APPLICATION OF LOW VOLTAGE DC-DISTRIBUTION SYSTEM – A TECHNO-ECONOMICAL STUDY

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ABSTRACT

Today's 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 European Union (EU) low voltage directive (LVD 72/23/EEC) [1] *defines the boundaries for the low voltage (LV) levels used in public distribution systems. According to the directive any electrical equipment designed to be used with a voltage rating between 50-1000 V AC and between 75-1500 V DC is a low voltage instrument.*

The utilization of the 1 kV AC-distribution system takes full advantage of the LVD 73/23/EEC directive's AC-definition. However, the DC voltage rating is still unexploited in public distribution systems. As the weight of cost efficiency and reliability requirements of distribution networks are expected to increase in the future, with the utilization of distributed generation, there will be demand for novel distribution techniques. The utilisation of the LV-DC-distribution opens new possibilities for network development. In this paper, the basic concepts and the techno-economical potential of the LV-DC-systems are discussed. Also aspects of developing required power electronic equipment for LV-DC-systems are introduced.

INTRODUCTION

Until today the main voltage levels in Finnish distribution networks have been 20 kV and 0.4 kV. Although the 1 kV AC low voltage level is today used in distribution networks, the application possibilities of LV-AC-distribution systems are limited to quite small transmission powers and short transmission distances. Hence, the techno-economic benefit of the LV-DC-system can be achieved through better transmission capacity compared to the LV-AC-system.

The recognized leading themes in the distribution network development are the cost effectiveness and system reliability. LV-DC-system enables decreasing the number and length of the medium voltage branch lines. This reduces the number of possible fault situations in medium voltage network, affecting typically hundreds of customers, and so improves the quality of distribution leading to the decrease of the outage costs. The power electronics in the DC-system also enable compensating voltage drop, dips and fluctuations originating from the network at the customer's end and so increase the customer's voltage quality. However, adding power electronics and number of components to distribution network increases the probability of inner system faults.

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. The increase of LV-network transmission capacity, achieved with the DC-system, enables application of smaller conductor cross sections than in LV-AC-systems. Also the number of distribution transformers decrease as there will no longer be need for the public 0.4 kV LV-network, when it is replaced with the LV-DC-network. Also remarkable investment cost savings compared to the construction of MV-lines is achieved, as LV components are inexpensive compared to MV components.

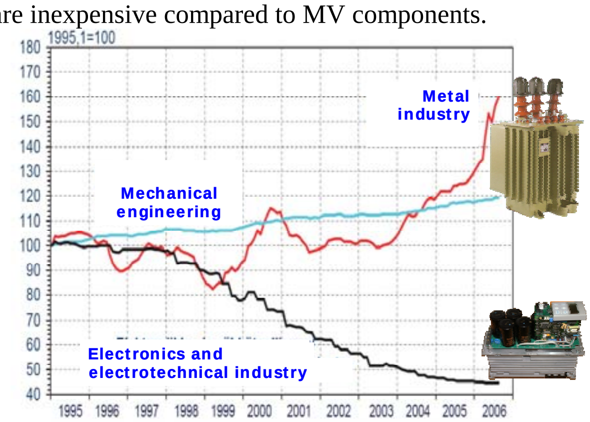

Figure 1 Price development in Finnish technology industry between years 1995-2006 [2].

FUNCTIONAL PRINCIPLES OF LV-DC-DISTRIBUTION

The objectives in development of the LV-DC-distribution systems are:

- Improvement of the quality of distribution and supply
- Decrease of the costs of electricity distribution business
- Open new business opportunities for component, system and service providers.

Functional purposes of the LV-DC-distribution system are to provide reliable electric energy transmission from MV network to the LV customers, to transform the voltage suitable for the LV customers and provide good quality voltage supply. Also the safety issues have to be considered and the LV-DC-system has to be compatible with present MV and LV systems.

For the actual DC-distribution network the first boundaries are defined by the low voltage directive (LVD 72/23/EEC), according to which the voltage level of LV-DC-system has to be 75-1500 V DC [1]. In unearthed DC-system the 1500 V DC voltage is allowed both between two conductors of the system and between conductor and earth. In earthed system the 1500 V DC voltage is applicable only between the conductors of the system and maximum 900 V DC is allowed against the earth [3]. Unearthed system enables more connection possibilities. It is also better solution from the safety point of view as the earth fault currents are small.

DC-system is an extension of the feeding AC-system. Hence, the LV-DC-system has to be fed with LV-AC-system. Reasonable solution is then to use the highest allowed LV-AC-voltage, 1 kV that enables maximum of 1440 V DC to be used without DC booster. By using three winding transformers of which nominal voltage of the two LV-windings is 1 kV it is possible to increase the voltage of the LV-DC-systems to the maximum allowed. The AC voltage is rectified to DC voltage right after the transformer.

DC-distribution system constructs of a DC-connection that replaces both the 20 kV branch line and traditional low voltage network. The power is transferred with DC-link all the way to the customers where the DC voltage is inverted back to AC voltage. In figure 2 is presented the principle of the proposed DC-distribution system compared with today's AC-distribution systems.

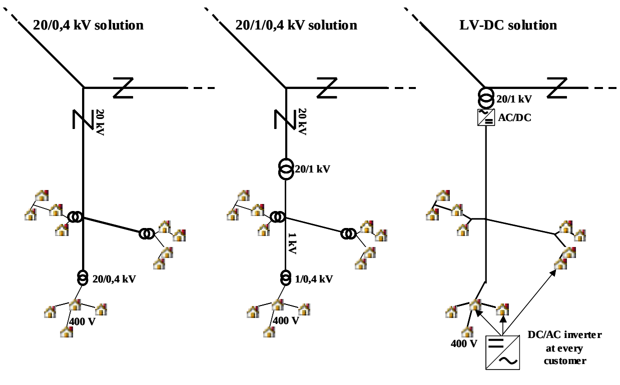

Figure 2. Feeding a customer group a) with the 20/0.4 kV solution, b) with the 20/1/0.4 kV solution, c) with the proposed DC-distribution system.

The DC-distribution system can be made with unipolar or bipolar connections. The difference between these two connections is the number of voltage levels. Simplified concepts for unipolar and bipolar connections are shown in figure 3.

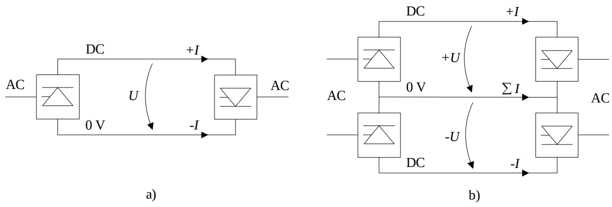

Figure 3. The connection concepts for a) a unipolar and for b) a bipolar system.

In unearthed 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. The customer inverters 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.

TECHNO-ECONOMICAL ANALYSIS

The techno-economical analysis consists of two parts. In the first part the technical feasibility of the DC-system is analysed and the technical potential is compared to traditional AC-system. In the second part the target is to determine the economical efficiency of the proposed DC-system as a part of distribution network. This analysis is based on an example case in which the costs and appearance of the DC-system are compared to the traditional 20/0.4 kV AC-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.

Technical analysis

The components in DC-distribution systems are expected to be mostly the same than in AC systems in the boundaries set by standardisation. LV-underground cables may be used in unearthed 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 [4][5][6]. The standards concerning low voltage aerial bundled cables does not mention anything about the application of these cables in the DC-systems [7].

Leaving aside cable standardization, the 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 transmission power coefficients between DC- and AC-systems with different cable connections can be defined with respect to the thermal limit and the voltage drop of the cable. In general with unipolar 1500 V DC-system 16 times more power compared to 0.4 kV AC-system and 2,5 times more power compared to 1 kV AC-system can be transmitted with the same voltage drop and 3~cable. The difference between maximum transmission powers of AC- and DC-system is a result of used voltages, DC-connection type and cable connections [8]. The transmission power as a function of the transmission distance is presented in figure 5 for the cable connections presented by figure 4.

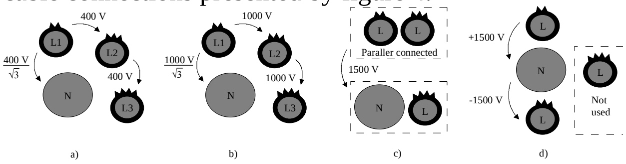

Figure 4. Connection solutions for a) the traditional 400 VAC system, b) the 1000 VAC system, c) the 1500 VDC unipolar-system and d) the ±750 VDC bipolar-system [8].

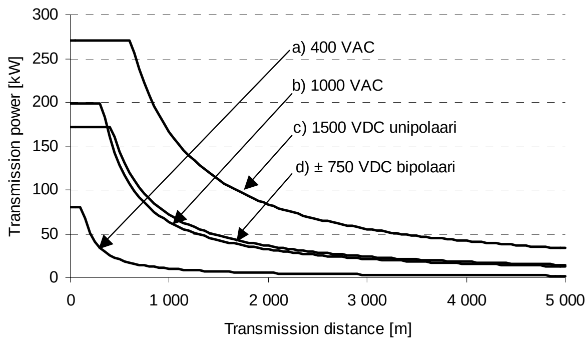

Figure 5. Maximum transmission powers of a 3x35+50 mm2 cable in AC and DC-distribution systems. Maximum voltage drop is 6 % [8].

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 coefficient between these systems is then 13.2. Transmission power and transmission distance coefficients show that considerably higher loads can be driven with DC-distribution systems compared to the AC systems.

Economical efficiency analysis

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 and LV-DC-system is approached through network design calculations. The ± 750 bipolar system is selected as an example DC-system as it enables the application of standard LV underground cables. In the DC-solutions only ploughed LV underground cables are used. The cross sections of the lines are chosen to meet the loads over the whole utilization time of the system. In the calculations it is assumed that the basic network topology does not change when the AC-system is replaced with the DC-system.

The costs of network components are mainly based on the national cost list KA 2:2003 [9]. The average outage costs for rural medium voltage network are 10 500 €/km [8]. 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 [8].

Table 1. General calculation parameters.

Parameter	Value
Lifetime [a]	40
Annual load growth [%/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 example network is shown in figure 6. The traditional 20/0.4 kV AC-distribution system constructs of an aerial MV-branch line with two LV transforming districts. The length of the MV-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 is divided evenly between the LV-districts. Load of each customer is 12 kW, giving the total load of 100 kW.

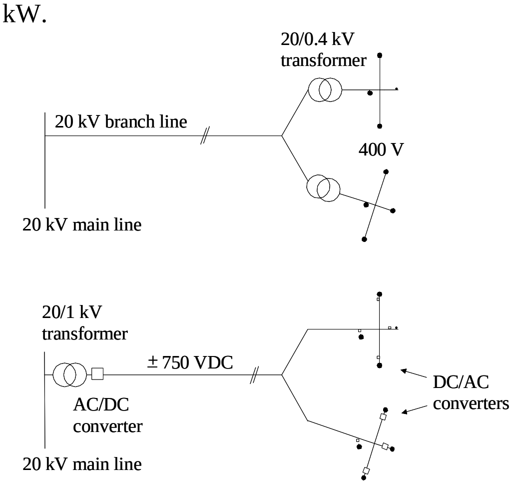

Figure 6. The example network for economical comparison between a traditional 20/0.4 kV and a ± 750 VDC bipolar distribution systems.

The DC-distribution district unites these two low voltage districts as a one large district. The costs of the DC-solution are in the first analysis defined without the costs of the power electronics to determine the maximum allowed costs of the power electronics. The results of this analysis are presented in table 2.

Table 2. Costs of compared distribution systems without the costs of power electronics.

Cost factor	Traditional 20/0.4 kV 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 cost difference the compared systems is 106 k€ in the favour of the DC-system when the costs of power electronics are excluded. The total costs of power electronics required in the DC-system are not allowed to exceed 106 k€ in order to maintain the DC-system as an economic solution.

The largest cost differences between the AC- and DC-solutions are found in the outage costs and in investment costs. The replacement of the medium voltage aerial branch line with LV-DC-line decreases the investment costs 38 k€. By adding the impact of the distribution substations and low voltage network of the AC-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 the unit costs of power electronic device are 4000 € for the needed 100 kVA rectifier and 3000 € for a 10 kVA DC/AC 3-phase inverter. In this case, one rectifier and at the load points two DC/AC inverters per customer, 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. However, this is just one case study of which results should not be generalized too widely.

CONCLUSIONS

In this paper the low voltage DC-distribution system and its techno-economical potential was introduced. The LVD 72/23/EEC allows using higher voltage rating in DC-systems than in AC systems. Also the RMS value of the DC voltage is higher compared to AC-voltage and in DC-system there is no reactive currents at steady state. These factors together enable the increase of the transmission capacity of the LV-network with DC-system. The gained benefits can be used to increase the reliability and economy of the distribution networks. The LV-DC-distribution system is an economical solution as a replacement of medium voltage branch lines at typical transmission powers of the rural networks.

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. The application of power electronic devices adds the number of network components that might add the possibility of inner system faults. 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 future challenges of DC-distribution examination lies in more specific study of economical application ranges and structures of power electronic devices.

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