THE UTILIZATION POTENTIAL OF LVDC DISTRIBUTION

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ABSTRACT

Low voltage direct current (LVDC) distribution is a promising solution, which benefits are large power transfer capacity with low voltage and improvements to reliability and power quality. Tests by the pilot implementation in Elenia Oy have given promising results. The power transfer capacity of the system has been calculated in the paper using voltage drop and maximum load of cable as boundaries. The branches of the MV network, which can be replaced by LVDC distribution, are determined based on the calculations and mass computation of the whole distribution area of Elenia Oy. Based on the done analysis, it can be inferred that LVDC distribution has a good utilization potential.

INTRODUCTION

Over 80% of electricity supply interruptions experienced by customers in Finland are caused by faults in 20 kV medium voltage (MV) network. Often in rural areas MV branch lines have to be built for individual secondary transformers, since the customers are scattered and the distances are long. These branch lines increase faults which cause interruptions to a whole MV feeder. Rural MV networks are typically located in forests. The major part of MV network has been built in the 1950's – 1970's, and thus needs to be renewed in the near future. The result of this renewal work must be able to respond to the future requirements in the following 40-60 years and be done as cost-effective as possible.

LVDC is one topic which develops distribution networks towards the smart grid and brings new opportunities to electricity distribution development. LVDC distribution is a promising solution for the renewal, the benefits of which are large power transfer capacity with low voltage and improvements to reliability and power quality. Moreover, it provides an easy connecting point for the distributed generation and energy storages.

However, LVDC is a totally new technology in distribution networks and with the present-day converters only a maximum operating time of 15-20 years is achieved, which is 1-2 times less than an average lifetime of other parts of the distribution network. Power electronics is constantly evolving, so the lifetime will likely grow in the future, and the structure will be modular and partly changeable.

It is possible to replace low-power MV branch lines by LVDC distribution. This paper presents the unipolar point-to-point LVDC distribution system with four-wire ground cables, which is planned in cooperation with Elenia Oy and ABB Oy Drives [1]. Based on this system calculations of its power transfer capacity are presented. The purpose of this paper is to determine, based on those calculation results, how large number of MV branch lines with a single transformer can be replaced by LVDC distribution in the distribution area of Elenia Oy, and based on outcomes consider its utilization potential.

Elenia Oy is the second largest distribution network company in Finland. It has approximately 408000 customers and distribution network of altogether over 62000 km. 22050 km of it is 20 kV MV network and 38625 km 0,4 kV low voltage network. There are also 21520 20/0,4 kV secondary transformers. The Elenia Oy's distribution network consists mainly of sparsely populated area, so development of the rural area network's distribution technology is especially important.

LVDC DISTRIBUTION SOLUTIONS

General structure of the LVDC distribution

Power electronics enable several new network structures, of which a unipolar point-to-point LVDC system is the easiest option from the perspective of distribution network company. This is due to the fact that the present secondary transformer can be replaced by a centralized inverter, when the low voltage network can be kept unchanged. This solution does not require changes in the customer-end like many other solutions, since there is no need for inverter. Fig. 1 illustrates the concept of point-to-point LVDC distribution system.

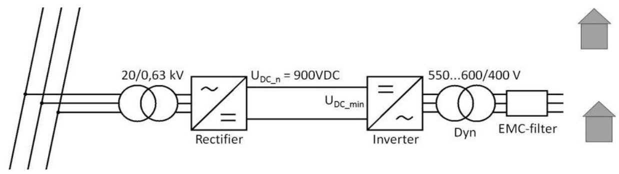

Figure 1. The point-to-point LVDC distribution system.

Advantages of the LVDC system

DC can be used at a higher voltage level because of the definitions of the AC and DC voltage ranges in the Low Voltage Directive 2006/95/EC, which defines the maximum value of low voltage as 1000 VAC and 1500 VDC [2]. The present AC cables can also be used with DC. Losses are reduced when using the same RMS voltage level, since with DC reactive power is not transferred at all. More detailed studies of LVDC can be found in [3], [4], [5] and [6].

The LVDC network forms its own protection area of which faults do not cause interruptions to the entire MV feeder. On the other hand, the LVDC system protects customers from short MV feeder interruptions with energy stored in the capacitances of the converters and in the LVDC network itself. Tests by the pilot implementation in Elenia Oy, which is based on point-to-point type of system, have showed that the LVDC system tolerates MV feeders' autorecloses without an interruption or a voltage drop and improve power quality of customer [1].

TRANSFER CAPACITY CALCULATIONS OF LVDC SYSTEM

The purpose of the calculations is to solve the transfer capacity of four-wire ground cables in the LVDC system presented in the figure 1. The calculations are made with three different voltage drop values and three cable types, which have different cross-sectional area. The inverter's techno-economic sensible dimensioning, wanted power transfer capacity and limitation of the transfer losses determine to which value of the maximum voltage drop will be limited to. Power and transfer distance are used in determining which cable type should be selected.

Calculation methods

Input voltage of the inverter is smaller than the output voltage of the rectifier by the amount of DC cable's voltage drop. Nominal values of the inverter are determined how large the maximum voltage drop can be. Voltage drop depends only on the DC-resistance and the current:

$$U_{h\_wire} = R_{DC\_wire} I_{wire} , \tag{1}$$

where U_{h_wire} is voltage drop of a single wire (V), R_{DC_wire} is DC-resistance of the single wire (Ω) and I_{wire} is current of a single wire (A).

The DC-resistance of the wire (r_{DC_wire}) as Ω/km at a temperature of 20 ˚C is known. Therefore, R_{DC_wire} can be calculated using equation:

$$R_{DC\_wire} = r_{DC\_wire} l_{wire} , \tag{2}$$

where l_{wire} is wire's length (km). Since the zero wire of AXMK cables is similar to the phase wires, equations (1) and (2) give the same result on all four wires of the cable. Thus, combining equations (1) and (2) the following can be written for the length of all the wires:

$$l_{wire} = \frac{U_{h\_wire}}{I_{wire} r_{DC\_wire}} \tag{3}$$

In the unipolar LVDC system the four-wire ground cable is connected to two wires in parallel. Parallel connection of wires halves the resistance compared to the single wire. However, when considering both outgoing and return conductors, the resistance is doubled. These cancel each other out, so with the unipolar connection the entire transfer resistance between rectifier and inverter is:

$$r_{uni} = r_{DC\_wire} , \tag{4}$$

where r_{uni} is the transfer resistance with unipolar connection.

Based on the equations (3) and (4), the length of the DC cable in the unipolar LVDC distribution system is:

$$l_{cable} = \frac{U_h}{I r_{uni}} = \frac{U_h}{I r_{DC\_wire}} , \tag{5}$$

where l_{cable} is the length of the cable (km), U_h is voltage drop of the cable (V) and I is current of the cable (A).

When calculating the maximum limit of power transfer as a function of transfer distance, the voltage drop is kept in the chosen maximum value and maximum lengths of DC cables are calculated using varying values of power. Therefore, the equation (5) can be written as:

$$l_{\max} = \frac{U_{h\_\max}}{I r_{DC\_wire}} , \tag{6}$$

where l_{max} is the maximum length of the DC cable (km) and U_{h_max} is the maximum voltage drop in the DC cable (V).

Since DC voltage remains constant, the transferred power determines the current. Thus, if the input power of the inverter (W) is denoted P, the current is:

$$I = \frac{P}{U_{DC\_input}} , \tag{7}$$

where U_{DC_input} is input voltage of the inverter (V).

When voltage drop is kept at the maximum value during calculation, then the inverter's input voltage is at its minimum value and equation (7) can be reformulated:

$$I = \frac{P}{U_{DC\_\min}} , \tag{8}$$

where $U_{DC\_\min} = U_n - U_{h\_\max}$, where U_n is the nominal output voltage of the rectifier (V).

The minimum input voltage of the inverter (U_{DC_min}) can be calculated from the nominal output voltage (U_{AC_n}):

$$U_{DC\_\min} = 1{,}03\sqrt{2} * U_{AC\_n} \tag{9}$$

Coefficient of 1,03 is a safety margin which prevents too tight dimensioning. According to this equation, a nominal output voltage of 600 VAC requires at least an input voltage of 874 VDC. Thus, voltage is allowed to drop 26 VDC from its nominal 900 VDC, which means a 2,9% maximum voltage drop across the DC cable. The optimal point between the short-circuit current supply capability and the allowable voltage drop will be set the inverter's nominal output voltage level probably between 550-600 VAC.

When the equations (6) and (8) are combined, the following can be solved for the maximum length of power transfer:

$$l_{\max} = \frac{U_{h\_\max} U_{DC\_\min}}{\Pr_{DC\_wire}} = \frac{U_{h\_\max}(U_n - U_{h\_\max})}{\Pr_{DC\_wire}} \tag{10}$$

When the value of power rises high enough, the current in equation (8) reaches the maximum limit, therefore the equation (10) can no longer be used. After the current limit is reached, the calculation for larger values of power needs to be proceeded by keeping the load current constant instead of the voltage drop. In this case, since the power is supplied using the maximum value of the current, the U_{h_max} has to be calculated using the input voltage of the inverter:

$$U_{h\_\max} = U_n - U_{DC\_\min} = U_n - \frac{P}{I_{\max}}, \tag{11}$$

where I_{max} is the maximum current in the wire (A).

Combining equations (10) and (11), the equation of the DC cable length can be written:

$$l_{\max} = \frac{U_n I_{\max} - P}{I_{\max}^2 r_{DC\_wire}} \tag{12}$$

Power transfer capacity of the LVDC system

Power transfer capacity of the LVDC distribution system is calculated with three types of AXMK aluminum cables, AX50, AX95 and AX150. Elenia Oy uses these cable types to construct new low voltage AC network and those are suitable also for the use of 900VDC. Data of these cables is listed in table 1. Since the current in unipolar connection is divided between two wires, the maximum current of the cable I_{max} is double compared to a single wires' maximum current I_{max_wire}. A_{wire} is the cross-sectional area of a wire.

Table 1. Data of the cables

Cable type	AX50	AX95	AX150
A_{wire} (mm^2)	50	95	150
r_{DC_wire} , 20°C (Ω/km)	0,641	0,320	0,206
I_{max_wire} (A)	150	220	290
I_{max} (A)	300	440	580

The maximum voltage drops for the calculation are selected from the corresponding values of the inverters' output voltages of 600 VAC, 575 VAC and 550 VAC, when U_n is 900 VDC. Based on the equation (9) those are 26 VDC, 62 VDC, 99 VDC, or 2,9%, 6,9% and 11%.

Results calculated with the equations (10) and (12) are shown in the figure 2. The curves present the power transfer capacity as a function of a DC cable's length. Thus, the curve shows the limit, below which the power transfer is possible. The linear part of the curves is due to the fact that the current is at its maximum limit and the calculation uses the equation (12) instead of the equation (10).

The same kind of calculations are proceeded with voltage drop limits 2,9% and 11%. With a voltage drop of 2,9 % a power of 100 kW can be transferred to the distance of 0,71 km using an AX95 cable. The transfer distance is increased to 1,63 km if a voltage drop of 6,9 % is used. Moreover, this transfer distance would be 2,48 km with voltage drop of 11 %, which is 3,5 times bigger than with the use of 2,9 % voltage drop.

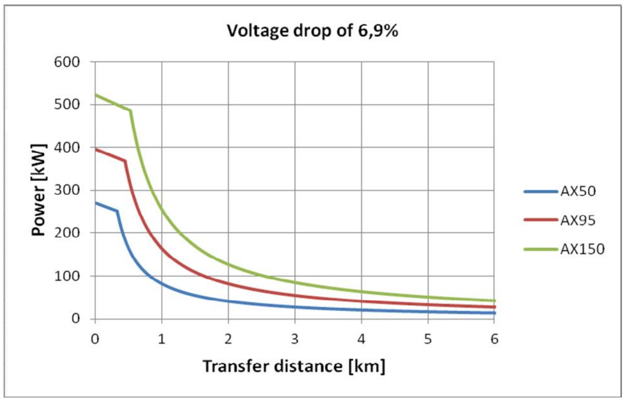

Figure 2. Power transfer capacity of the DC cables when the voltage drop limit is 6,9%.

POTENTIAL OF LVDC IN ELENIA OY

The mass computation has been done with the Network Information System (i.e Tekla NIS) for the entire distribution network of Elenia Oy. The mass computation performs, for example, a load flow calculation of the network and makes an updated list of network data. The analysis is limited to branch lines of a single transformer and tails of the multi-transformer branches. These are locations where LVDC distribution would primarily be used. Branches less than 100 meters long are not included in the analysis. Data from the mass computation is summarized and presented in table 2.

Table 2.Summarized data from results of mass computing.

The total amount of sections (pcs)	8308
The total length of sections (km)	4809
The average length of sections (m)	579
The average age of transformers (a)	29
The average nominal power of transformers (kVA)	88
The total amount of aerial line in the sections (%)	99
The total amount of over 40 years old transformers (pcs)	1016

According to the table 2, the total length of sections for the analysis is 22 percent of the entire length of MV network of Elenia Oy.

Network data processing

The nominal power of the existing secondary transformer can be used with good probability for evaluating the power, which the LVDC system has to be able to supply. Since the efficiency of the inverter is high, the assumption that the inverter supply its entire input power can be used in this analysis. Thus, the following can be written:

$$S_n \approx P, \tag{13}$$

where S_n is the nominal apparent power of transformer (VA) and P is input power of the inverter (W).

The existing MV network topology, where a large number of branches are implemented linearly, needs to be considered.

When this kind of branch line is rebuilt by cabling, the cable will be built along roads and fields, when possible. Therefore, ground cable can be a significantly longer than the currently used linear branch line. The average difference in length can be estimated to be 15 percent, so the lengths of line sections are multiplied by 1,15 for analysis.

Results of the analysis

Comparison the sections' lengths and transfer power to the maximum limit curves of transfer capacity (Fig. 2), determines whether it is possible to replace the section by LVDC distribution with the given maximum voltage drop value or not. The results of the analysis are summarized in figure 3. The figure shows the percentage of line sections replaceable by LVDC distribution in Elenia Oy.

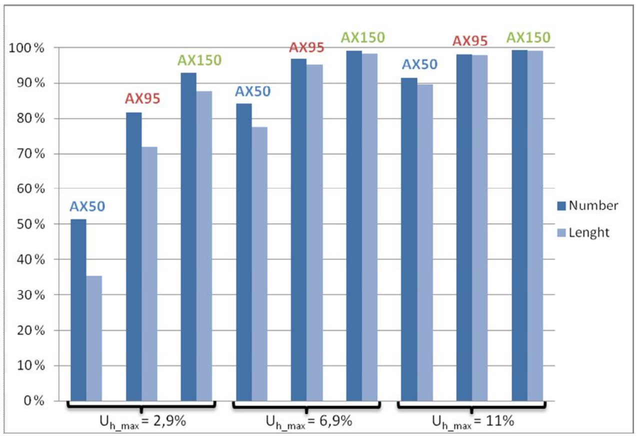

Figure 3. Summary of the results of the analysis. "Number" means the amount compared to amount of all sections and "Length" means the replaceable sections' length compared to length of all sections. The cable types are presented above and the voltage drop limits below the bars.

From the results can be noticed that even with a voltage drop of 2,9 % and using AX50 cable half of the line sections can be replaced using LVDC distribution. However, percentage of the length of the sections is 16 percentage points lower, reflecting mainly the replaceability of short sections of lines. Although, most of the sections' length can be replaced even with a voltage drop of 2.9%, when using a cable of larger cross-sectional area.

Based on this analysis, the use of a voltage drop limit of 6,9% seems to be the most techno-economically sensible alternative of the three options. In that case, power transfer capacity of AX50 cable is enough to replace most of the line sections, and thus cable costs can be kept low.

Large part of the sections must rebuilt in the near future because of ageing. Based on the results of analysis, LVDC distribution is a usable solution for rebuilding branch lines with a single transformer and its power transfer capacity is high enough. Depending on voltage drop selection, in Elenia Oy there are 4216-4767 km line sections, which can be replaced by LVDC distribution. This is 19-22 percent of the entire length of MV network of Elenia Oy.

It seems to be also technically possible to replace short and low power multi-transformer branch lines with LVDC distribution. Thus, in multi-transformer branches more heavy-gauge gables and probably also higher voltage drop than 6,9% would have to be used, so that the power transfer capacity would be sufficient. Moreover, cable dimensioning and calculation of sufficient transfer capacity must be done case-specific, but the calculation methods and curves presented in this paper can also be utilized for designing multi-transformer branch lines.

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