LVDC RULES – TOWARDS INDUSTRIAL-SCALE APPLICATION OF LOW-VOLTAGE DIRECT CURRENT IN PUBLIC POWER DISTRIBUTION

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ABSTRACT

The modern low-voltage direct current (LVDC) distribution system merges ICT, power electronics and conventional grid technologies into single system. This paper gives an overview to the LVDC RULES research project and presents its first key results. The foundations of the project are laid by the lessons learned during earlier research projects. Impacts of providing ancillary services for the network operators and an infrastructure for emerging energy market services are discussed. Studies of the impacts of the system properties and active functionalities on the economic feasibility are presented. Finally the paper converges into the introduction of a modular LVDC concept, and a summary of the main specifications for equipment design.

INTRODUCTION

LVDC power distribution has been recognised potential solution for several use cases from renovation of existing public networks to electrification of remote areas with renewables based standalone systems. Consequently, LVDC has been and continues to be a subject of intense research and development. During the past decade the research of LVDC for public power distribution has progressed from theoretical fundamental research into applied research, in which experimentation in the real application environment is in important role. Several research actions have been initiated and completed around the world, many of them including realisation of real-life environment research sites [1]-[13]. In Finland, the research and development has been characterised by the strive towards techno-economically feasible solutions. Field trials have been carried out since 2008. The research results have revealed, that using LVDC in public distribution is technically and economically viable, but also that in order to fully benefit from the opportunities, well-optimised optimised solutions on competitive prices as well as LVDC specific knowhow are needed.

The technology readiness level (TRL) has been steadily increasing, but the large scale commercial exploitation of LVDC is still in its infancy. So far new commercial solutions have emerged only for certain special use cases, such as for data and telecom centrals [5]. In autumn 2015, a new three-year research project – LVDC RULES – was launched to take the final steps towards the industrial-scale application of LVDC also in public distribution networks. The project aims to seeking the best ways to translate the accumulated research knowledge into commercially feasible solutions. Respectfully, the research topics range from converter design to professional training, and from management processes to technical standardisation. The work culminates into building of a new pilot installation into the distribution network of Elenia Oy.

PRIOR WORK

Fig. 1 illustrates the concept of public LVDC distribution system designed for sparsely populated areas in Nordic operational environment The concept and its background are well-introduced in [1]-[4].

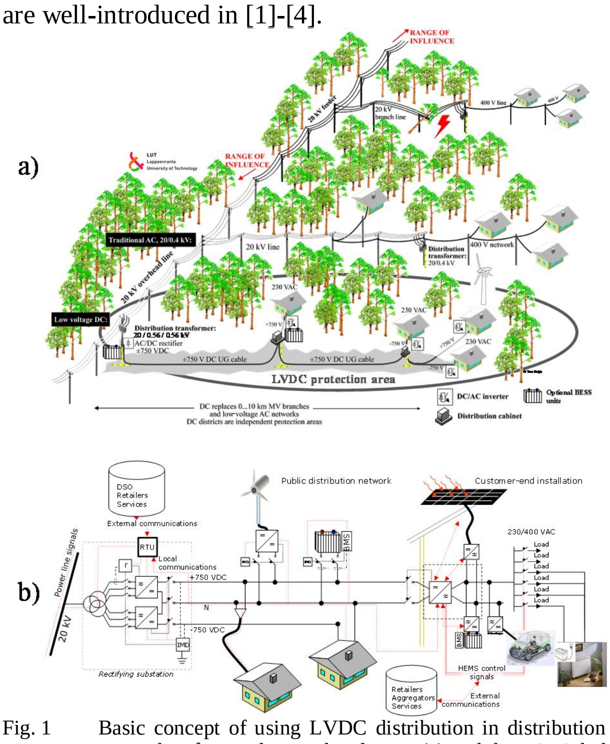

Fig. 1 Basic concept of using LVDC distribution in distribution networks of sparsely populated areas (a) and the principled equipment structure of an LVDC microgrid (b).

Owing to its transmission capacity, the ±750 V / 1500 V LVDC system can be efficiently used instead of low-voltage (LV) a.c. networks, but also for replacing lateral medium-voltage (MV) line sections. Consequently, the whole network shortens, the number of protection zones increases, and the amounts and durations of the interruptions experienced by the end users reduce [2]. The supply security can be further improved by exploiting the locally available generation and storage resources and enabling the LVDC system to be operated in island mode [3][4]. This reduces vulnerability to major blackouts and opens an excellent opportunity for the Nordic distribution system operators (DSOs) to improve supply security without expensive large-scale underground cabling of MV networks in rural areas.

The LVDC distribution has been proven as a cost-effective option for network renovation with significant techno-economic application potential. According to previous case studies tens of percentages of the existing a.c. distribution networks could be replaced [1][6] in Nordic operational environment. According to the studies at least two basic network configurations can be feasibly used: (1) the link-type solution, later referred as hybrid AC-DC topology, in which the LVDC system is used only to replace suitable medium voltage lines (similarly as the 1 kV a.c. system); and (2) the network-type solution, later referred as full DC topology, in which the LVDC system replaces both the medium voltage branch line and the low-voltage a.c. networks as presented in the Fig. 1 above. Application potential for similar LVDC solutions can also be found from completely different operational environments [7]-[8][9].

The LVDC technology can have a significant influence on the role of microgrids in public power distribution and further on integration of renewables and electrical energy storages. For instance, an LVDC network can provide infrastructure for green energy communities, as suggested in [7]. The integrated ICT system [3] enables efficient harvesting of the distributed resources to provide ancillary services for all the stakeholders: customers, electricity traders, local distribution company and power system operator. Some ancillary services are based on inherent functionalities of the converters and are available almost without any communication. Such are, for instance, the abilities to control the reactive power exchange with the MV network and correct power quality deviations in interconnected a.c. systems. Some are by definition based on system level functionalities, such as the above mentioned island operation and demand response. The system level functionalities are communications dependent.

Experiences from field trials in Finland

Common goals for field trails have been to provide a proof of concept; to give feedback about the technical challenges, design flaws and functional development needs emerged in the actual application environment; and to set up real-life development environments to support research (living labs).

The first field trial in Finland was realised in 2008, when Ensto Finland Oy and Porvoon Energia Oy converted an existing low-voltage a.c. line into d.c. operation. Although the system was able to supply loads as planned, it suffered from shortcomings related to energy efficiency, voltage control and fulfilling the protection requirements in the customer end. It was learned that the technology concept itself is functional, but also that further research is needed to understand the system operation and to optimise the equipment. The second field test site was commissioned roughly two years later, in 2010, by Elenia Oy and ABB Oy Drives [10]. The setup comprised of two back-to-back connected grid-tie converters. It was proven that network embedded converters can provide support to the network and improve the power quality. The main technical challenges were due to the harsh environmental conditions. It also became clear that using modified industrial converters becomes too expensive and leads to poor energy efficiency. These two early setups have now been decommissioned.

The two newest research sites were commissioned in 2012 and 2014. They are both in continuous operation as a part of local utility networks. The first one was realised by LUT and Suur-Savon Sähkö Oy and uses ±750 V d.c. network to supply power to four residential customers [4]. The second one was built by Elenia Oy and ABB Oy Drives and is based on use of 750 V d.c. link [11]. Both setups have been operating as planned and have provided the final proof of concept and viability of the technical solutions, and especially, that building safe and reliable LVDC distribution networks is possible. [4][11]

Together the field trials have proven the need for life-cycle cost optimisation based design of equipment and especially converters [12]. They have also illustrated that the LVDC technology provides exceptional platform for implementing complex control and monitoring functionalities [3], and that these can be feasibly used to harvest local resources for providing ancillary services. Based on the field trials it can be concluded, that the technology is mature enough for commercialisation.

LVDC RULES PROJECT

The main objective of the LVDC RULES project is to enable transferring of the LVDC technology from laboratories and research sites into everyday use in Nordic distribution companies. In the project, technologies, methods and processes are researched and developed to define the best solutions achievable with today's technology for starting the commercial application.

The work is divided into four overlapping main themes, that are (1) Functionalities and technology solutions; (2) Impact on distribution networks and business; (3) Active resources and renewables; and (4) Standardisation, recommended practises and professional training. Main results will be the technology solutions and recommended practices verified through the realisation of the new pilot installation. The work is conducted in collaboration by Lappeenranta University of Technology, Elenia Oy and Ensto Finland Oy.

Examples of the addressed research questions are:

- What is the value and criticality of the different functionalities to the DSO?
- What kind of ICT system and interfaces are needed for implementing the critical functionalities?
- What are the life-cycle cost-effective power electronics and protection solutions and network configurations?
- What kind of maintenance program and other processes the life-cycle management requires?
- How distributed generation, energy storages and ancillary services affect the feasibility and the business opportunities?
- What kind of professional training is needed and how the required skills can be transferred to existing personnel of DSOs' and service providers?
- What are the detailed needs for developing standardisation?

In addition to technology methodologies and processes, also business impacts as well as socio-economic and societal aspects are considered. Understanding the drivers and boundaries, which arise from the energy system and market evolution and the technological state of art, are prerequisites for successful definition of the system functionalities and further the technical specifications that dictate the detailed design of the equipment and software. Fig. 2. depicts the scope of the project.

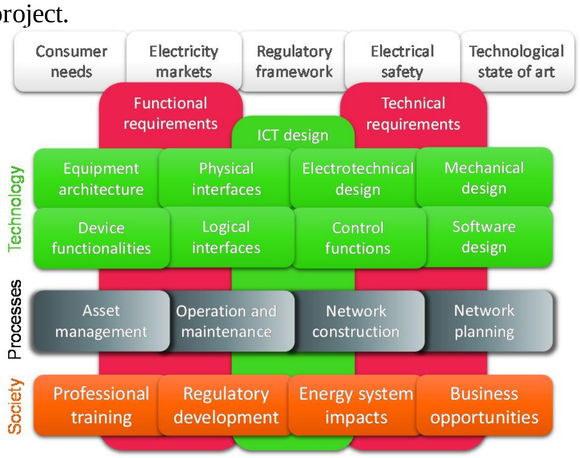

Fig. 2. Scope of the LVDC RULES project.

Communicating with the SME sector is emphasised in dissemination of the results. The nimble SME sector has seen to have an pivotal role in putting the results in practise. Hence, public expert workshops are arranged during the project to engage the relevant stakeholders and to intensify dissemination of the results. The project is a part of the 'Green Growth' program of the Finnish Funding Agency for Technology and Innovation (Tekes).

Preliminary results

The research work has been started with determination of possible ancillary services that can be realised based on LVDC system functionalities and offered to market players. Examples of considered ancillary services for DSOs are:

- Remote control and status supervision of system, converters and switchgear (SCADA functions)
- Monitoring the quality of voltages and currents (alarms and data on demand)
- Online condition monitoring of LV and MV equipment (alarms and data on demand)
- Identification of faults in LV network
- MV network reactive power compensation based on voltage droop, scheduling or static setting
- Control-hub for customer-end demand management automation, possibility for setting load limitation
- Control of MV interface active power flow by utilising d.c. interconnected BESS and demand response
- Capability to temporary island operation if local generation and storage capacity available

The next steps are to define the criticality and value of the ancillary services, and the costs of implementation. Requirements are set especially for the ICT system design, but the selected functionalities affect also to the network configurations. Consequently, simultaneously with the determination of the active functionalities an investigation of the techno-economic equipment and system configurations have been initiated.

Fig. 3 and Fig. 4 present results from a preliminary case study, an objective of which has been to compare the costs of the unipolar hybrid DC-AC topology with the bipolar full DC network topology. The case area is located in the network of Elenia Oy and has 13 residential customers. Only the investment costs and cost of losses of cabling and converters were considered. The study period was 45 years. All the converters are assumed to have similar efficiency curve and unit price per kVA. The nominal powers of used converters were selected based on hourly peak loading, but the smallest unit size is 15 kVA. The need to oversize the converters for supplying short-circuit currents was not considered. Similar case studies have been conducted during the development of the software tools that will be used in further analyses.

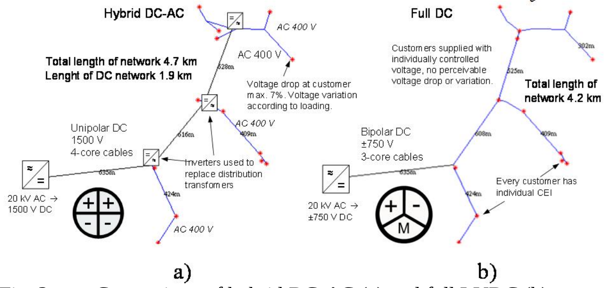

Fig. 3 Comparison of hybrid DC-AC (a) and full LVDC (b) network topologies to supply power for 13 customers in the example area.

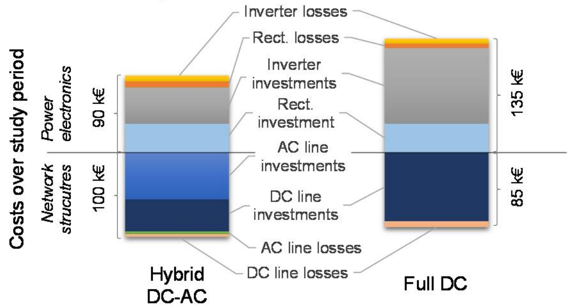

Fig. 4 Costs of line structures and power electronics over the study period of 45 years.

The full DC topology leads to shorter network, but the hybrid DC-AC solution has lower costs. The transmission capacity of the used 1500 V unipolar connection and the dominant role of the inverter costs tilt the scale on its favour. However, the difference is small and the value of the ancillary services enabled by the CEI in the full DC topology can tilt the scale on its favour. Because all cost components were not considered, the result is merely suggestive. As a conclusion it has been decided not to select a single configuration for the further research, but to develop equipment so that it can be applied in various different setups. This is expected to provide higher benefits, but also will make the planning processes complex.

To allow equipment design, the crucial electrotechnical parameters need to be defined. The design criteria presented in [4] have been considered mostly appropriate. Based on earlier research, ±750 V / 1500 V was selected as the nominal voltage. At least +10/-25% variation in the d.c. voltage should be tolerated by the inverters. All components belong to overvoltage class IV. The earthing system is IT in public network and TN-S in customer installations.

For the inverters, controlled 160 A_{RMS} a.c. short-circuit current supply capacity was considered sufficient. This is enough to allow fast enough operation of C16 circuit breakers. If a customer has protection devices requiring higher operating current or in the case of hybrid DC-AC solution, higher short-circuit capacity may be needed to ensure operation of protection at every customer. The impacts of these limitations on equipment as well as other systems engineering issues will be discussed in detail in further publications. Fig. 5 illustrates the modular equipment concept and options for the technologies used in local communications.

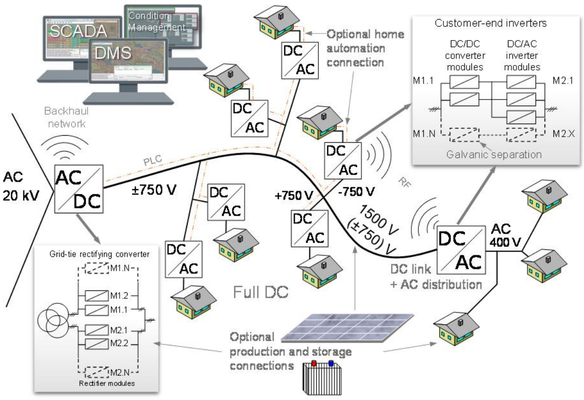

Fig. 5. Illustration of the principled structure of the planned new pilot installation. The goal is to enable testing functionalities of both full DC and hybrid DC-AC topologies as well as of different communications techniques.

In addition to the needs of cooling, pivotal requirements for the mechanical design of converter equipment are set by the maintainability. Also the possible need for moisture elimination after long outages may need attention. Both aerial bundled cables and underground cables are going to be used. Use of aerial line structures pose challenge for the EMI filter design. From electrotechnical perspective there is no obstacles for the use of ABCs [13].

CONCLUSIONS

The LVDC technology under development can have a significant influence on the role of microgrids in public power distribution and further on the structure of the whole power system. Within the past decade, the technology has reached the readiness for commercialisation. The LVDC RULES project focus on seeking the best solutions, cost-effectively achievable with current know-how, for the first generation of commercial equipment for public LVDC distribution.

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