Low-voltage DC Electricity Distribution – On Technological and Economic Immaturities and Development Needs

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SUMMARY

This paper discusses the essential immaturities in the utilisation of low voltage DC (LVDC) in public electricity distribution. The emerging possibilities to use DC in public power distribution by utilities and in electrical systems of private premises, have recently gained growing global interest. Several scientific publications have presented the obtainable benefits in theory, and efforts are put in the practical installations as well. However, LVDC being a novel application in distribution there are obviously several development needs which should be addressed before it can be regarded as widespread applicable. In order to obtain practical experience of utilising LVDC technology in utility distribution, a real network research platform has been constructed into a real public distribution network. This field installation is used to supply power to the existing customers which were prior connected to the low voltage AC network. The continuous operation of the on-site system has proven the applicability primarily from technological and safety perspectives. However, several issues have been recognized during the research and implementation which require further R&D to enable the more widespread utilisation, in practise. The issues include aspects of technology, standardisation and electricity distribution business. The paper describes the fundamental requirements which are needed for the LVDC to become a viable solution in electricity distribution. Consideration includes both technical and economic aspects and utilises the results and experiences from the performed LVDC research and real network implementation.

KEYWORDS

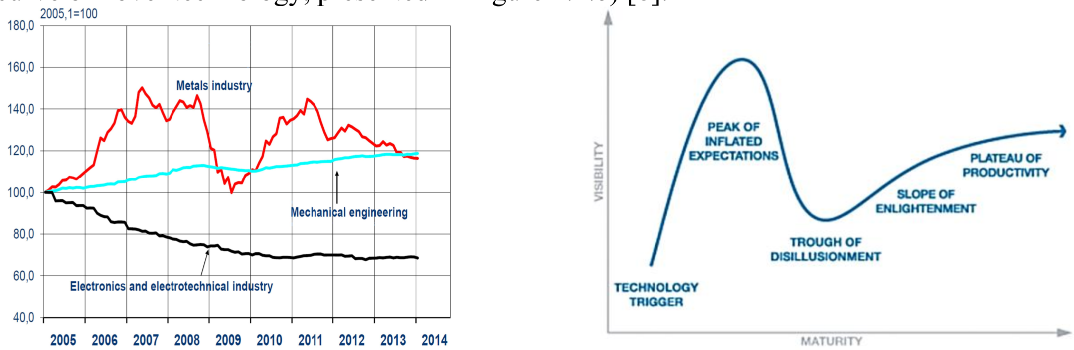
Low voltage, direct current, LVDC, electricity distribution, distribution business, electricity market, standardisation, R&D, development, smart grid

1. INTRODUCTION

The incoming transition in the electricity distribution business represents a challenge and an opportunity, simultaneously. The tightening energy efficiency objectives, need for substantial network renovation and increasing requirements on the security of supply need to be tackled. Concurrently, there are changes in the customer behaviour, such as increasing amount of electronic loads and local generation. Now, as the distribution and electricity-end use is facing probably the greatest changes since the electrification, by utilising the technological innovations there is a unique possibility to consider also novel solutions.

Referring to the technology development the other half is the price development. Figure 1.1.a) represents the development of the producer prices in technology, in Finland [1]. By combining the favourable technology and price development new possibilities arise. One novel application is power electronics and DC in distribution, which has emerged during the past few years, globally. There are several pros which support the utilisation of DC in low voltage distribution [2] [3]. Furthermore, the typical household includes nowadays dozens of appliances which use DC internally, often fed with poor efficiency AC/DC power supplies. In fact, there are nowadays quite few household appliances which require AC power in operational sense. Performed studies suggest that DC is suitable for low voltage distribution, if applied to feasible case areas [4]. Further savings could be possible if the use of DC is extended to indoor premises [3] [5] [6]. Moreover, majority of the renewable-based small-scale distribution generators produce DC power. The viability of the low voltage DC (LVDC) distribution can be justified by two primary facts: 1) efficiency improvements are obtainable with LVDC, if applied to feasible targets [4] and 2) LVDC provides a promising platform for Smart Grid (SG) concept and related functionalities, by nature [7].

LVDC distribution system is a novel concept and commercial plug&play solutions are not yet available. Therefore, there are neither established practises nor business models. In fact, the base in distribution is totally AC emphasised, which is natural as AC has been dominant in the field since the "war of currents". The utilisation of DC can thus be considered to be on the travel along the general hype curve of novel technology, presented in Figure 1.1.b) [8].



a) b)

Figure 1.1 Producer prices in Finnish technology industries a), adapted from [1] and novel technology hype cycle b) [8].

The curve is abstract, but for now, as the expectations have been constituted, the LVDC is facing the challenges related to the more wide-spread utilisation. The potential of the concept is being analysed, and the early adopters are beginning to benchmark the real-world applicability. The experiences of these early adopters have a meaningful effect on the future of the novel technology. To be able to analyse the usability of LVDC systems, in practise, a real network installation has been constructed and it has been in operation in Finnish DSO's (Järvi-Suomen Energia Oy) network, since June, 2012 [9] [10]. So far, the installation has proven the possibility to utilise DC and power electronics in distribution, safely. This paper aims at discussing the principal fields in which the immaturities and challenges occur and analyses the state-of-art and actions needed for proceeding along the hype curve.

2. LVDC SYSTEM DESIGN

Before discussing the topics in more detail, it is necessary to present an overview of the public electricity distribution LVDC system and to explain the essential system design tasks. Because LVDC application targets are to be found globally it is easy to understand that the operational environment has great effect on the drivers, design process and applicable structures.

2.1 Overview of the LVDC system

The main LVDC system components are the rectifying substation, DC mains, customer-end inverters (CEI) and information & communication technology (ICT). Main structure alternatives are unipolar and bipolar DC mains, either earthed (TN) or earth isolated (IT), voltage level being below 1500VDC in unipolar and below ±750VDC in bipolar, to meet the definition (75-1500 VDC) according to the low voltage directive (LVD) [11]. Figure 2.1 illustrates a principled structure of an LVDC distribution system, including also SG components [10].

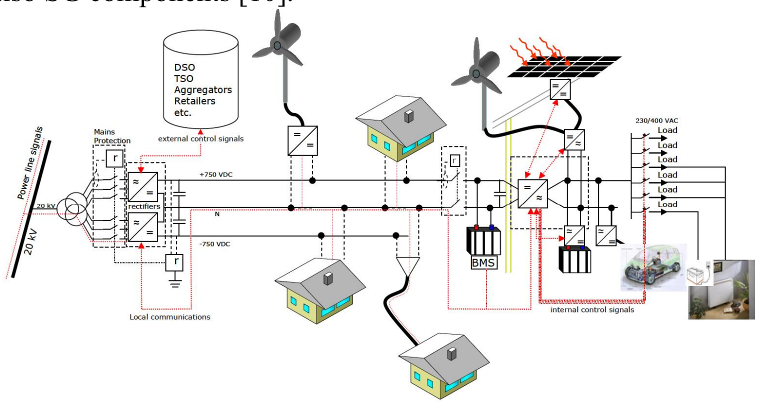


Figure 2.1 Example of the bipolar ±750VDC, earth isolated (IT) LVDC system setup with DERs [10].

When the resources in the LVDC and customer networks become remotely controllable, the system actually becomes a market place, which enables the utilisation of the resources also for various purposes and for various actors, which are discussed further in [12]. Essential requirements are thus bidirectional power and communication flows from MV network to the customer-end and vice versa.

2.2 Design aspects

Figure 2.2 illustrates LVDC related system design themes and particularly important subtasks.

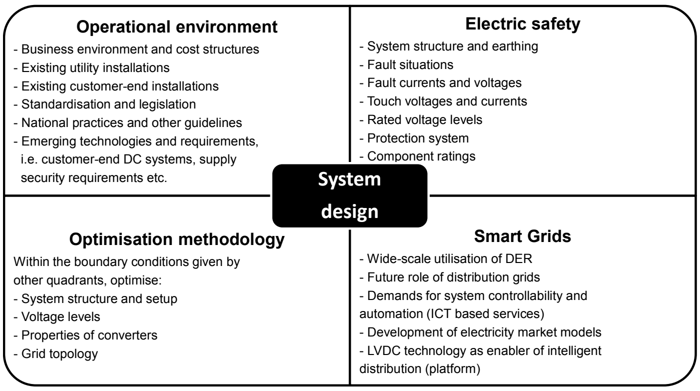


Figure 2.2 LVDC distribution system design aspects

The process itself begins from certain operational environment. The existing practices and guidelines are applied to some parts of the system, yielding a retrofitting task in any case. Thus, it is necessary that the applied technology is compatible with the existing practices and guidelines. Furthermore, the DSOs are in different positions and operate with different electricity market models and strategies. The operational environment, earthing conditions, applied practises and legislation, regulation, customer behaviour and requirements on quality of supply etc. differ partially even in Nordic but especially when the scope is broadened. Therefore, also the techno-economic solutions are highly case-dependent, i.e. in the design process the emphases of the different aspects vary, leading to different results. The SG environment can be considered as an underlying theme which steers the design. It is a challenge as the development of the SGs has been going on globally for years and the concept is still being under intensive research. Finally, the aim is to find economically optimum solution within the technical boundary conditions, as usual. If the DSOs are considered, at least the following list of principal questions concerning the utilisation of LVDC can be addressed without even going into the details:

- What is the expected role in long- and short-term?
- Where are the possible targets?
- What are the applicable structures and voltage levels?
- How is the system considered in the regulation?
- What are the LCCs/savings with the system?
- Is the quality of supply ensured?
- Is the system safe?
- What are the dimensioning principles?
- How is the system modelled?
- How is system and protection configured?
- What are the required components?
- Where to obtain components and products?
- Is the system compatible with the existing structures?
- Is the system in line with the standardisation and legislation?
- Who will build-up and maintain the system?
- How is the condition and lifetime estimated?
- How to integrate it with ICT systems?
- How is the system operated and monitored?
- Does the system enable the integration of DERs and other SG functionalities?

The list can be easily extended but the main purpose was to point out the variety of design tasks and imminently arising questions concerning the technology. The topic is discussed further in [13].

3. DISTRIBUTION BUSINESS AND ECONOMICS

The utilisation of LVDC would basically mean that it is considered in the strategic planning (long term) representing a new solution for developing the distribution networks. It would be necessary that the benefits are indisputable. According to the performed studies, there are numerous application targets for LVDC in Finnish distribution networks; in some cases even more than 30% of the existing rural MV branch lines could be converted into the LVDC systems [4]. In addition, LVDC can be utilized in suburban and urban distribution. Interpret from the Finnish results concerning the feasible targets, respective ones are to be found not only in other Nordic countries but globally as well. The market potential of the LVDC systems is thus quite massive. In reality, for the accurate results it would be necessary to have more accurate knowledge of capital –and operational costs and their expected development. The real challenge instead is: how to estimate the economic, environmental and societal benefits, especially when the expectations on future distribution are considered? If it is generally seen socio-economically feasible that should be the case also in techno-economic sense. The commercialisation necessitates that sufficient interest arises.

3.1 Role of the utilities

From the DSOs' perspective such a novel system includes many risks and suspiciousness is understandable. If the widespread utilisation of DC is considered, there are two alternative approaches through which it may realise: 1) from utilities to buildings and 2) from buildings to utilities. It is likely that the customers are not willing to invest into piloting technology without the clear economic incentives and ready-to-use appliances. The residential customer installations are very static compared to the commercial buildings and the technology has to be benchmarked before the residential mass is involved. The easiest and probably the only way towards the more widespread DC utilisation is thus "through the utilities" preferably by exploiting the mature application areas and existing network components and installations, where applicable [13].

3.2 Prerequisites for the market establishment

To be able to consider the real-world applicability of LVDC distribution further in practice, it is necessary to develop methodology and tools for the system planning which considers the aspects presented in Figure 2.2 so that the benefits of LVDC in operation could be estimated. That, in turn, requires the knowledge of components illustrated in Figure 3.1a). For the technological commercialization, it is necessary from the manufacturers' perspective that there exist drivers and demand which create the market for the products. For the establishment it is necessary that there are sufficient, well-justified drivers for the novel technology together with the guidelines, meaning mostly the standardization. For the standardization development it is necessary that enough information is produced, globally, from many operational environments. Figure 3.1b) presents the key actors in the LVDC development. Now, as the development on SGs is ongoing, it is essential that the DC alternative is acknowledged in a non-discriminative manner, especially when more detailed concept and model definitions are considered.

Figure 3.1 Primary information for the DSO's analyses a) and key actors in the LVDC development b).

To sum up the situation, at the moment there are enabling technology, research results on obtainable benefits and few research setups, globally. Standardisation work is ongoing by IEC workgroup (SMB/SG4) titled as "LVDC distribution systems up to 1500VDC" which has been set up in 2009 to coordinate the standardization of DC distribution systems [14]. In other words, the triggering phenomenon has occurred but the conditions are not established for widespread utilisation. The main reasons are that there are no experiences of planning such systems, application-specific products or business models.

3.3 Regulation and reliability

It is necessary that the use of power electronics improves the supply system reliability. For instance, in Finland the recent change in the Electricity Market Act requires actions to improve the security of supply during the coming decades [15]. By including the converters and other required components the reliability experienced by the customers is affected by the reliability of those, for better or worse. It has to be recognised that in addition to the legislation and customers there are usually investors or owners of the DSOs which have expectations concerning the profits. The lifetime of the converters is around 10a and long-term experiences of exposing the LVDC equipment to harsh climate conditions are rare [16]. The increased complexity and number of components increase the possibilities for the reliability issues. In that sense, it is necessary that there is availability for the standardised products, which are capable of operating in DC distribution in varying operational conditions and can be easily replaced. The legislation and the regulation models try to encourage DSOs to find innovative solutions which provide socio-economic benefits as well as improve the supply security. To strengthen the incentives, the regulation models have to be able to take into account the power electronics; the financial value, life-times and control capabilities. LVDC microgrids including centralised energy storages and both centralised and user-end generation and which are capable to safe island operation are a rival for large-scale underground cabling of rural MV networks. The role of such is not clear from the regulation point of view. Especially the use of centralised energy storages, or more precisely the use of stored energy, seems to be a problem. Thus, at the moment setting up and operating such systems is somewhat vague.

3.4 Service providers

Referring to the bulleted list in section 2.2, there is a need for expertise in various fields such as in developing the system planning and modelling tools. With the system planning, see Figure 2.2, and modelling, see Figure 3.1a), there is a minor dilemma at the moment, as with the present equipment the results are not such which could be expected, if few "evolution rounds" were completed. There is however no drivers for the evolution without the demand for the products in the first place.

One issue especially related to the practise is that the know-how on the novel systems is lacking. For instance, the on-site research setup includes both commercial and custom-made components. The complexity increases significantly compared to the AC distribution and need for maintenance and condition monitoring increases. Therefore, in addition to the trained personnel it is necessary that the commercial LVDC setups are constructed of such modules, in such a way that faulted components can be easily replaced in the field. It is desirable that the applied modules would be physically compatible and suitable widely for the LVDC use.

The integration of the LVDC systems to existing SCADAs and DMSs is one practical issue. The primary questions are; what are the standard communication protocols and interfaces through which

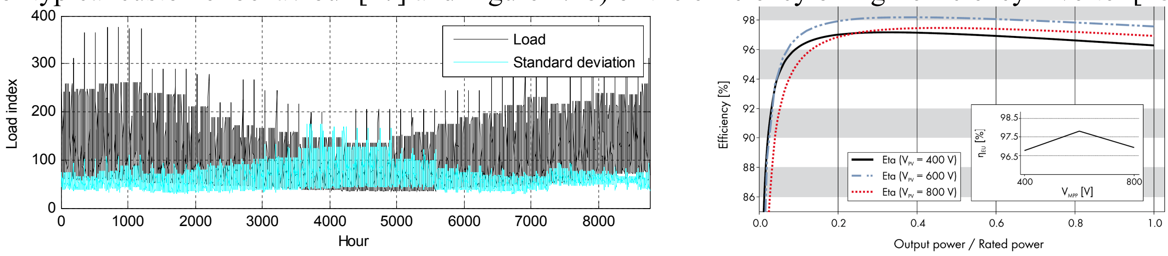
LVDC systems are operated and how the gateway can be used for providing the access to the customer. The overall management of the latter part of the distribution requires investigation, both on physical and conceptual levels. Possibilities are that new business opportunities emerge for the third parties which could provide services for the ICT and data management.

4. DISTRIBUTION TECHNOLOGY

The issues which concern the technology in LVDC use are especially related to the use of converters and DC compatibility of the network components such as cables, protection devices, accessories, etc. The following subsections address the principal technical barriers.

4.1 Converter efficiency

The efficiency of the power electronics is one of the main challenges in the LVDC utilisation. As an application environment the utility distribution differs greatly from the typical industry application. The dimensioning of the converters has to be done according to the peak demand of the customer during the lifetime, in this case during the lifetime of the converter. This leads to a situation in which the nominal power of the converter rarely corresponds with the load of the customer, see Figure 4.1a) of typical customer behaviour [17] and Figure 4.1b) of the efficiency of high-efficiency inverter [18].



a) b)

Figure 4.1 Load behaviour of a Finnish customer, having no electric heating and an electric heated sauna a) [17] and efficiency of commercial SMA solar inverter b) adapted from: [18].

As Figure 4.1b) shows, the efficiency is greatly reduced during the low load hours. For instance, in Finland the total efficiency of electricity transmission and distribution system is above 96% [19]. This sets requirements also for the converters because it is inadmissible that the “last mile” decreases the system-wide efficiency. To overcome the converter efficiency issues, one possible solution which may provide benefits is the utilisation of modular converter structure, in which only the needed number of modules to supply the loads would be switched on [20]. Solution would also enable redundancy between the modules. The efficiency and cost of the converters are thus in crucial role in the LVDC system. To make matters worse, it is necessary to provide fault currents to the conventional protection devices, fuses and circuit breakers (CB). This issue is discussed in the following section.

4.2 Electric safety and protection

In a novel system electric safety is a natural choice for the priority number one. When the protection is based on the feeding of the fault currents, from converter perspective it is problematic. This concerns especially the CEIs, rather than the rectifier. If the protection of the system is based on the components, the operations of which are based on characteristic curves, the overdimensioning of the CEIs is necessary. This complicates further the efficiency objectives. For instance, for Finnish households the typical recommendation is that the supply network is capable of providing 250A short-circuit current. At the moment the field setup is equipped with high nominal power CEIs so that in case of the faults, the inverter control reacts to limit and supply long-enough fault current to cause the fuse or CB to operate [21]. If it would be possible to utilise the measurements and controlling, for instance, CEI-controlled CBs, the overdimensioning could be avoided [21]. The concern related to the “alternative protection solutions”, especially the power electronics based, is mostly related to the reliability of the operation. There are numerous microprocessor based relays in operation nowadays and more complicated distribution systems cannot be protected without utilising the more sophisticated methods after all. In LVDC system there are multiple active devices and measurements, which together with ICT system could actually be utilised for constituting differential protection like protection setup. For the planning, there is a need for the modelling tools for the system fault analysis.

4.3 Network components

One concern is related to the DC use of the existing components. Especially DC related nuisances are the exposure to corrosion and polarisation of the component structure. The primary network components in the LVDC system are transformers, cables or overhead lines, protection devices and accessories such as insulators, cabinets, busbars, blocks etc. For the protection devices, there are quite many products available mainly thanks due to the PV industry. For the cabinets and majority of the interior components the DC rating exists but the application-specific specialities may prevent the direct applicability. One specific issue is with the conductors. Not all of them are rated for DC use. Some studies are available, in which the exposure to the DC was studied but these are of course accelerated tests and the full confidence cannot be guaranteed [22] [23]. It would be essential, that the typical conductors were tested for the DC use, so that the existing structures and components could be utilised, if possible. This is the case also with the indoor installation cables. The DC applicability concerns naturally all of the components as for now the LVDC use often means applying of the fittest available. One issue which concerns almost all of the products is the DC voltage rating which is more related to the standardisation.

4.4 Standardisation

The lacking standardisation is one major issue as the guidelines have been written for the AC use. Some of the existing DC related standards are partially applicable for the LVDC but there are only fractions of required information available. It has been discussed in [13] that which are the underlying risks in the novel system standardisation. The challenges arise as either the DC rating for the necessary components is lacking, or, the rating is too low. The availability or rating of the equipment can be harshly divided into three groups: 1) none, 2) below 400, 600 or 1000VDC or 3) full rating up to 1500VDC. It is impossible to construct the system to be fully DC compatible when some of the system parts are not compliant. The issues arise at the latest when the commissioning of the system is performed [24]. Another field of standardisation which is essential for LVDC is related to the electro-magnetic compatibility (EMC). The present standardisation concerns mainly frequency ranges below 2 kHz or above 150 kHz leaving the critical frequencies out of range. The issue is discussed for instance in [25]. Moreover, the standardisation considers at the moment generally only the power consuming, not grid-forming power electronics and there are no respective testing methods described.

5. CONCLUSION

LVDC is a promising alternative for the future distribution as it provides efficiency improvement and platform for SG functionalities. The concept is now facing the challenges related to the real-world implementation. Due to the novelty of the system, there are no planning methods or tools, established business models, standardisation, or commercial plug&play technology. In general, LVDC has not yet established its role in the distribution system development but as the benefits have been noticed the research is going on, globally, and travel along the hype cycle continues towards commercialization.

6. ACKNOWLEDGEMENT

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