sjögren, D. Karlsson and J. E. Daalder, Voltage Stability Studies Using PSS/E. *Bulk Power System Phenomena III,* Davos, pp. 651-661, 1994.

[E.7] D. Karlsson and D. J. Hill. Modelling and identification of Nonlinear Dynamic loads in Power systems, *IEEE Transactions on Power Systems*, Vol. 9, No. 1, pp. 157-166, 1994.

[E.8] N. Krantz, M. Gustafsson and J. E. Daalder. Voltage Collapse with a Laboratory Power System Model. *IEEE Stockholm Power Tech 1995*, PS-07-01-0113, pp. 191-196, 1995.

[E.9] W. R. Lachs and D. Sutanto. A Voltage Stability Indicator based on Rotor Heating. *IEE 2nd Int. Conf. on adv. in Power System Control, Operation and Management,* Hong Kong, pp. 97-102, 1993.

[E.10] G. K. Morison, B. Gao and P. Kundur, Voltage Stability Analysis Using Static and Dynamic Approaches. *IEEE Transactions on Power Systems*, Vol. 8, No. 3, pp. 1159-1171, 1993.

[E.11] D. Popović, I. A. Hiskens and D. J. Hill. Investigations of load-tap changer interaction. *Int. Journ. of Electrical Power & Energy Systems*, Vol. 18, No. 2, pp. 81-98, 1996.

[E.12] F. G. A. Sjögren, S. G. Johansson and J. E. Daalder, Behaviour of generator current limiters near the point of voltage collapse. *Stockholm Power Tech 1995*, STP PS 07-06-0492, pp. 221-226, 1995.

[E.13] K. T. Vu and C.-C. Liu. Dynamic mechanisms of Voltage Collapse. *Systems & Control letters 15*, pp. 329-338, 1990.

[E.14] K.T. Vu and C.-C. Liu. Shrinking stability regions and Voltage Collapse in Power Systems, *IEEE Transactions on Circuits and Systems-I: Fund. Theory and Appl.*, Vol. 39, No. 4, pp. 271-289, 1992.

[E.15] W. Xu, Y. Mansour and P. G. Harrington. Planning methodologies for voltage stability limited power systems. *Int. Journ. of Electrical Power & Energy Systems*, Vol. 15, No. 4, pp. 221-228, 1993.

Appendix

$X=1.5$, $X_c=20$, $P_0=0.575$, $P_g=0.075$, $E_g=1.07$, $X_g=1$, $T_p=40$, $T=40$, $k_1=2.5$, $k_2=0.003$