SELECTION OF VOLTAGE LEVEL IN LOW VOLTAGE DC UTILITY DISTRIBUTION SYSTEM

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ABSTRACT

This paper concentrates on estimating the techno-economically feasible voltage levels for a low voltage d.c. distribution system. The paper points out that there are various aspects which affect the final selections. The approach in the paper is applying of the traditional network planning methods to a novel field of practise. The paper aims at 1) describing the essential aspects in the optimization formulation 2) presenting calculation results and 3) analyzing both the reasons for, and, practical meaning of the case results from Finnish and Korean operational environments.

INTRODUCTION

In low voltage d.c (LVDC) distribution system the electricity is supplied to the customers by utilizing d.c. The use of d.c. is enabled in EU by the low voltage directive LVD 2006/95/EC according to which the low voltage range is between 75-1500VDC [1]. The principal LVDC system components are rectifying substation (a.c./d.c.), d.c. mains, customer-end inverters (CEI, d.c./a.c.) and a communication system [2]. The main drivers for the LVDC system are the possibilities to achieve increased transmission capacity and decreased life cycle costs (LCC) [3].

If the Smart Grid (SG) environment is considered, the latter part of the electricity supply chain including the LV network and customers is becoming more active. There can be for instance energy storages (ES), electric vehicles (EV) and other distributed energy resources (DER) connected to the grid and the customer can actively participate to the electricity market through controllable resources. Ultimately, the group of customers may form communities which are at least partly self-sufficient in terms of electric energy. This suggests microgrid (μG) operation. There has to be active network devices and upper level control algorithms and management systems which enable such an activity. Naturally, this requires also information exchange capabilities. LVDC system includes by nature the core components of the active network and provides versatility for the future distribution [2,4]. Figure 1. illustrates an example of the LVDC system core including also other active system components which were described.

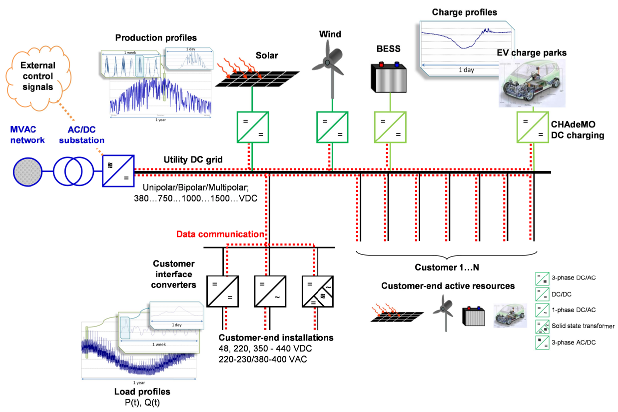

Figure 1: Illustration of the LVDC system [4].

In d.c. distribution, the use of power electronics enables the optimization of the utilized voltage levels. There are various proposed voltages which could be selected for the utility distribution systems [4]. It is also a question of standardizing the preferred ones. The standardization organizations have noticed the need to establish various LVDC related standardization and the work has been started by IEC SMB/SG4 and is being continued by recently formed SEG:4. The feasible voltage levels are eventually application-specific and it is necessary to consider the situation from the utility distribution perspective so that the potential of the novel technology can be utilized effectively, and, most importantly, safely.

The paper presents the essential aspects due to which the voltage level selection is one of the most important planning subtasks in LVDC distribution systems. Finally, when the selection are made, the task has to be approached carefully taking into account the relevant boundary conditions. In this paper, both Finnish and Korean operational environments are used to present the case results of different environments. The paper concentrates on the voltage level selection process by 1) describing the essential aspects in the optimization formulation 2) presenting calculation results and 3) analyzing both the reasons for, and, practical meaning of the results.

LVDC system design aspects

LVDC system is a promising alternative for low voltage distribution but the retrofitting task including the existing installations and power electronics becomes easily somewhat complex, especially when there are no existing practices. This necessitates the system engineering approach [4]. LVDC system has to comply with the existing installations (utility/customer), standardization, legislation and other applicable guidelines. The voltage level depends on the structure of the system but affects further system design such as converter selection and protection coordination. Principal design tasks are selection of the structure (bipolar/unipolar) and earthing scheme (IT/TN). Operational environment has a meaningful effect as existing installations and earthing conditions have to be acknowledged from electric safety perspective. Voltage level affects directly for instance to the touch voltages. The effect of the voltage level on protection and earthing has been considered more detailed in [5]. Eventually, when the utilized voltage levels are considered it is crucial to acknowledge the other system design tasks described in [4], so that the result is especially: 1) safe & reliable, 2) feasible over utilization time, 3) compliant with the existing installations, and relevant guidelines and 5) serves for the future purposes. In this context the overall system design is not discussed further.

FORMULATION OF THE OPTIMIZATION

The general distribution system planning objective is the constitution of a system which fulfills the technical requirements as economically as possible over the total utilization time. The role of the LVDC in strategic planning of the future systems depends on the competiteveness of the concept, which is dependent for instance on the utilized voltage levels. There are not many such case analyses available. This paper utilises the same methodologies as in [4] but concentrates entirely on the voltage level selection. The examples in the paper are one of the fundamental application examples of the LVDC distribution. It is assumed that ageing overhead line (OHL) LV network and part of the feeding MV line is renovated and replaced by underground cabled (UGC) LVDC system. In the paper, only the obvious voltage dependent parts were selected into consideration.

Customers

For the dimensioning of the network components, it is necessary to estimate the maximum power demand. For one customer it can be done by utilizing equation [6]

$$P_{\max} = \overline{P} + z_a \cdot \sigma \qquad (1)$$

in which $\overline{P}$ = Mean power
z_a = Normal distribution excess probability a.
σ = Standard deviation of the mean power

It is assumed that the customer behavior is normally distributed which yields total power according to the desired confidence value, e.g. z_a=2.32, which is used for dimensioning of the CEIs. For instance, by utilizing the Finnish load behavior data [7] for each hour of the year, the result is as depicted in Figure 2.

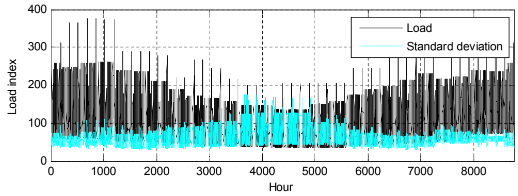

Figure 2: Load behavior of a detached house without electric heating and with electric sauna [7]. Index value of 100 represents the mean power of the customer.

Another solution is to utilize the automated meter reading (AMR) data of customer behavior, if sufficient data from the past is gathered. For instance, in a real world renovation example there is a possibility to use the power demand information of the existing setup when dimensioning the LVDC system. In the paper, using of the AMR-measurements was not possible. Instead, the customer grouping data [7] was used for both the Finnish and Korean cases. The annual customer energy was randomly varied between the customers on a small range defined in Table 1. Despite that the Korean customer behaviour is different from the Finnish customers, a satisfactory representative customer group was found. In Korea, the annual delivered energy is lower than in Finland, but there exists noticeable spiking due to boilers. It was noticed that a Finnish type customer "detached house with sauna" match relatively well and was therefore used for the Korean customers. For the Finnish customers detached house with electrical heating and boiler was used. In the paper the division of customers between the poles in bipolar system is done according to the annual energy so that at each possible node the minimum difference is reached. Further analyses should be performed to determine which approach provides the lowest costs and according to which criteria the division should be performed. The higher the load difference between the poles, the worse is the case. In the paper, the customer-end fault current supply capability was neglected and the CEIs were dimensioned according to the peak power demand.

Network

For calculating the total costs of the network, in addition to the network investment costs, it is necessary to obtain the Net Present Value (NPV) of the losses over the utilization time. The costs of other network components, such as protection equipment are neglected in this analysis. The network costs, C_{netw}, can be expressed as

$$C_{\mathrm{netw}} = C_{\mathrm{equip}} + \gamma \cdot C_{\mathrm{loss}} \qquad (2)$$

in which C_{equip} are the capital costs of the equipment and C_{loss} costs of the losses of one year, capitalized by using the the factor γ [6]. In this analysis it was assumed that the load remains constant in the end of utilization time T. The assumption is based on the described LVDC application case, i.e. renovating the existing OHL network to cabled one. Therefore also the load growth was neglected as we are not building up a new, developing area. Installation costs are neglected as there is no obvious depedency between voltage level and installation costs. Instead, the acquisition costs of the cables and converters are included.

The dimensioning of the conductors is done according to the techno-economic approach. Unless the thermal limit or voltage drop is reached, it is feasible to select greater diameter if the loss savings over utilization time covers the difference in investment costs. The voltage drop limit is set 1) due to the d.c./a.c. conversion and 2) stability of the network. In this case it is assumed that customer system remains intact, i.e. customers are having 230/400VAC three-phase connection. This further necessitates that d.c. mains voltage is at least $U_{\mathrm{dc}} = 565\mathrm{V}$. Otherwise the limit is defined according to the stability of the d.c. network. In practice the maximum voltage drop is effectively limited by the techno-economic dimensioning of the conductors. Another question related to the planning of the network, which affects further to the optimization, is the structure of the network, i.e. unipolar or bipolar d.c. network. Both are considered in the calculation. Mainly the differences are in voltage stress (network and switching components), simplicity, transmission capacity and redundancy. Both solutions are applicable and the selection is dependent on the emphasized characteristics for the application. The connection of the utilized conductors affects to the network costs. Figure 3. illustrates the examples of connection alternatives in case of (UGC) and (OHL) network for both mentioned structures [3]. In this case a) and c) were used for bipolar and unipolar structures, respectively.

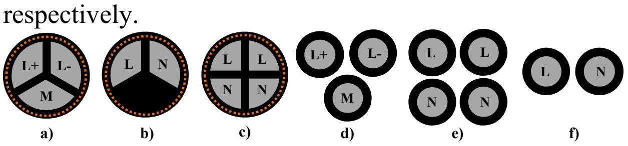

Figure 3: a) Conductor connection in Bipolar-UGC b) unipolar-UGC, c) unipolar-UGC d) bipolar-OHL e) unipolar-OHL and e) unipolar-OHL. [3]

Converters

Due to the novelty of the d.c. distribution the economies-of-scale are quite limited and readily available prices are difficult to obtain. The utilized voltage levels and the customer behaviour differ greatly from the industrial applications in which the converters are typically used. Therefore, as the case results of the voltage depedency were the main content of the paper rather than the absolute cost values, the price behavior was simplified according to the best knowledge, correspondingly as in [4]. For the converter efficiencies the same chart as in [4] was used. The harsh assumption for the price per kVA was 250€/kVA for nominal power below 50 kVA and 200€/kVA for higher power class. Furthermore, the price of the converters was divided into voltage dependent component and base component. The converters have certain base cost of manufacturing which realizes despite the voltage level and was assumed to be ¾ of the total price. Furthermore, the increase of the price was divided into three parts: 5% for 600-900VDC, 20% for 900-1300VDC and 50% for 1300-2200VDC. These are harsh simplifications which include inevitably error. However, if we consider LVDC as established practice there are likely to form certain favored voltage levels and nominal powers which reduce the prices, compared to present market situation. The renewing of the converters was assumed to occur every 10 years. The present value (PV) of value V at time t, interest rate being p, can be calculated by [6]

$$PV(t) = V_t \frac{1}{\left(1+{}^{p}\!/_{100}\right)^{t}} \tag{3}$$

Calculation parameters

In practice the utilizable voltage range ends to 750VDC with bipolar and to 900VDC (earthed) or to 1500 VDC (earth isolated) with unipolar [8]. Especially, in bipolar case the free room for the design is narrow but sufficient to improve the cost efficiency. The calculation was not limited to these values but was instead carried out also above the LV range to be able to better explain the nature of the cost development. Table 1 lists the parameters.

Table 1: Parameters used in the calculation.

Variable				FIN		KOR
Utilization time [a]				40		40
Utilization time, converters [a]				10		10
Customer energy [MWh/a]				15-17		4-6
CEI nominal power [kVA]				15		5
Interest rate [%]				5		5
Price of power losses [€/kW]				50		60
Price of energy losses [€/kWh]				0.05		0.06
U_{DC} [VDC]				600-1500		600-1500
Cable data FIN [9,10]				Cable data KOR [11]		
A mm^2	$R_l\Omega$/km]	Price LV,MV [km]		R_l [Ω/km]	Price LV,MV[km]*	
25	1.20	8101	16990	0.727	5370	9870
35	0.868	8728	17646	0.524	7250	11750
50	0.641	9667	18631	0.387	9824	14324
70	0.443	10919	19944	0.268	13799	18299
95	0.32	12485	21586	0.193	18531	23031
120	0.253	14050	23227	0.153	23200	27700
150	0.206	15929	25197	0.124	29353	33853
185	0.164	18120	27495	0.09	35792	40292
240	0.125	21564	31107	0.075	46802	51302
300	0.1	25322	35047	0.06	58127	62627

* Initial data provided by KEPRI.

The Finnish cable prices are obtained from [9] according to which the linearization was done to cover also the few lacking diameters. The Korean data was provided and linearised to match the diameter series, correspondingly. For the voltage levels which exceed the low voltage range, the conductor prices include additional cost component. The behavior is described in the model to be linear between 1.5 kV and 10 kV. The 10 kV cable prices were estimated to be ¾ of the 20 kV prices. In practise, there would be certain favoured diameters in the companies but in this case the purpose was to illustrate the behavior and therefore the diameter between the nodes was selected among the whole availability.

CASE RESULTS AND ANALYSIS

In addition to the described variables, two topologies were selected for the case calculations. Furthermore, both the unipolar and bipolar structures were covered, both for the Finnish and Korean environments. It is known that the optimal voltage is highly dependent on the number of customers and delivered power. Therefore, two different cases were selected to be 1) fewer customers & long transmission distance, i.e. sort of a "range-extender". The case 2) is more customers & short transmission distance, i.e. "capacity extender". The first case suits actually well to be a representative of the Finnish LVDC application. The second case instead describes better the more densely populated environment.

Case 1 : Range extender

The network and the customers of the first case are depicted in Figure 4 and the results in Figure 5.

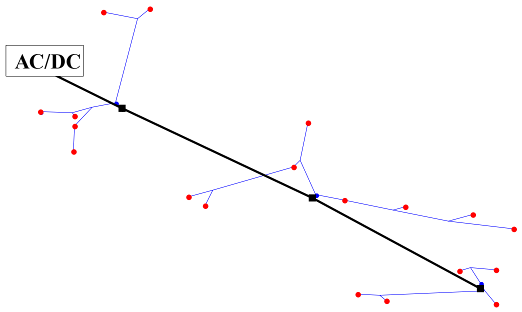

Figure 4: Transformer circuit and connected customers for the described case 1). The total network length is approx. 7 km. There are 19 customers, marked with red dots. In total, three MV/LV substations were replaced.

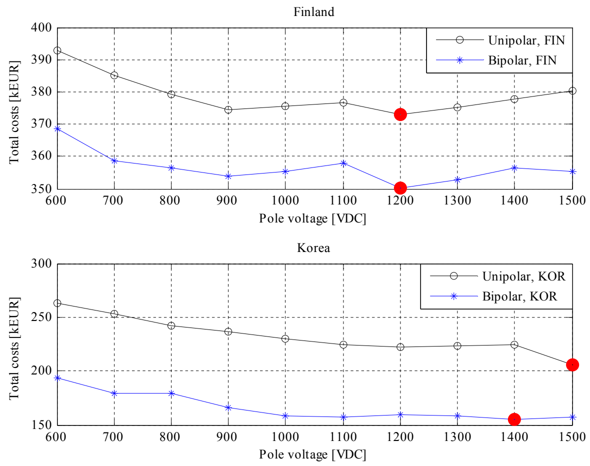

Figure 5: Case 1, total costs over utilization time for unipolar and bipolar structures in Finnish and Korean cases. Minimum points are marked with red dot.

It should be noted that by comparing 700 VDC bipolar and 700 VDC unipolar systems, we are actually comparing two pole ±750 VDC system to a 750 VDC single pole system. In unipolar system, the power is fed by one pole and another working as a return conductor. In bipolar system the customers are divided between the poles and in middle conductor there exists the unbalance current between the two poles. By comparing Korean and Finnish cases, it can be seen that the transferred power affects to the costs greatly. The main cost component is the inverters. It can also be seen that if the power density remains at a moderate level, the optimal voltage range is wide, if only the lowest ones are avoided. Two specialties can be spotted. The first is in Finnish case, at 1200 VDC. It can be seen that power electronics losses are beginning to dominate between 900-1100 VDC, until there is a drop at 1200 VDC. It is traced down to a diameter reduction in the main feeding cable beginning from the rectifier. It is a natural phenomenon due to the increased voltage and resulting reduced current. The same phenomenon occurs in Korean unipolar case at 1500 VDC.

Case 2 : Capacity extender

The network and the customers of the second case are depicted in Figure 6 and the results in Figure 7.

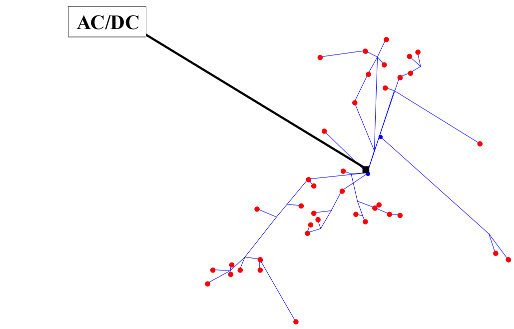

Figure 6: Transformer circuit and connected customers for the described case 2). The total network length is approx. 2.6 km. There are 39 customers, marked with red dots. One MV/LV substation was replaced.

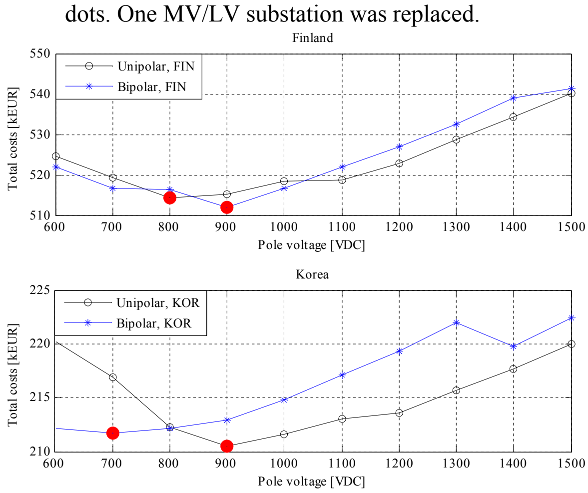

Figure 7: Case 2, total costs over utilization time for unipolar and bipolar structures in Finnish and Korean cases. Minimum points are marked with a red dot.

The results suggest that when the network is short and there is enough load, the dependency of the costs on voltage level is quite similar in unipolar and bipolar cases. It should be noted that in this case we had 4 wire unipolar cable which basically means the equal pole resistance with the bipolar system pole. A high number of customers together with sufficient power fix the costs to a certain level. If the Korean and Finnish cases are compared, the only meaningful initial difference is the customer power which results in the higher acquisition price of the CEIs, multiplied by the customers. Moreover, the losses generating equipment in the system is in that case increased as well. The costs develop in such a way that at first, the base level is created due to the rectifier, CEIs and cables, throughout the voltage range. Then, the line becomes twisted from both ends, at lower voltage levels side due to cable loss behavior and higher voltage levels side due to increasing converter costs. The result is kind of a bath tub curve. This is well represented in the second case. In the Korean case the difference between unipolar and bipolar with low voltage levels is caused by cables. In unipolar system, there are greater diameters in use, especially at the feeding line beginning from the rectifier. In addition, the Korean costs are increased more rapidly along when greater diameters are taken into use. It should be noted that in the second case there is relatively long main line feeding the group of customers. When the diameter can be reduced by increasing the voltage, the costs come down rapidly.

Voltage level selection

Finally, when the selections are made, it is a design task to constitute a system which is also safe, i.e. the earthing and protection setup should be considered simultaneously [4,5]. Furthermore, it should be studied how wide is the component availability. For instance, exceeding some of the familiar voltage levels such as 400 VDC or 600 VDC may result in reduced availability. In addition, not only are the customers fed by 3-phase AC. Further studies concerning voltage level selection should address the cases with residential 1-phase and direct d.c. customers. Although the system enables versatility, it should preferably be considered from the long-term point of view, that what kind of systems are, for instance, nationally the most applicable to serve the societies in the future. The sensitivity analyses would be beneficial to further point out how great potentiality leaps are expected as a result of new generation converters. At this point the estimates are very valuable when the practices are being developed for the novel technology. Although the rapidly developing technology is generally a positive phenomenon, from DSOs perspective it is a challenge as decisions done today may be outdated in just a few years.

CONCLUSIONS

Utilization of LVDC enables the voltage level optimization within the boundaries set by the application. The optimization requires recognition of the application and operational environment as a whole, i.e. system engineering perspective. The paper presented case examples of Korean and Finnish environments. The main outcome of the paper is that the feasible voltage levels for d.c. distribution are typically obtainable in the limits of the present standardization. It is reasonable to consider voltage levels above 600 VDC for rural distribution.

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