POSSIBILITIES OF THE LOW VOLTAGE DC DISTRIBUTION SYSTEMS

Tero Kaipia, Pasi Salonen, Jukka Lassila, Jarmo Partanen
Lappeenranta University of Technology
P.O. Box 20, 53851 Lappeenranta
Finland
Emails: tero.kaipia@lut.fi
pasi.salonen@lut.fi

ABSTRACT

Expectations both on electricity distribution techniques and the distribution business are growing. The EU low voltage directive (LVD 72/23/EEC) [1] enables the use of 1 kV low voltage level as a third distribution voltage level between the traditional 20 kV and the 0.4 kV networks. This has proved to be a cost-efficient solution to enhance the reliability of electricity distribution. Similarly with the AC low voltage systems, the EU low voltage directive defines the boundaries for voltages used in the DC low voltage systems. According to the directive, any electrical equipment designed for use with a DC voltage rating between 75 and 1500 V DC is a low voltage instrument [1]. This includes also the distribution systems. The DC-systems and power electronics are the emerging technologies in electricity distribution.

The utilization of the DC low voltage distribution opens new possibilities for network development. For example, with the same voltage drop and the same 3~cable 16 times more power can be transmitted with a 1.5 kV DC-system than with 0.4 kV AC system. In the proposed paper, the basic concepts and the techno-economical potential of the low voltage DC-systems are discussed. Also aspects of developing required power electronic equipment for low voltage DC systems are introduced.

1. INTRODUCTION

The recognized leading themes in the distribution network development are the cost effectiveness and system reliability. Until today the main voltage levels in Finnish distribution networks have been 20 kV and 0.4 kV. Since the benefits of the 20/1/0.4 kV system were noticed, the distribution network is now changing towards this kind of system. Thus, the 20/1/0.4 kV system has proven to be profitable solution its application possibilities are limited to quite small transmission powers and short transmission distances. As the weight of mentioned drivers of development increase with utilization of distributed generation (DG) there will be demands for novel distribution techniques [2]. A solution emerging from the same basic idea than the 20/1/0.4 kV system is the application of DC-distribution system.

Nowadays electricity distribution networks construct mainly of the three-phase AC systems. Consumer voltage in traditional distribution system is 230/400 V and the nominal frequency in Europe is 50 Hz. The utilization of the 1 kV distribution systems takes full advantage of LVD directive’s low voltage AC-system definition. The EU directive LVD 73/23/EEC covers equipment designed for use with a voltage rating between 50-1000 V for alternative current and between 75-1500 V for direct current [1]. Although AC voltage rating is today used in its full capacity the DC voltage is still unexploited in distribution systems. Component prices of power electronics have constantly been decreasing in the last decade allowing power electronic devices to be used in greater number of applications. DC-distribution enables the improvement of the customer's electricity quality beyond today's level with lower costs compared to AC systems. A basic concept of DC distribution system is presented in figure 1. As the application of the proposed DC system adds the number of network components and also mixes AC and DC distribution, the distribution system in total becomes considerably more complex than traditionally. This makes the design process difficult [3] and also adds the number of possible system faults.

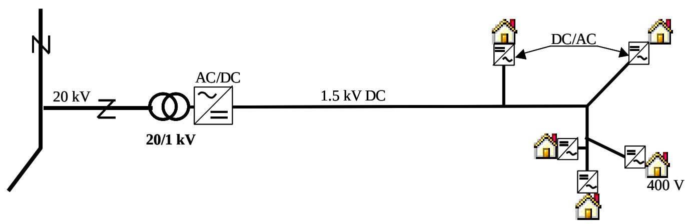

Figure 1. *A basic concept of implementing DC distribution in the public low voltage network.*

The economical benefit can be achieved through the better transmission capacity of low voltage DC-distribution compared to low voltage AC-distribution. With the same costs of losses smaller conductors compared to AC distribution can be used. In addition to that there is no need for public 400 V low voltage distribution. The DC network could also be a good solution for connecting small scale DG to the distribution network [2]. The proposed system is still on an experimental phase and is developed mainly for economical efficiency analysis. There are still plenty of technical questions to be concerned including the power electronic devices and the actual structure of the system.

2. DC-DISTRIBUTION SYSTEMS

From the reliability point of view, the main principle of the low voltage DC system is the same than in the 20/1/0.4 kV system; a possibility to enhance the reliability of distribution cost efficiently. By applying DC low voltage system or by 1 kV system, the length of the medium voltage network can be reduced [4]. With these systems the number and length of branches in the 20 kV medium voltage network can be diminished. This reduces outage costs of the entire distribution network compared to the traditional 20/0.4 kV system. The idea of proposing the DC system is to give a reliable and economical alternative to both; shorten the length of the medium voltage network even more than is possible with the 1 kV AC system and also increase the customer's voltage quality.

DC distribution system constructs of a DC connection that replaces both the 20 kV branch line and traditional low voltage network. In this case the low voltage transforming district contains only a wide DC connection between 20 kV main line and contact points of the customers. In the DC distribution systems the medium voltage is transformed to low voltage using same 20/1 kV transformer than in 20/1/0.4 kV distribution systems. The AC voltage is rectified to DC voltage right after the transformer. The power is transferred with DC-link all the way to customers where the DC voltage is inverted back to AC voltage. Because of inverting DC voltage direct to customers operating voltage there is no need for additional distribution transformers inside the transforming district like in the 20/1/0.4 kV system. In figure 2 is presented the principle of the proposed DC-distribution system with comparison of system structure to the traditional AC systems.

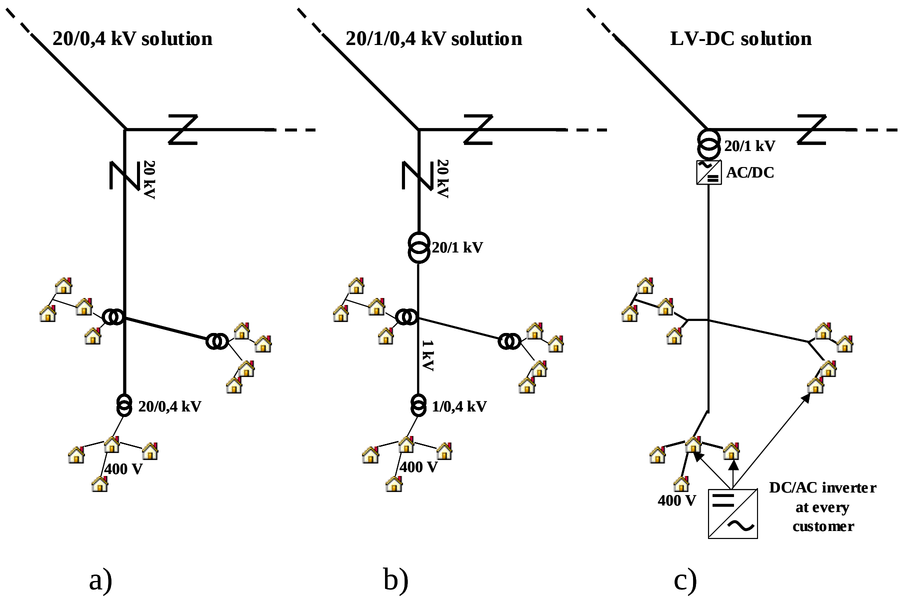

Figure 2. *Feeding a customer group a) with the 20/0.4 kV solution, b) with the 20/1/0.4 kV solution, c) with the proposed DC-distribution system.*

The DC distribution system can be made with different connection types. The most common are uni-, and bipolar connections. The difference between these two connections is the number of voltage levels. Simplified concepts of uni-, and bipolar connections are shown in figure 3.

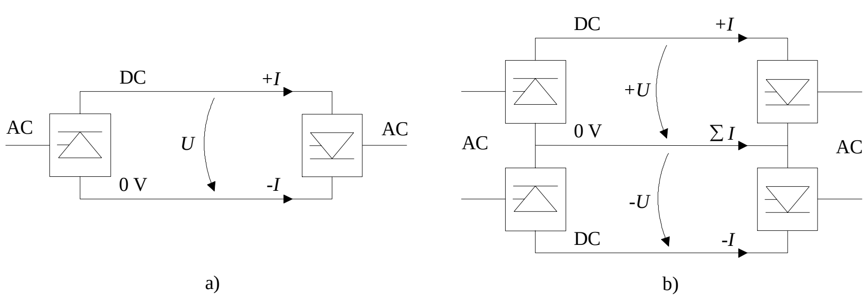

Figure 3. *The connection concepts for a) a unipolar and for b) a bipolar system.*

In the bipolar system the loads can be connected either (1:) between the current conductor and zero conductor, or (2:) directly between the ± conductors. Both of these solutions have their problems. In the first mentioned bipolar solution there is a problem when the loads are not identical and the system falls into unbalance. In this case there will be a continuous current flow in the zero conductor. The inverters required at the customers end will also need more components, because the zero potential level will have to be formed between the system zero and phase conductor for producing required alternative voltage. In the second case, in which the loads are connected directly between the ± conductors, the problem is the increased costs of the power electronic devices due to the higher voltage level. The unipolar system is inexpensive but decreases the transmission capacity of the system and also needs inverters capable of forming the zero potential level between the system zero and phase conductor at the load point.

3. ANALYSIS OF THE DC-DISTRIBUTION

The techno-economical analysis consists of two phases. In first phase the technical feasibility of the DC system is analyzed and different solutions are illustrated with comparisons of these systems to each other. At this point the technical potential is also compared to traditional AC systems. In the second phase the target is to determine the economical efficiency of the DC system as a part of distribution network. This analysis is done through example case in which the costs and appearance of the DC system is compared to the 20/0.4 kV solution. In the example calculations a DC- and AC-transforming districts are designed to feed a group of customers with respect to similar technical boundaries. One of the main targets in economical analysis is to determine the maximum costs of the power electronic devices needed in the DC system.

3.1. Technical analysis

The components in DC-distribution systems are expected to be mostly the same than in AC systems if standardization allows using components with DC voltage. Low voltage underground cables may be used in DC systems if system voltage between two conductors is not higher than 1.5 kV and between earth and conductor is not higher than 0.9 kV [5][6][7]. The standards concerning low voltage aerial bundled cables does not mention any possibilities or limitations to the application of these cables in the DC systems and therefore it is assumed that they can not yet be used in actual DC systems [8]. Because of the limitations set by the standardizing, the full potential of low voltage directives DC voltage definition cannot be taken advantage without designing the new cables for DC distribution systems. This is one of the constructional problems in application of the system and full analysis of the utilization of the standard low voltage components in the DC systems is needed and will be carried out in the near future.

Leaving aside cable standardization the DC distribution system can be compared to the traditional distribution system if the cables are assumed to be suitable for the both AC and DC systems. Cables designed for the three-phase AC systems can also be used in the DC distribution systems if the conductor connections fill up the demands of the DC distribution line. The possible conductor connection solutions for four-conductor cable are shown in figure 3. The used connection solutions have an influence to transmission line resistance and thermal endurance.

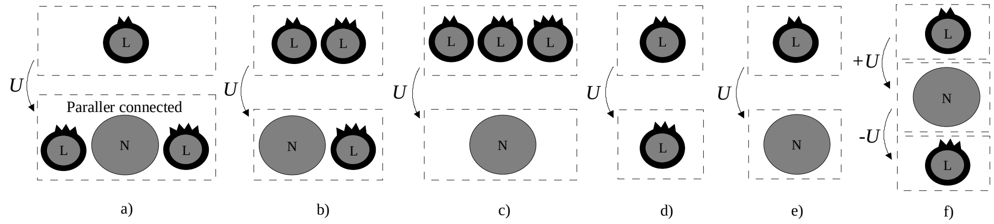

Figure 4. *The possible connection solution for a-e) a unipolar and for f) a bipolar system.*

The transmission power coefficient between DC and AC systems with different cable connections can be defined with basic calculations. The transmission power coefficients can be defined with respect to the thermal limit and to the voltage drop of the cable, depending on the transfer limit. In the calculations the transmission distance is kept constant. From the same equations that are used for calculating the transmission power coefficients, similar coefficients for transmission distance can be solved with respect to the voltage drop. Therefore transmission distance coefficients depending on the voltage drop are the same than the transmission power coefficients and can be red from same table. In the calculations of the transmission distance coefficient the transmission power is kept constant. Transmission power and transmission distance factors for four conductors containing cable is shown in table 1.

Table 1. *Transmission power and transmission distance coefficient for AC and DC distribution systems. DC voltage is 1500 V in both uni-, and bipolar DC distribution systems. DC systems cable connections are shown in figure 3.*

Cable [mm^2]	Limit	Traditional distribution system	1000 V distribution system	Unipolar DC system	Unipolar DC system	Bipolar DC system
				Connection b)	Connection d)	Connection f)
3x35+70	Thermal	1,00	2,50	3,40	2,17	4,33
	Voltage drop	1,00	6,25	16,31	8,97	28,13
3x70+95	Thermal	1,00	2,50	3,94	2,17	4,33
	Voltage drop	1,00	6,25	14,80	7,73	28,13

Transmission power and transmission distance coefficients show that more power can be transmitted with DC distribution system compared to the AC systems. With unipolar DC distribution system 16 times power can be transferred than with a traditional 400 V distribution system. With bipolar DC distribution system the transmission power coefficient is over 28 if $\pm$ 1500 V voltage is used. At the thermal limit of the cables the transmission power coefficients are smaller than at voltage drop limit. Difference between maximum powers in the AC and the DC system is a result of DC connection type, used DC voltage and used cable connections. The transmission power as a function of the transmission distance is presented in figure 5.

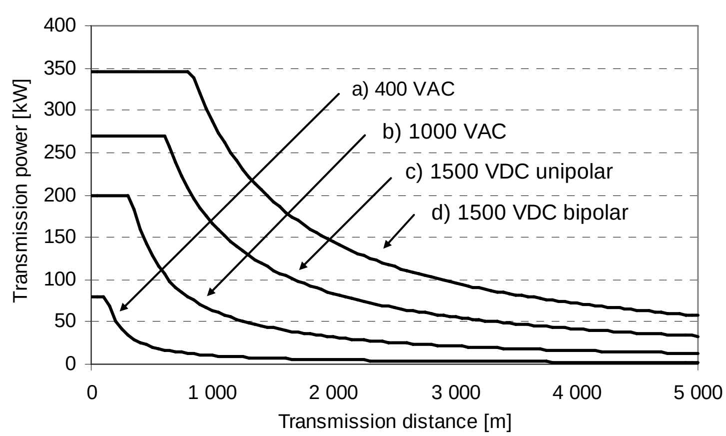

Figure 5. *Transmission powers using 3x35+50 mm^2 cable in AC and DC distribution systems. Maximum voltage drop is 6 %.*

The lines in figure 5 show that for example in 500 m distance the maximum transmission power for 400 VAC system is 20.5 kW when at the same distance the maximum power for 1500 V unipolar DC system is 270.5 kW. The transmission power factor between these systems is then 13.2. The same comparison for ± 1500 V bipolar DC system gives the factor 16.9 and the maximum transmission power for bipolar DC system is 345.0 kW. Used cable connections for this comparison are shown in figure 6.

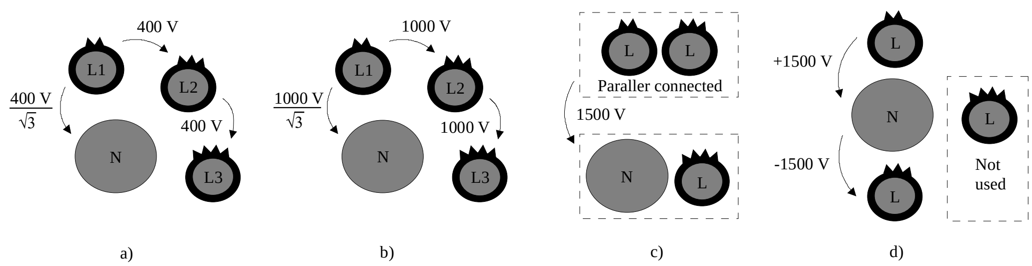

Figure 6. *Connection solutions for a) the traditional 400 VAC system, b) the 1000 VAC system, c) the 1500 VDC unipolar-system and d) the 1500 VDC bipolar-system.*

Higher voltage rating in the DC distribution system leads to smaller currents and therefore smaller power losses than in the AC low voltage system. The power loss factors between AC and DC systems can be calculated by keeping the transmission power and the transmission distance constant. Power loss factors for DC systems are smaller compared to the traditional 400 VAC distribution system, when using the same cables and cable connections which were used for calculating the coefficients in table 1. For example, the power loss factor of the 1500 V unipolar system is 0.06 for 3x35+70 mm^2 cable when cable is connected with connection solution presented in figure 4 b). In practice the smaller power losses can be employed to use smaller cable sizes that decreases investment costs of a cable [3]. However, shift to smaller cable sizes increases the power loss factors and therefore the real factors at utilization aren't the same than plain calculated factors for different cable connections.

3.2. Economical efficiency analysis

The technical analysis of DC distribution system presented the difference between AC and DC systems. The benefits gained from technical side of view can be used to build more economical distribution networks compared to traditional AC systems. The total cost difference between traditional 20/0.4 kV system and ± 750 bipolar system can be analyzed through a theoretical network design calculations. The example network for this theoretical case is shown in figure 7.

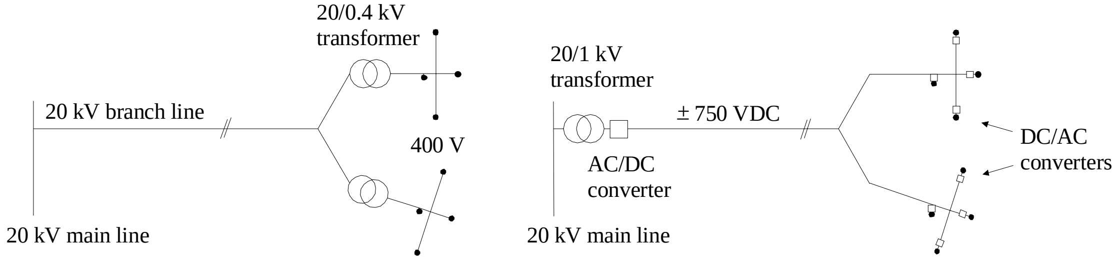

Figure 7. *The example network for economical comparison between a traditional 20/0.4 kV and a ± 750 VDC bipolar distribution systems.*

In the calculations it is assumed that the network structure is the same in both cases. The traditional 20/0.4 kV distribution system constructs of an aerial medium voltage branch line with two low voltage transforming districts. The length of the needed branch line is 3.5 km and the lines dividing customers to separate districts are 0.5 km. The area includes 8 customers and 2 km of low voltage network in total, which divides evenly to two districts. Each customer's power is assumed to be 12 kW. The DC distribution district unites these two low voltage districts as a one large district. In the DC solution all used low voltage cables are underground cables including the DC line that replaces the medium voltage overhead line used in the 20/0.4 kV solution. All underground cables are installed by plough. The cross sections of the lines are chosen to meet the loads over the whole utilization time of the system. The material costs for cable sizes not listed in the national cost list KA 2:2003 [9] are approximated with empirical function based on costs of existing cables. The unit costs of the 20/0.4 kV transformer and single pole-mounted substation are taken directly from the national cost list KA 2:2003 [9]. The average outage costs for rural medium voltage network are 10 500 €/km [4]. All customers at LV districts are assumed to be residential customers and the outage costs of the low voltage network are calculated as a function of transmission power using the customer group-specific energy-weighted CENS (cost of energy not supplied) values. Other calculation parameters are shown in table 3.

Table 2. *The calculation parameters for techno-economical comparison between traditional 20/0.4 kV and ± 750 VDC bipolar distribution systems.*

Parameter	Value
Lifetime [a]	40
Annual growth of consumption [%/a]	0
Interest rate [%/a]	5
Power factor	0.95
Price of power losses [€/kW]	30
Price of energy losses [€/kWh]	0.03
Peak operating time of losses [h]	1000
Interruption time in permanent fault [h]	1
Maintenance costs in medium voltage aerial network [€/km,a]	95
Maintenance costs in low voltage cable network [€/km,a]	20
Fault repair costs in medium voltage cable network [€/fault]	1640
Fault repair costs in low voltage cable network [€/fault]	1600

The total costs of the traditional 20/0.4 kV network for presented lifetime are 176 k€. Correspondingly, the costs of the ± 750 V bipolar DC-distribution system are 70 k€ when the costs of the power electronic devices are excluded. The cost difference between these two systems is 106 k€ in the favor of the DC system, which sets the limit for the maximum costs of the power electronic devices. If the sum of the investment costs and costs of power losses of the power electronics required in the DC system are higher than 106 k€ the traditional 20/0.4 kV distribution system becomes more economical than DC distribution system at the studied case. The costs of compared systems are presented in table 3.

Table 3. *Costs of the traditional 20/0.4 kV and ± 750 VDC bipolar distribution systems.*

Cost factor	Traditional 20/0.4 V distribution system	Bipolar ± 750 VDC distribution system	Cost difference
Investments [k€]	104	45	59
Losses [k€]	9	19	-10
Outages [k€]	47	0	47
Fault repair [k€]	7	3	5
Maintenance [k€]	8	3	5
Total [k€]	176	70	106

The largest cost differences between the AC and DC solutions are found in the outage costs and in investment costs of the branch line. The replacement of the medium voltage aerial branch line with DC low voltage line decreases the investment costs 38 k€. By adding the impact of the distribution substations and low voltage network of the 20/0.4 kV solution, the total investment cost difference is increased to 59 k€. Outage costs in the AC solution are over 47 k€ higher than in the DC solution. The outage cost difference is a consequence of shortening the medium voltage network and the individual protection area formed by DC distribution system.

The harsh estimation of power electronic device costs are 4000 € for the needed 100 kVA AC/DC converter and 3000 € for a 10 kVA DC/AC 3-phase inverter. In this case, one AC/DC converter and at the load points two DC/AC inverters per load point, making 16 in total, are needed. Efficiency of power electronic devices is assumed to be 0.96. In this case the investment costs of the power electronic devices needed in the example case are 52 k€ and the costs of power losses are 4 k€ from the lifetime. The total costs of the power electronics are then 56 k€ which are 50 k€ smaller than the calculated cost difference (106 k€) of the AC and DC solutions in the example case. This makes the DC system the most profitable solution for this region. However, this is just one of the first economical efficiency studies and the results should not be generalized too widely before further analysis.

4. BENEFITS AND DISADVANTAGES

The introduction of new technology comes with its own benefits and disadvantages. LVD 72/23/EEC allows using higher voltage rating in DC systems than in AC systems. Because of the higher voltage rating and higher RMS value of DC voltage, compared to corresponding AC voltage, the transmission capacity of a low voltage DC system is higher than with corresponding low voltage AC system. The voltage loss is smaller because the inductances of the system have no effect in the electrically continuous state; In DC system there is no reactive currents. DC resistance is smaller than AC resistance that also decreases voltage and power losses.

Application of the DC system reduces voltage fluctuations at the customer's end and the operating voltage can be kept nearly constant. The customer's operating voltage can be produced from wide range of DC voltages as long as the voltage of the DC link is over 560 V, voltage needed by the 12-pulse inverter to produce 400 V three-phased-supply. This means that the voltage drop and voltage dips resulted from different parts of the network can be repaired with active inverter control if DC voltage in inverter poles is greater than required minimum voltage to produce customer's operation voltage. The only customer disruption in DC distribution is voltage break if DC voltage falls under the required minimum DC voltage. In the fault situations the bipolar distribution system can also be used in half capacity if the loads in this case do not exceed capacity limits of the system components.

As the distribution system becomes more complex and the number of components in the system increases there are also more possible targets for system faults compared to simpler traditional system. The disadvantages of DC systems occur mainly in the power electronic devices. The lifetimes of electronic devices are shorter than in the case of the traditional network components. Power electronic devices also increase losses and produces voltage harmonics to the network. Harmonics filtration has to be used which increases the total costs.

The number of network components increases because of power electronic devices, which may increase the number of faults. However, these faults affect only to the customers located in the DC distribution district. The harm caused by a DC fault is quite small compared to the situation of a fault incidence on a medium voltage line in which the fault impacts to all the customers connected to the feeder and can also be seen by customers on other feeders connected to same primary substation with the faulted feeder. From this point of view the application of the DC system, which replaces a part of the medium voltage network, reduces the average number of outages affecting a customer and so reduces the system average interruption frequency (SAIFI).

5. CONCLUSIONS

The results of the DC distribution system analysis show the potential of the system. Customer's voltage quality improves when voltage dips, fluctuations and short time voltage drops can be eliminated using power electronic devices. With the low voltage DC distribution systems also higher transmission powers and transmission distances can be achieved when compared to the traditional low voltage system. The higher power handling capacity produce smaller power losses, which enables the use of smaller cable cross-sections than in the corresponding AC system. By combining these benefits of the proposed DC system the total costs of constructing and operating a distribution system can be decreased. Building more economical and reliable networks than today is one of the future goals in the electricity distribution business.

The DC distribution system is a economical solution as a replacement of medium voltage branch lines at typical transmission powers of the rural networks. The benefits compared to traditional 400 V system are smaller outage and investment costs. The harsh estimation of power electronic device costs indicates that the constantly decreasing prices of the power electronic components don not set obstacles to the introduction of the low voltage DC distribution. The future challenges of DC distribution examination lies in more specific study of economical ranges and basic structures of power electronic devices.

6. REFERENCES

[1] European Commission. Low voltage directive LVD 73/23/EEC. European commission directive: Brussels, 1973.
[2] Lohjala, J., Kaipia, T., Lassila, J., Partanen, J., Järventausta P., Verho P., Potentiality And Effects Of The 1 kV Low Voltage Distribution System. In proceedings of the FPS Conference 2005.
[3] Kaipia, T., Lassila, J., Partanen, J., Lohjala, J., Principles and tools for the 20/1/0.4 kV distribution network planning. In proceedings of the NORDAC Conference 2006.
[4] Lohjala, J., Kaipia, T., Lassila, J., Partanen, J., The three voltage level distribution using the 1000 V low voltage system. In proceedings of the CIRED Conference 2005.
[5] SFS 4879. 0.6/1 kV poewr cables. XLPE-insulated Al-cables. Construction and testing. National cable standard. SESKO Standardization in Finland.
[6] SFS 4880. 0.6/1 kV power cables. PVC-insulated PVC-sheathed cables. Construction and testing. National cable standard. SESKO Standardization in Finland.
[7] SFS 5800. 0.6/1 kV power cables. Cable for energy boards AXMKE. Construction and testing. National cable standard. SESKO Standardization in Finland.
[8] SFS 2200. 0.6/1kV cables. Aerial bundled cable (ABC), AMKA. National cable standard. SESKO Standardization in Finland.
[9] Sähköenergialiitto SENER ry. National cost list of network components KA 2:2003, Adato Energia Ltd., Finland 2004.