An LVDC Distribution System Concept

Pasi Salonen, Tero Kaipia, Pasi Nuutinen, Pasi Peltoniemi and Jarmo Partanen

Abstract— **An LVDC distribution system is a new innovation in a field of electricity distribution. This paper presents the basic principles to use power electronics devices in electricity distribution systems. Recent technological and economical developments in power electronic components enable to apply power electronics in LV network. This development makes an LVDC distribution system concept establishment possible. In this respect the occurring progression connects power electronics and distribution system development strongly together. The LVDC distribution system basic concept concentrates at DC/AC interface focusing on implementation of customer-end inverter. The previously made analyses have shown that presented LVDC distribution system has existing techno-economical potential in electricity distribution networks.**

***Index Terms*— LVDC, electricity distribution, concept**

I. INTRODUCTION

THE demand for undisturbed electricity is growing while society relies more and more on electricity. The occurring outages have more effects to the customers and outage costs increases. At the same time the climate is changing and causing bigger storms than before. The network disturbances caused by storms have become larger and the number is increased. These challenges have raised demand for more reliable network solutions compared to traditional 20/0.4 kV 3-phase AC distribution systems. The LVDC distribution system concept responds to these challenges in field of electricity distribution.

In the early days the first electricity distribution systems were based on DC technology but were rapidly replaced with AC systems due to its benefits compared to DC. Today's utilization of DC technology concentrates mainly to HVDC transmission systems, industrial distribution and electric drives. The technical and economical developments during last decades have established opportunity to create a new competitive distribution system based on modern power electronic technology. From technological point of view the DC distribution system is a new concept in electrical distribution and it generates a new area of business to power electronic device manufacturers.

Paper is presented at the Nordic Workshop on Power and Industrial Electronics (NORPIE). The workshop was held on Helsinki University of Tehnology in faculty of Electronics, Communication and Automation, Espoo, Finland, 9-11 June 2008.

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II. IMPLEMENTATION OF LVDC IN DISTRIBUTION NETWORK

A. LVDC Distribution System Topologies

An LVDC distribution system constructs of power electronic converters and DC link between the converters. The topology of LVDC distribution system can have different kind of variations. Common to these different topologies are that AC/DC conversion is always located near MV line. The DC/AC conversion can instead be located at different locations. Depending on the location the LVDC system can be either a HVDC link type solution or a wide LVDC distribution district where the DC/AC conversion is made at the customer-ends.

The wide LVDC distribution district can be compared to existing LVAC network topology with multiple branches. In this case there is no need for separate 3-phase AC network because the AC lines have been replaced with DC lines. Example of basic implementation of an LVDC distribution system is shown in figure 1.

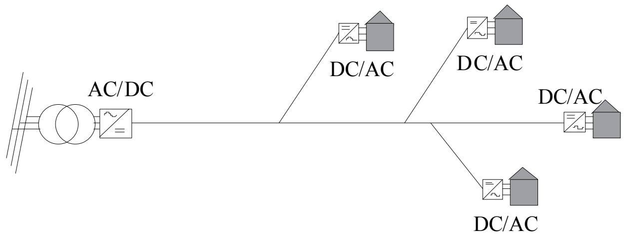

Fig.1. Example of a wide LVDC distribution district.

The HVDC link type solution constructs of a one DC line which interconnects two separate AC networks. In this kind of solution the customers are connected to a common 3-phase LVAC network. The DC link must be connected to customer AC network via transformer to ensure suitability with existing AC system. Example of an LVDC link distribution system is shown in figure 2.

Fig.2. Example of an LVDC link distribution system.

B. LVDC System Connections

The LVDC distribution system can be made with two basic implementations; unipolar and bipolar. The unipolar system has a one voltage level via energy is transmitted. All the customers are connected to this one voltage level. Unipolar DC system is shown in figure 3.

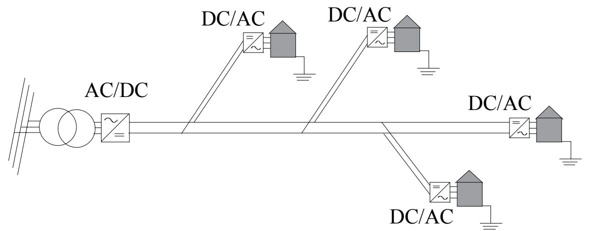

Fig.3. Example of an unipolar LVDC distribution system.

In the bipolar system two unipolar systems are connected in series. In the bipolar system customers can be connected between voltage levels with multiple ways. The connection alternatives are 1) between a positive pole, 2) between a negative pole, 3) between positive and negative poles and 4) between positive and negative poles with neutral connection. Bipolar DC system with connection alternatives are shown in figure 4.

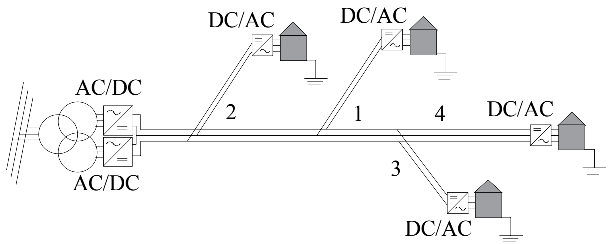

Fig.4. Example of a bipolar LVDC distribution system with different customer connection alternatives.

The customer connections 1 and 2 can lead unsymmetrical loading situations between DC poles in system. The overvoltage is consequence of current superposition at neutral wire. The possible overvoltage can be restricted with cable cross-section selection.

The connections 1 and 2 are chosen to be used in studied ± 750 VDC bipolar system. The main lines of system contain all three conductors but customer connections are 2-wire cables connected between positive or negative pole. Therefore customer supply voltage is either + 750 VDC or - 750 VDC.

C. Grounding Arrangement and DC Voltage Level

The DC distribution system can be made with ungrounded IT system or grounded TN system. The grounding arrangements in case of bipolar DC system are shown in figure 5.

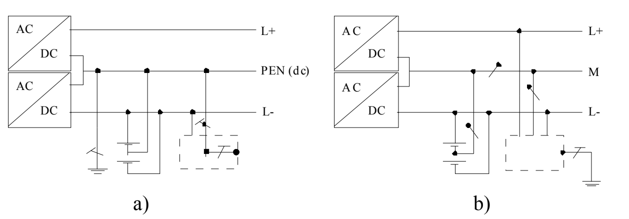

Fig.5. Grounding arrangements in case of a) grounded and b) ungrounded bipolar LVDC distribution system.

The system grounding arrangement has influence to system maximum voltages. The European Union directive 2006/95/EC defines DC voltage between 75 – 1500 VDC and AC voltage between 50 – 1000 VAC [1]. The LV standardization defines allowed maximum voltages in different grounding arrangements which are shown in table 1 [2].

TABLE I

MAXIMUM VOLTAGES FOR GROUNDED AND UNGROUNDED SYSTEMS [2]

Grounding arrangement	Voltage against earth [VDC]	Voltage between conductors [VDC]
Grounded TN system	900	1500
Ungrounded IT system	-	1500

In both grounding arrangements must be taken attention to that LV transformer neutral point can not be grounded like in traditional 20/0.4 kV AC system. The transformer neutral point grounding modifies DC system behavior from the intended.

D. Cables

The standardization allows LV cables to be used in DC voltage. The defined maximum voltage between conductors is 1500 VDC and between earth and conductor 900 VDC [5][6]. In LV aerial bundled cable standard is not said anything about cable usage in DC voltage [7]. The existing cables are mainly 4- and 5-wire cables which can be connected in parallel to take advantage of all cables conductors. Example connections for unipolar and bipolar DC systems are shown in figure 6 in case of 4-wire AXMK cable.

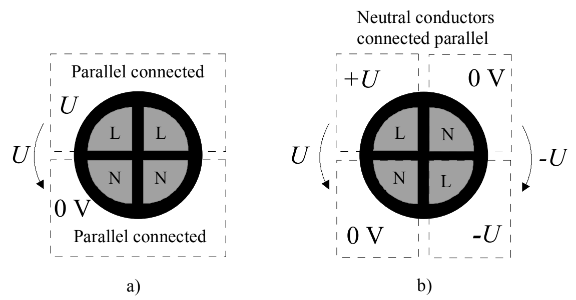

Fig.6. Possible cable connections for DC transmission line using 4-wire AXMK cable when DC distribution system is a) unipolar or b) bipolar system.

The transmission power coefficients between different kind of DC systems and traditional 20/0.4 kV AC system depends on the used DC systems topology, voltage, cable sizes and cable connections. The transmission power and transmission distance coefficients for 4x120 mm^2 AXMK cable are shown in table 2. Coefficients are calculated with presented cable connections in fig.6. In calculation is assumed that load is divided equally between poles in bipolar system.

TABLE II

TRANSMISSION POWER AND TRANSMISSION DISTANCE COEFFICIENTS FOR AXMK 120 MM^2 CABLE FOR AC AND DC DISTRIBUTION SYSTEMS

Distribution system	Traditional 400 VAC system	Unipolar 900 VDC System	Bipolar ±750 VDC system
Thermal limit	1.0	2.6	2.2
Voltage drop limit	1.0	5.1	7.0

The coefficient shows that with used cable connections and voltage difference between AC and DC systems enables LVDC distribution system to transfer more power than traditional 400 VAC distribution system.

The transmission powers in function of transmission distance are shown in figure 7. Curves corresponds the transmission and distance coefficients shown in table 2.

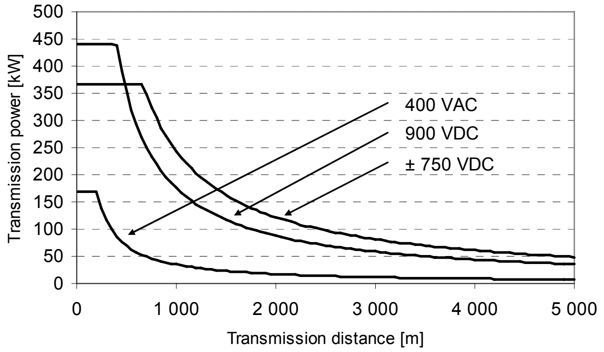

Fig.7. Transmission powers in function of transmission distance in AC and DC distribution systems. The used cable is AXMK 4x120 mm^2 with connections shown in fig.6. Maximum voltage drop is 6 %. Bipolar system poles are assumed to be loaded symmetrically.

Shown cable connections are useful only with existing LV cables which can be used in DC voltage. In the future it is desirable to introduce new cables which are designed especially for DC systems.

E. Power Electronic Converters

Power electronic converters have been used in industrial applications for many years. Despite of large scale of existing devices there is no device to fit system directly because of the special requirements of the system.

The AC/DC converter can be passive diode bridge or active bridge. With the passive bridge the power can be transmitted to the LVDC system only. With active bridge the power transfer can be bidirectional which enables DG to be connected into DC system. The active bridge makes controllable black start possible also. Using passive bridge the DC system can not be connected directly to supply because of the high charging currents. The passive bridge needs a separate device for system starting.

The DC/AC conversion can be made with either 1- or 3-phase bridges depending on the customer. The used converter topology can be either half or full bridge. The full bridge has advantages compared to half bridge like better controllability and no need for big capacitors than in half bridge converters [8]. It also has higher voltage capacity because of two voltage levels which enables the customer operation voltage creation from lower DC voltage than in half bridge inverter.

The power electronic device usage demands customer voltage filtering to meet sufficient voltage quality. Used filter topology can be LC, LCL or L+LC. [8]

The used DC/AC converter in studied bipolar ± 750 VDC distribution system is 1-phase full bridge inverter which nominal power is 10 kVA. The used filter topology is LC filter. Studied customer-end inverter with LC filter is shown in figure 8.

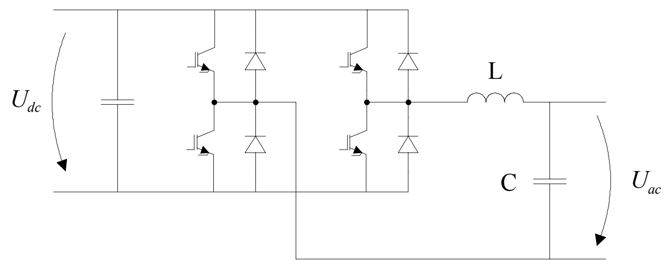

Fig.8. Customer-end 1-phase full bridge inverter with LC filter.

The AC/DC conversion is made with two 6-pulse bridges connected in series at DC side. Used LV transformer is delta-delta and delta-star connected transformer with 30 degree phase shift between secondary voltages which eliminates part of harmonic content at primary side.

F. Benefits and Challenges

The LVDC distribution system introduces benefits compared to AC systems. The LVDC distribution system has higher transmission capacity than traditional 400 VAC system resulting from the voltage difference between the systems. The transmission capacity can be over 16 times at the voltage drop limit and over 4 times at thermal limit compared to the traditional 400 VAC system. The transmission capacity coefficient depends on the used DC voltage level, LVDC system topology and the used cable connections if same cable is used in both systems. Example of transmission powers are shown in fig.7. [3][4]

The voltage quality also improves resulting from inverter's active voltage control. As customer AC voltage is made of much larger DC voltage than is needed the customer operating voltage can nearly be kept constant.

For the same reason MV or DC network disturbances as voltage fluctuations and dips can be repaired and they may not appear in the customer operating voltage. The voltage dip repair ability depends of capacitance connected to DC system.

The high transmission capacity enables LVDC distribution system to replace a part of MV line. As the LVDC distribution system creates its own protection zone for the DC system the faults occurring in the DC line causes outage to the customers in the DC district only. Therefore systems reliability increases while MV line length reduces (SAIFI). [3]

Resulting from higher transmission capacity the smaller cable cross-sections can be used in the LVDC distribution system than in traditional 400 VAC distribution system which reduces distribution system total costs. [3][4]

The higher transmission capacity causes smaller currents and smaller power losses if the cables sizes are same in both systems. The actual power loss difference can however be smaller than transmission capacity presume if the cable sizes are not equal. [3][4]

If the LVDC system is used to replace multiple districts due to high transmission capacity the number of LV transformers decreases as DC distribution system includes only one LV transformer in the beginning of LVDC system.

In addition to benefits the new distribution system introduces challenges as well. The DC system is more complex than traditional 20/0.4 kV AC distribution system which makes system operation more difficult.

The LVDC system introduces challenges to electrical safety as well. Because of attained DC voltage levels the LVDC system can cause high earth voltages in difficult grounding conditions which may require LVDC system arrangement to be ungrounded IT system. The power electronic devices introduce new challenges to distribution system also. The power electronic converter usage can cause switch faults and complicate protection device operations. One of the converters challenges is sufficient fault current capability.

Lifetimes of power electronic device may be only a quarter than traditional ones. Short lifetimes emphasize maintenance issues and costs of converters.

III. Functional Definitions

The LVDC system needs to fulfill nearly same requirements than LVAC network. The requirements concerns about LV standardization, environmental, maintenance and lifetime issues.

The LVDC system is read as a part of the supply system which it is connected to. The maximum supply voltage for AC/DC converters can then be 1000 VAC [1]. For the same reason the LVDC distribution system need to fulfill the same LV electrical safety requirements than the AC network with few exceptions.

The maximum DC voltages are shown in table 1. The voltages are allowed to vary within ± 10 % of nominal voltage [9]. The ripple of voltage is allowed to be the same or less than 10 % [2].

Power factor of the AC/DC converter should be over 0.9 in load situations. The harmonic current distortion should be less than 5 %. The AC/DC converters must be able to start automatically when mains supply return after outages. [10]

The customer operating voltage can be sinusoidal 230 VAC in 1-phase and 400 VAC in 3-phase systems within ± 10 % of nominal voltage. The voltage frequency can be 50 Hz within ± 0.1 Hz of nominal value. [10]

The DC/AC converter harmonic current and voltage distortions should be less than 5 %. Power factor in output should be between 0.8 – 1.0. The DC/AC converters must compatible with existing installations and it needs to fulfill its safety instructions. It also needs to function properly with existing safety devices. In addition the DC/AC converter needs to be able to start automatically after outages. [10]

One of the aims of LVDC distribution system concept is higher energy efficiency compared to the traditional 20/0.4 kV distribution system. The power electronic devices energy efficiency should be over 98 %. The unit sizes of AC/DC converters can be 50 – 300 kVA and DC/AC converters up from 10 kVA. The larger converter sizes may be constructed of parallel connections of smaller devices. [10]

The environmental issues set requirements for the system to operate outdoors within a range of -40 to +60 ºC [10]. The overvoltage endurance must be taken care of especially for sensitive power electronic devices.

The aimed power electronic device lifetime is 15 – 20 a. The lifetimes are shorter compared to traditional AC network components which emphasize the maintenance issues of converters. The construction needs to be modular for easy maintenance and the connection to the system need to be plug-and-play type solution for easy replacement. [10]

IV. Electrical Safety

The LVDC distribution system differs from a traditional 3-phase AC distribution system in many ways. Compared to the traditional system the LVDC distribution system is more complex system and have more different fault cases. As the challenge of the new concept the DC distribution system needs to meet electrical safety regulations defined in the LV standardization.

A. LVDC Network Grounding Arrangement

At distribution network faults the LV standardization defines maximum contact voltage limit to be 120 VDC in DC systems. Occurring contact voltage at fault point is always only a part of earth voltage. Therefore earth voltage limit is defined to be twice as contact voltage limit. The earth voltage limit is thereby 240 VDC. [2]

The research results shows that grounded TN system can introduce high earth and contact voltages over allowed limits already at small earth resistances values in a 750 VDC system [11]. The example network used in ground fault analysis is shown in figure 9. The fault location is 3.5 km apart from MV line.

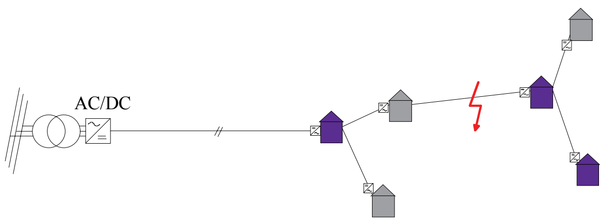

Fig.9. Example network for ground fault in TN system [11]

The equivalent circuit for fault situation is shown in figure

10 where X_m is transformer reactance, R_s is simplified bridge resistance, R_j are cable resistances and R_m is earth resistance. Only the faulted pole is drawn in the figure.

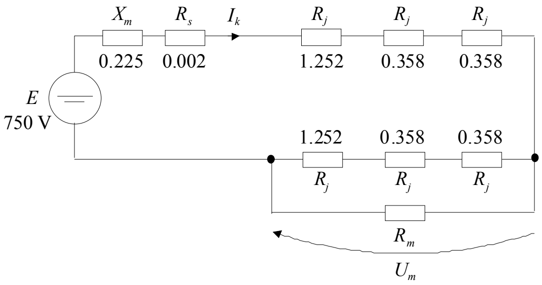

Fig.10. An equivalent circuit for a bipolar ± 750 VDC distribution system ground fault between positive pole and neutral. Only the faulted pole is drawn in figure. [11]

The earth voltage in function of earth resistance during ground fault in TN system is shown in figure 11. The allowed earth voltage 240 VDC is also drawn in figure.

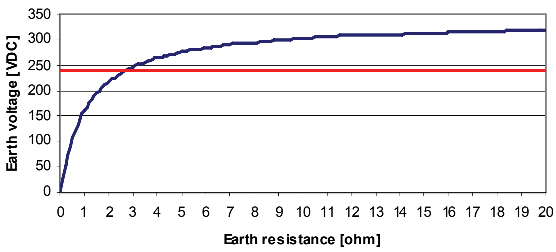

Fig.11. Earth voltage in function of earth resistance during ground fault in TN system. [11]

Because of high earth voltages the LVDC system grounding arrangement needs to be ungrounded system to meet defined earth voltage limit in difficult grounding conditions. Earth voltage in IT system ground fault results only small earth voltages because lack of fault current return path. However the high earth voltages can arise in IT systems in double ground fault situations when two ground faults creates fault circuit through ground.

The LV standardization demands insulation monitoring to be used in ungrounded systems to indicate first fault [2]. At the first fault protection system is not required to operate but it needs to announce alarm [2]. However the operation at first fault is desirable against double fault situations.

B. Customer Network Grounding

The customer operating voltage is produced directly with inverter so there is no need of voltage transform before customer. Because of energy efficiency reasons separate LV transformer at customer is not desirable. For this reason customer network is not galvanically isolated from DC network. Because of galvanic connection the customer network grounding arrangement needs to be IT system. The customer network needs also to be equipped with ground fault monitoring devices.

The customer network grounding arrangement can be grounded TN system if galvanic isolation transformer is used between DC and customer networks. Without galvanic isolation the groundings forms short circuits through ground.

C. Power Electronic Devices

The main difference is that power electronic devices are used in the network which introduces new challenges compared to traditional AC distribution system. The devices introduce switch faults which can produce for example voltage dips and alternative voltage to DC network and DC voltages to customers AC network. The main protection against switch faults is converters self diagnostics and protection functions. For backup protection can be used fuses and overvoltage protector.

The DC system needs to be compatible with existing protection devices. The inverters short circuit current capability needs to fulfill used circuit breakers or fuse current requirements. Sufficient short circuit current can be attained with converter switch overdimensioning in converter design. The harsh estimation shows that 10 kVA inverter needs to be capable to feed two times its nominal power in fault situations. [10]

As additional protection method with insulation monitoring in IT systems can be used 30 mA residual-current devices to ensure electrical safety. For a fire protection can be used 300 mA devices in front of customer network. The residual-current device type must be selected to fit with power electronic converters. The difference between the types is in DC component tolerance. Therefore regular type of residual-current device can cause faulty operation while any faults not exist.

The traditional AC system protection relies on separate protection devices which are needed to protect the system against occurring faults. Power electronic devices enable protection function integration to the AC/DC and DC/AC converters which reduces number of separated protection devices. The integration can decrease system investment costs as number of separate protection devices decreases. The protection functions may also precipitate protection operation time. The protection functions can be used for backup protection method also.

V. Applications

The benefits of LVDC distribution system enable LVDC system to have many targets of applications. The system can be applied in both rural and city networks. It is also suitable for new construction and renovation targets.

In rural networks DC distribution system can be used in as a MV branch replacement at typical transmission powers. Depending on the used LVDC system the LV network behind the branch can also be replaced with DC network. The research results shows that several dozens percent of MV network length could be replaced with LVDC distribution system in rural networks depending on the network structure

[4][12][13]. The LVDC system also suits for cases when MV line is too expensive or LV transmission capacity is limited. In rural networks these cases can occur for example in underwater lines.

In city the LVDC can be applied for example to transmission line between electricity stations, public lightning or apartment house electrification. In the city the LVDC may be a good alternative for LV renovation targets which transmission power has reached its limits. In these cases transmission capability can be increased with changing the AC system to LVDC system using existing transmission lines without expensive excavation.

The LVDC system can also be used in ship electrification and industrial networks. The LVDC system can improve these systems energy efficiency while conversions between AC and DC can be reduced. [10]

A. Renovation Example

The renovation example is calculated for a real rural MV branch line. In the calculation is compared systems total costs between a traditional 20/0.4 kV system and a ± 750 VDC bipolar LVDC distribution system. The total power of the branch is 220.1 kW and number of the customers is 33. All customers are assumed to be domestic customers.

The traditional 20/0.4 kV system constructs with MV branch and six LV districts (1-6). The total length of MV branch lines are 4.1 km and LV lines are 6.0 km. The ± 750 VDC bipolar distribution system constructs a one wide DC distribution district which AC/DC conversion is made at beginning of the MV branch and DC/AC conversions are made at customer-ends. The example network is shown in figure 12.

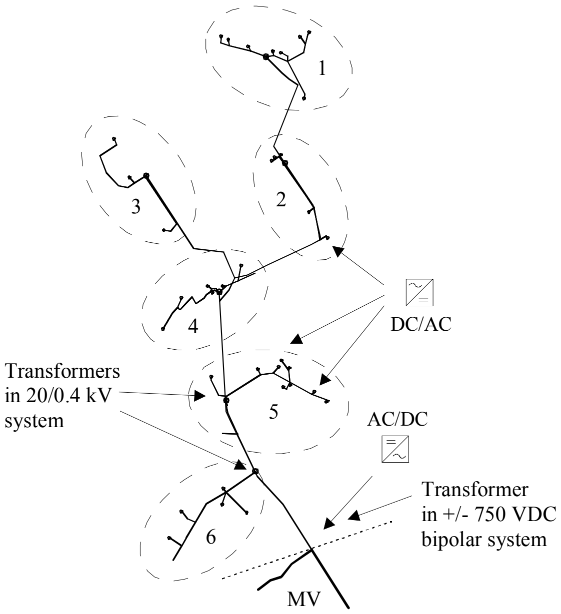

Fig.12. Example of MV branch replacement with ± 750 VDC distribution system.

The harsh power electronic converters price estimations are 1500 € for 10 kVA DC/AC converter and 2000 € for 50 kVA AC/DC converter. Sufficient unit sizes are assumed to be multiples of these basic units. Used calculation parameters are shown in table 3.

TABLE III
CALCULATION PARAMETERS [10]

Parameter	Value
Lifetime [a]	40
Lifetime of power electronic devices, 1st generation [a]	10
Lifetime of power electronic devices, 2nd generation [a]	15
Interest rate [%]	5
Power factor	0.97
Time of load growth in supply network [a]	40
Time of load growth in LV network and branch line [a]	10
Peak operating time of losses [h]	1000
Efficiency of power electronic devices [%]	0.96
Interruption time in permanent fault [h]	1

The costs are calculated assuming that network structure is same in both systems. All cables are assumed to be installed by ploughing. The cost classification for both systems is shown in table 4.

TABLE IV
COSTS OF TRADITIONAL AND LVDC DISTRIBUTION SYSTEMS [10]

System	Traditional 20/0.4 kV System [k€]	Bipolar ± 750 VDC system [k€]
Investment – network	168.41	85.60
Investment – power electronic devices	0.00	160.37
Power losses – network	16.27	15.23
Power losses – power electronic devices	0.00	20.61
Outages	118.32	0.20
Maintenance and repair	25.25	6.05
Total costs	328.25	288.06

Using bipolar system reduces network costs nearly half than in traditional system because smaller cable cross-sections can be used and the number of LV transformers decreases from six to one. The outage costs decreases resulting of DC systems own protection zone. Compared to the traditional system LVDC system introduces new cost components resulting of power electronic converters.

The result shows that total costs reduce 12 % for DC system advantage. Even so investment costs are 46 % more in LVDC system than in traditional system because of high power electronic devices investment costs. Power electronic device investment costs emphasizes because of short lifetimes which causes need of device renovations during distribution system lifetime.

VI. CONCLUSION

This paper presented the LVDC distribution system concept. The European Union directive 2006/95/EC enables DC voltage to be used in electricity distribution systems up to 1500 VDC [1]. The LVDC distribution system has many advantages compared to traditional 20/0.4 kV distribution system. Research results shows that LVDC distribution is economical solution for many targets of applications. One of the targets is rural distribution where LDVC distribution is suitable for MV branch replacement at typical transmission powers.

An LVDC distribution system can be constructed with many variations. In this paper is concentrated to bipolar ± 750 VDC distribution system. The bipolar ± 750 VDC distribution system grounding arrangement needs to be ungrounded system in areas with difficult grounding conditions because ground faults can introduce earth voltages over allowed limits in grounded TN system.

The LVDC distribution system is more complex than traditional distribution system which complicates system operation and protection. Usage of power electronic devices introduces new fault situations and complicates protection system. Occurring challenges needs to taken care in converter designing and protection device selection.

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