A SYSTEM ENGINEERING APPROACH TO LOW VOLTAGE DC DISTRIBUTION

Tero KAIPIA, Janne KARPPANEN,
Aleksi MATTSSON, Andrey LANA,
Pasi NUUTINEN, Pasi PELTONIEMI
Pasi SALONEN, Jarmo PARTANEN
Lappeenranta University of
Technology – Finland
tero.kaipia@lut.fi

Juha LOHJALA
Suur-Savon Sähkö Ltd.
– Finland
juha.lohjala@sssoy.fi

Wookyu CHAE, Juyong KIM
Korea Eletric Power
Research Institute – Korea
wkchae@kepco.co.kr

ABSTRACT

This article focuses on the overall system engineering aspects of low voltage DC (LVDC) electricity distribution.. The interdependencies between different parts of an LVDC distribution system are discussed emphasising the issues related with the interconnection of user-end LVDC installations and public LVDC systems. The main objective is to illustrate the importance of the total system engineering over the piecewise design approach. The aspects affecting on the selection of the DC voltage level, system structures and earthing arrangements are considered. A methodology for selecting the techno-economic optimal voltage level within the boundary conditions set by the DC system application and the operating environment is introduced with example calculations. Presented discussions and results provide support especially for the development of the standardisation of the LVDC technology

INTRODUCTION

The global interest towards LVDC distribution has increased rapidly during past years. The benefits of using modern power electronics based distinct LVDC distribution systems in different applications are presented in numerous scientific articles. Often listed benefits of DC distribution systems are, for instance, reduction of electromagnetic interferences, decrease of life-cycle costs, improvement of energy efficiency and increase of reliability. Evidently these all are achievable in certain use-cases and within particular boundary conditions. However, it is unclear that what will happen when some of these LVDC applications are brought together. Incompatibility of the different parts of a larger LVDC system can lead to a poor total energy efficiency and unnecessary increase of the life-cycle costs. Evidently, comprehensive understanding of the interconnections between the versatile applications and use-cases is required. As is well known, a global optimum is rarely a sum of local optimums.

Low voltage DC systems both for the indoor installations of buildings and for the public electricity distribution networks of utilities are under rapid development. Prominent efforts are but on the R&D of these systems globally. This has also awoken the standardisation organisations. System standardisation requires practical experiences from different applications and use-cases of LVDC systems. What, how and when to standardise are important questions. The IEC strategy group 4 (SG4-LVDC) has recommended that the standardisation of the LVDC systems should be done by application areas based on market needs and availability of practical experiences. However, a considerable risk lays in the piecewise standardisation, as the standardisation of one application or use-case may have an undesired influence on the development or profitability of other applications. So far the only application areas considered mature enough are LVDC systems for data centres and telecom centrals. In these applications the DC power source is used not only to feed servers and other such ICT equipment, but also in lighting, air conditioning and charging of electrical vehicles (EV). Also other application environments such as homes, industry and public LVDC electricity distribution systems, i.e. utility DC grids, have to be taken into account while drafting the first standards.

NEED FOR SYSTEM PERSPECTIVE

Versatile LVDC systems have been used or proposed to be used in several applications. At least following five use-cases can easily be listed for LVDC distribution systems:

1) **Public LVDC systems**
LVDC system can be used to improve the technical and economic performance of the low voltage power distribution and to increase the overall security of supply. Examples of public applications are, for instance, utility grid low voltage power distribution and public lighting systems. [1][2][3]

2) **Data and telecom centres, transceiver stations**
LVDC system can be used to improve the energy and cost efficiency of electric systems supplying servers and other communications electronics and to increase the reliability of power delivery. [4]

3) **Electro mobility**
LVDC systems have been widely used in traction [5] and are becoming common also along with other EVs. Batteries and many other electric energy storages can be directly connected to DC voltage. DC is also used for fast charging of EV batteries (CHAdeMO) [6][7]. LVDC systems with energy storages are also applicable in small and medium sized diesel-electric marine vessels instead of LVAC to improve power quality, increase energy efficiency, and reduce costs. [8]

4) **Distributed generation and renewable energy**
Small-scale electricity generators are often DC power sources. Instead of converting generated DC always to AC, the DC power sources could be connected to common DC mains with DC load devices. Another aspect is to connect several small-scale generators to AC mains through the same DC rail. Both of these solutions also provide natural coupling points for batteries enabling efficient harvest of variable renewable power sources. Generally, the use of

common DC mains decreases the amount of power electronic conversions compared with similar AC system and thus increases the energy efficiency and decreases the costs. [9][10]

5) **Industrial applications**

LVDC (and HVDC) rails have traditionally been used in manufacturing industry to supply electric motors. The use of DC could easily be extended, for instance, to lighting of hallways and production bays. [8]

6) **Electrical installations of buildings**

Most of the modern end-use appliances of detached houses, apartment buildings, commercial buildings and offices use DC internally. Losses in the internal conversions can be reduced if the devices are supplied directly with suitable DC-voltage. Improvement in energy efficiency and reduction of the costs are anticipated as a result of LVDC systems, especially when combined with the use-case 4).[11][12]

Almost all of the low voltage levels between 120 VDC up to 1500 VDC have been proposed to be used in the listed use-cases. Respectively also all the different basic earthing systems (TN, TT and IT) have been proposed. The voltage level and earthing system are closely interconnected properties of any electric system, and reflect both the use-case and application environment. Selection of almost any of the combinations for a single use-case, or furthermore a specific application within the use-case, can be rationalised, because the design principles and perspective, the surrounding conditions and the system structure itself all affect the selection of the optimal voltage and earthing system alternative. The versatility of solutions should, however, be allowed up to some extent. For instance the used rated voltages and earthing systems can vary nation-to-nation similarly as they vary nowadays, and can then reflect the common practices and conditions in each country. However, the requirements from electric safety perspective, such as allowed switch-off times for fault protection or allowed touch voltages and currents, and recommended voltage and current ratings for DC system equipment could be based on global agreements.

Although it appears that the LVDC systems for the mentioned use-cases can be designed and optimised quite independently, clear interdependencies can be found. Obviously interaction between the use-cases occurs when two or more of them exist simultaneously in a power system and especially if they are directly connected to each other – that is quite probable. E.g. utility grid LVDC system (1) is used to supply a building with DC distribution system (6), DC connected DG units (4) and EV fast charging stations (3). All these systems exist probably because they are profitable for their owners or users. However, in worst case scenario they all or at least some of the partial systems are incompatible with each other – ie. the voltage levels, earthing systems, voltage control principles, etc. differ from each other so that the partial systems cannot be directly connected with each other. In this scenario additional power converters for voltage conversion and/or for galvanic isolation will be needed, costs and losses of which will rapidly eat-out the other benefits of DC system. Fig 1 illustrates the main factors influencing the public LVDC distribution system from system engineering perspective.

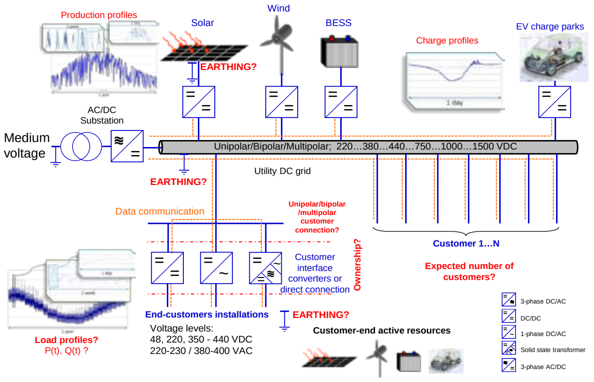

*Fig. 1 Overview on alternative DC system structures and their main properties from utility grid perspective***.**

When the already widely used LVDC applications mentioned in the use-case listing are neglected, the utility grid LVDC distribution is probably among the most rapidly commercialised applications. There is significant economic potential for utility LVDC grids regardless of the existence of mentioned user-end DC applications [1][2]. The first test installations for modern utility grid d.c. applications have already been realised [3][13][14]. Furthermore, the public distribution grids are anyway constantly renovated and in near future large proportion of the existing distribution systems become to the end of their technical life-times all around the world. This opens an opportunity to upgrade the primary technical solutions of utility grids. Considering also the Smart Grids, LVDC enables more controllability through the active network parts.

The transition of the user-end electric systems from AC to DC voltage can be very long and slow process. The end-users are not willing to invest into a novel system if the existing one is working properly and can be maintained in use with moderate costs. Without clear cost incentive or other drivers, the LVDC distribution at least in existing detached housing will not happen. In commercial side the transition is easier, especially in the new construction cases or in the case of full renovation. Nevertheless, the life-cycle cost efficiency of the LVDC system will still be the main driver together with the energy efficiency – assuming that the safety and security of the LVDC alternative is at least on the same level with existing AC systems. At the moment it seems that the questions related with the electric safety and equipment of the building DC-systems need some final answers, although lot of work has already been done – partially thanks to increase of PV system installations.

SYSTEM ENGINEERING APPROACH ON DC VOLTAGE LEVEL SELECTION

Selection of the voltage level is one of the most important tasks in defining an LVDC system setup. The selection affects the further system planning and decision-making ranging from the earthing scheme to the component selection. Emphasising the electricity safety aspects is always preferable. The optimal DC voltage depend also from the interrelations between the different applications, as explained in earlier chapter If the goal is determination of generalizable system concept, it is reasonable to define a voltage range, rather than selecting single value, in which the nominal voltage for a particular setup can be selected during the design.

Methodology

The method of techno-economic application ranges [2], [15] can be used for defining the DC voltage range for versatile DC system setups. In the analysis applicable parameters – or dimensions of the techno-economic application range – are for instance the transmission distances, load density and demand, life-cycle costs and naturally the DC system voltage.

The proposed method is based on total cost optimisation similar to distribution network planning [15]. In this case the task is evaluation of the life-cycle total costs of LVDC systems with alternative voltage level for a particular application within the predefined boundary conditions and interfaces to neighbouring systems. The number of considered cost components is reduced to the ones directly related with the voltage level selection. The objective function of the optimisation is presented in Eq. (1)

$$F = \min(C_{\mathrm{tot}}) = \min \int_{u}^{U}\int_{0}^{T} \left(C_{\mathrm{capex}}(u,t) + C_{\mathrm{opex}}(u,t) + C_{\mathrm{out}}(t)\right) dt\,du \quad (1)$$

where C_{tot} are the total costs of a DC system over the utilisation period T with rated voltage U, C_{capex} are the capital costs of equipment, C_{opex} are the operational cost (e.g. losses, maintenance, etc.), and C_{out} depict the cost of equipment outages and customer interruptions.

Case: Utility grid LVDC

The selection of the voltage level for an LVDC system used in public electricity distribution depends from the applicable LVDC system structure (unipolar or bipolar system), type of customer connections, power demand, expected transmission distances and properties of equipment including related costs. Furthermore, the earthing system affects the level of possible touch voltages and the structure of converters, and thus, the selection of rated voltage. Especially the customer connection is of great interest, as the customer installations can be realised both with AC or DC system, which means possible combination of almost all of the above mentioned use-cases. If the system is limited to be used at residential areas only the use-cases 2) and 5) can mostly be neglected.

Depending from the user-end installations, customer-end DC-converter or customer-end inverter (CEI) is required in the customer interface. The DC-converter is required if the utility grid DC voltage is too high for building installations or when electric safety requires different earthing systems to be used in utility grids and in user-end installations. Roughly saying voltages above 440 VDC are no longer applicable in user-end installations, at least in the case of detached housing [11]. Furthermore, earthing of an LVDC system is not generally recommended due to increase in the level of touch voltages and currents during faults when the DC voltage exceeds 400 VDC [16][17][18]

In general, higher voltage level in distribution system provides more power transmission capacity and lower distribution losses. However, as the power electronics is included in the system, the behaviour is not as straightforward. In fact, the efficiency of the converters tends to decrease and thus the cost of converter losses increase when the voltage is increased. Also the acquisition prices of the components become more expensive as the voltage rises. An example of the efficiency curve for the CEIs, DC/DC- and the grid-tie converters as the function of DC voltage and converter loading is presented in Fig. 2.

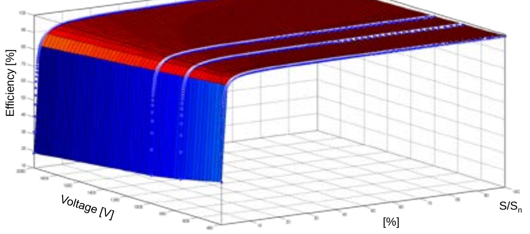

Fig. 2 Efficiency curve for converters in the LVDC system as a function of DC voltage and power demand

The efficiency of the converters decrease rapidly when the converter is operating on low loads compared to its nominal power. It is also important to notice that the converter efficiency reduces in all cases when the DC voltage increases. This is caused by the need to select higher voltage rating transistors. Moreover, during low loads the switching losses of the transistors are in dominating role over the conductivity losses. The costs due to converters are especially emphasised when CEI or DC-converter is required in the customer interfaces as the costs due to these converters become quickly dominant in the total life cycle costs of the DC distribution system.

By taking into account the impact of DC voltage on the life cycle costs of converters and cabling in LVDC system, a cost plane, revealing the optimal DC voltage, can be drawn. Fig 3. presents an example of the cost plane for bipolar system with 3-phase CEIs. Fig 4. presents an otherwise similar situation than the Fig.3, but without taking into account the costs of CEIs. When comparing to the Fig. 3 the impact of the costs of CEIs is clearly shown.

In the examples of Fig 3. and Fig 4. the customers are evenly distributed 100 m away from each other alongside a DC feeder so that the number of customers increases linearly with respect to the length of the feeder. Load growth is assumed to be 1 %/a over the first 10 years. The energy consumption is 5 MWh/customer,a in the beginning and follows the typical Finnish residential load profile. The interest rate in economic calculations is 5% and the utilisation period (life-time) of the system 40 years. Common XLPE insulated PVC sheathed low voltage underground power cables according to standard IEC 60502-1 are assumed to be used. Investment costs of cables are based on the cost list published by the Finnish Energy Market Authority. The cost of converters is assumed to be 250 €/kVA for rated powers below 50 kVA and 200 €/kVA for converters with higher nominal rating. Converters are renewed between every 10 years.

Neither the upper nor the lower voltage range is the most feasible as the optimum can be found in most cases between 600-1000 VDC. Optimum is case dependent and the optimal voltage area wide and flat. Power electronics have huge impact on the optimal voltage. Increasing the line length per customer improves the profitability of high voltage levels. Especially the cost and supply security benefits achieved when using LVDC networks to replace lateral medium voltage branch lines favours the high DC voltages. However, to see this effect the total costs and reliability of both MV and LV networks have to be considered simultaneously [2],[15].

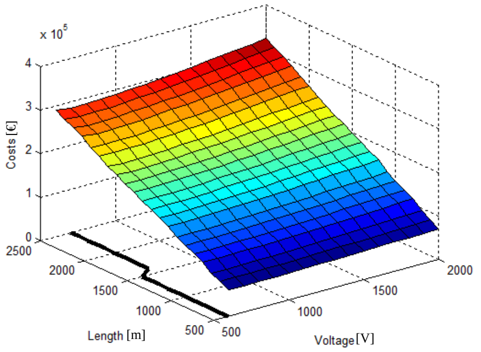

Fig. 3 Life-cycle voltage dependent costs for a bipolar LVDC system feeding residential loads. The line in voltage-length level presents the optimal voltage level.

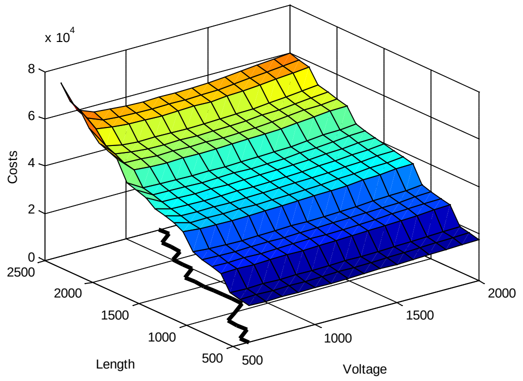

Fig. 4 Life-cycle voltage dependent costs for a bipolar LVDC system feeding residential loads without the costs of CEIs. The steps in the plane are caused by the stepwise increase of the nominal power of rectifier along with the number of end-customers.

If the customers need DC connection, two optimum voltage ranges can be seen. Another is located on the voltage area around 400 VDC on which the customers can be directly supplied without any customer-end converters. The second optimum is again located between 600 and 1000 VDC. However, in this case it is crucial to remember, that the 400 VDC voltage in bipolar system is too low to out-perform the existing three-phase 400VAC system.

CONCLUSIONS

A comprehensive system engineering approach taking into account widely enough the technical and economical dependencies between different LVDC use-cases is needed to ensure the compatibility between applications. System engineering approach enables development of energy efficient economic and flexible LVDC systems and respective guiding standardisation.

Information of the use-cases of LVDC systems and related system characteristics should be collected widely before making any far-reaching decisions regarding used DC voltages or other key properties either in standardisation or in the system planning. Decisions made during the system engineering depend from the design perspective. Optimising an LVDC distribution system for building installations leads inevitably to different technical structures than design of the system for public utility grid distribution purposes. As the modern power electronics based LVDC technology is still quite immature, enough freedoms for system designers and developers should be given by the standardisation. Otherwise barriers on the development of cost and energy efficient LVDC applications can be created. However, the safety issues have to be emphasised.

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