CONSIDERATIONS ON IMPACTS OF DER INTERCONNECTION ON LVDC DISTRIBUTION SYSTEM ENGINEERING

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ABSTRACT

The paper discusses the interconnection of distributed energy resources into low voltage direct current distribution system. In the paper, the importance of comprehensive planning and implementation design of the system including distributed energy resources is highlighted. The main outcome of the paper is the description of principal requirements set for the system structures and setup as a whole including relevant aspects from technical and electricity market perspectives.

INTRODUCTION

The electricity distribution business has to respond to various expectations and development needs which are going to be faced and an evolutionary phase is evidently seen during the coming years. Main drivers in the transition are the energy efficiency objectives and increased requirements regarding the security of supply. Smart Grid (SG) environment has been described widely to be the environment of future distribution and general acceptance has been achieved at least regarding 1) the existence of various distributed energy resources, the need for 2) information exchange capabilities and 3) system management and controlling [1] [2]. Eventually the goal of the distribution system development is to strive to socio-economically feasible solutions which, in turn, require applying of system-wide approach on the analysis on applicable practices.

The recent price and technological development of the power electronics [3] has increased the interest towards utilization of DC in widespread applications [4] [5]. One of the emerging fields of applications is electricity distribution. Low voltage direct current (LVDC) distribution has been concluded to be promising solution in techno-economic sense for certain target areas [6] [7] [8]. In addition, there are possibilities to supply homes and offices efficiently with DC [9] [10]. By utilizing DC in distribution it is possible to enhance the efficiency through increased transmission capacity and increase the controllability through active network devices, i.e. converters. Utility LVDC distribution is used to replace the existing LV distribution and possibly also some of the lateral medium voltage (MV) lines, with rectifying substation, DC network and customer-end inverters (CEI) or converters in case of DC customers [11]. The converters and common ICT communication throughout the LVDC system provide a medium for various technical and market purposes and capabilities for system monitoring and management [12]. In that sense, the backbone for implementing SG functionalities is present in the LVDC system by nature. As a concretization of the LVDC research, there is a field test installation in operation in one of the Finnish distribution system operator's (DSO) network [13]. Figure 1 depicts the overview of the LVDC distribution system including components of an active distribution system.

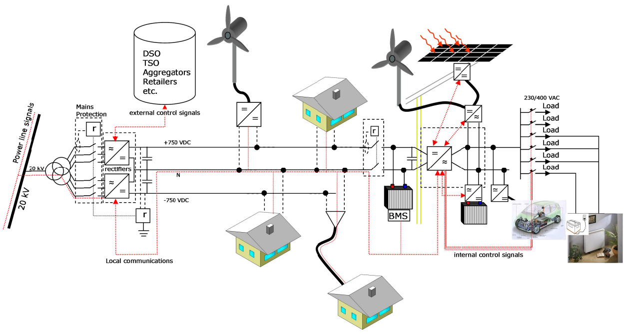

Figure 1: LVDC distribution system overview. [11]

Although LVDC is a promising platform for implementing the SG functionalities, there are certain issues which should be considered in the planning phase of the system. The objective of the paper is to analyze how the implementation of the DERs affects the LVDC system engineering and to highlight the importance of comprehensive planning procedures. The purpose is to describe the primary requirements from technical and market perspectives when the LVDC system including DERs is utilized in the SG environment. The challenges arise as there are neither long term experiences nor definitive guidelines on how to proceed with the LVDC. Therefore, sufficient information of relevant aspects should be brought to the discussion, to support the LVDC development, for instance, the ongoing standardization conducted by IEC SMB/SG 4 [14].

LVDC AND SMART GRID ENVIRONMENT

Smart Grid (SG) is an environment which aims at the efficient use of the electricity by enabling the use of new technologies, services and functionalities. These are, for instance, end-user demand response (DR), electric vehicles (EV) and electric energy storages (eES), connection of distributed generation (DG) and increasing use of automation through embedded ICT capabilities [1] [2]. Many of these functions are related especially to customer level and low voltage (LV) networks. Thus, it can be considered that the role of the customers and LV networks increase in the future. The first steps are already taken in many countries through automatic meter reading (AMR) installations and increasing share of installed small-scale distributed generation, especially the PV plants. Figure 2 illustrates the concept of interactive customer gateway.

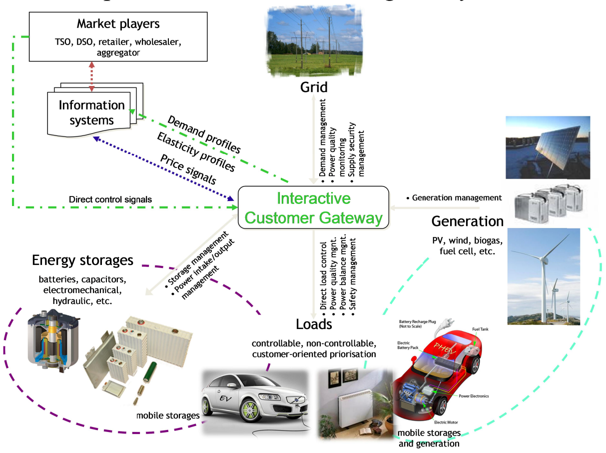

Figure 2: Illustration of interactive customer gateway. [15]

Considering the LVDC as a promising platform which enhances the distribution efficiency and enables the implementation of various SG functionalities the relevant question arising is – how to design the system to enable the versatility, in practice? Eventually, the assessment of viable solutions is done by considering the service criteria which have to be fulfilled, cost-efficiently. Nowadays the service criteria concern mainly the quality of supply. In SG instead, there are various novel presumptions for the capabilities of the grid and the system altogether. For instance, eESs can be utilized to operate in grid-connected and island modes [16] and also for demand response (DR) purposes, such as, the battery packs of the EVs as well. In addition, there can be several parties who are interested in participating in the operation, but on different levels and from different basis [15]. There are thus specific needs especially for the management and control of the active network parts [17] [18]. Referring to the socio-economic perspective, the system has to be capable of 1) operating in a future electricity distribution 2) by providing the required functionality from SG perspective 3) in a cost-effective way.

INTERCONNECTION OF DERS – PRIMARY OPERATIONAL REQUIREMENTS

Considering the various forms of DERs, especially the batteries and PV-plants are of great interest from LVDC distribution perspective. The supportive atmosphere, reachable grid parities, developed markets and the positive hype has provoked the PV installations in many countries. On the other hand, storing of electric energy is the basis for versatile power systems, considering also the capability for island operation. Furthermore, the increasing penetration of EVs would appear directly as an increasing number of decentralized energy storages. Therefore, as DERs are discussed in the paper these are primarily assumed to be PV plants and battery energy storage systems (BESS). Referring to the discussed SG environment, the following sections concentrate on the relevant requirements which are set for the LVDC system from different perspectives.

Market perspective

In SG, the existing customers become an active part of the operation. For instance, customers may become prosumers, the resources of which can be utilized by the aggregators. The required functionality from market perspective is the possibility to benefit of the resources of the multiple customers for trading, preferably by minimizing the harm experienced by the customer. This can be considered to be the interest of the DSO as well, mainly from the network load perspective. Especially the inclusion of BESSs releases the versatility by acting as a decentralized buffer. Thus, from market perspective the controlling and bidirectional power transmission capabilities are essential. This suggests converters to be capable of bidirectional power flow and fast enough communication between the different network devices. The most important property of CEIs from market perspective is the local processing capacity, enabling the local optimization of actions by combining both the needs of trade and markets as well as the needs of the grid as a market place. To sum up, market oriented functionalities set two primary requirements: 1) need for controllability and 2) two-way power transmission capabilities.

Quality of supply

As mentioned, the quality of supply is in the key role in the development of distribution systems. The main advantage of the implementation of BESS, for instance to DC mains, is that it enables the operation of the system during the outages. In the healthy state, the BESS stabilizes the possible fluctuations in the network by acting as a buffer between customers and the MVAC network. The LVDC system which includes BESS and local generation forms at least partially self-sustained part of the network, in which the production and generation may vary. Moreover, the CEIs are preventing the disturbances to transfer between the customers and also between LVDC and MVAC network. From the design perspective, relevant aspects concern mainly the dimensioning of the DERs and controlling and protection of the system. In practice, the communication is indispensable part of the system, especially for the management of the DC µGs, as discussed in [18].

Protection

In the LVDC system the converters and signaling, depicted in Figure 1, are utilized for the monitoring, protection and system management purposes. Instead of dimensioning the converters for the characteristics of the protection devices, the tripping could be done by using the measurements, internal logic and external trip signaling for the breakers [19]. The converters are nevertheless monitoring the voltage and current of the network and are thus capable of detecting and issuing the tripping in very short time. In the fault situations the DERs may contribute to the feeding of fault current and on the other hand interfere with the detection of the abnormal state in the network. However, the converters could be utilized to perform as differential protection relays, if sufficient performance is guaranteed in the communication. Another surplus is, that the protection is based on distributed, independent units, the observations of which can be compared, thus increasing the reliability of protection. Without DER-interface converter, mainly in case of BESS, it is required to use traditional protection methods. At least overcurrent and undervoltage protection are then necessary to prevent the unintentional feed. The protection arrangements have been discussed for instance in [20] and for µGs in [21].

ICT-system

As already concluded in many occasions, the operation of LVDC system and functionalities of SG rely heavily on the ICT system. Regardless of the AC and LVDC systems with DER included, especially the management of group of units, there has to exist some sort of upper level decision making and controlling algorithms. The question then becomes what is the gateway of signaling to the single units in the network. The possibilities and challenges are discussed in [22]. For instance, for a practically functional "real time" DR a minute-resolution is crucial. For protection, the scale is milliseconds. Therefore, high-speed communication is essential. The benefit of the LVDC system is that it forms a natural entity, beginning from the rectifying substation and including group of customers and devices. As there is a communication medium throughout the system, the gateway of Figure 2 exists for monitoring, management and operation purposes. By interconnecting BESS into the DC mains, it is possible to operate the system during the outages. Furthermore, local generation and controllable loads benefit the community even extended period of time. To sum up, ICT is in practice necessary for the operation of the LVDC system, even without the DERs. However, only the interconnection of the DERs enables the further utilization of the LVDC system for the discussed SG functionalities.

DERS AS A PART OF SYSTEM DESIGN

The interconnection of DERs into the LVDC system can be simplified to two principal cases. In the first case there is an existing LVDC distribution system into which the DER is assumed to be connected. In the second case, the DER or various DERs are already considered in the planning phase of the LVDC system. The approach becomes thus either 1) proactive or 2) reactive which are discussed further in the following sections.

Reactive approach

The reactive case would basically represent the case in which the traditional AC distribution is replaced with an LVDC distribution system including only the essential functionalities to enable the operation of the system. The need for implementation of DERs could then emerge, for instance, by the initiative of group of customers. Depending on the primary system design the implementation of the DERs may become challenging and expensive if the existing system structures are required to be altered afterwards. This leads to increased costs in terms of planning, labor and premature depreciation of replaced components, i.e. network asset. It is essential to acknowledge that the DERs are the key for versatility, the utilization of which has to be taken into account in the planning of the LVDC system. The versatility often means also increased complexity.

Proactive approach

Compared to the reactive approach the proactive approach considers the DERs already in the planning and implementation phase. In practice, the system may 1) be implemented without the DERs but being capable of being extended to include ones with minor effort or 2) be implemented with DERs in the first place. It can be considered that from system perspective the two cases are alike, i.e. the system is regarded as an entity. The following section extends the design theme by including also related aspects from overall system design.

System engineering approach

In general, the design of a novel LVDC distribution system is a multidimensional planning and optimization task in the result of which especially the operational environment, electric safety and SG readiness should be considered comprehensively. So far, the paper has discussed the environment and the essential ones of the general requirements which are set due to the inclusion of the DERs. It should be acknowledged that the interconnection of DERs do not merely set the requirements but the efficient utilization of them for the discussed purposes. In this section the task is approached from system planning and implementation perspective. Figure 3 depicts the relevant design themes.

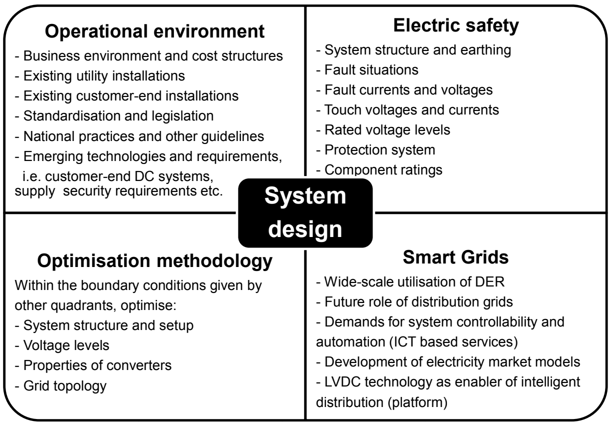

Figure 3: LVDC system design themes and relevant topics.

As Figure 3 shows, there are several different topics involved in the planning of LVDC system. Few of those affect significantly to the rest of system planning, namely, the system structure, earthing and utilized voltage levels. Naturally, these are affected by the applicable standardization and possibly also national legislation, but more importantly, the electric safety of the system. Depending on the earthing system selection and resulting safety issues, the requirements for the protection are different. The research setup installation is constructed as underground cabled, bipolar ±750V, earth isolated (IT) DC network with galvanically isolating customer-end inverters [11]. Referring to the reactive vs. proactive approach, the research setup represents the reactive case. The underlying reason is, that the setup is constantly being developed in line with the performed research by applying the knowledge and technology to novel environment. For instance, to enable the controllability of DC mains voltage and two-way power transmission after BESS implementation, the rectifier was changed to active grid-tie converters. It is acceptable in research case, but considering the more mature phase of LVDC utilization these issues should be considered on the engineers' desks.

DER related design themes

Out of the general design tasks especially DER related topics are

- ICT requirements for controllability
- Properties of converters
- Fault situations and protection scheme

of which especially the latter two are affected by the selection of system structures and voltage levels. From the DER perspective, the voltage level affects to the acquisition prices of the interface converters. The background of voltage level selection is discussed in more detail in [4]. Moreover, in case of directly connected BESS the voltage level affects to the number of needed cells, connected in series to match the pole voltage of the DC mains, affecting therefore directly the price of the battery pack. On the other hand, in direct coupling the costs of the DC/DC converter can be avoided. In bipolar system, to ensure backup supply for both poles, there should exist storage capacity connected to both of the poles.

System dimensioning

The system dimensioning concerns mainly the requirement for the self-sustained operation of the LVDC system. One interesting question instead is if the implemented DERs can affect the dimensioning of the rest of the LVDC system. In theory it is possible, if the DERs are dimensioned sufficiently, and if consumed energy can be matched with the generation including the possible capacity of the BESS. However, in practice, it is the responsibility of the DSO to that the network capacity is sufficient, regardless of the DERs, over the utilization time, which can be over 40 years. It is possible that the network dimensioned today may actually become partially loaded during the utilization time due to increased share of local generation and flexible consumption. On the other hand, increasing installed DER capacity in the customer-end networks and changes in the market price of the electricity could lead to significant variation in the power flow in the network. The variation may result also due to rapid changes in the PV production. These are such issues which should be considered from the system design and management perspectives.

CONCLUSIONS

The paper discussed the effects of DER interconnection on the LVDC distribution system planning. The DERs are in key role of enabling the active networks. LVDC is a promising platform for future distribution and implementation of various SG functionalities, including the DER interconnection. In the paper the necessity of system engineering approach was justified by analyzing the inclusion of the DERs in the system and resulting requirements for the system structures and setup. Research experiences from planning and implementation of a real network research site were utilized. The main outcome of the paper is that the interconnection and utilization of the DERs should be considered in the system planning to avoid excess costs and ensure the further extensibility of the system.

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