PROSPECTS OF DEVELOPMENT OF LVDC ELECTRICITY DISTRIBUTION SYSTEM ENERGY EFFICIENCY

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ABSTRACT

The subject addressed is the energy efficiency (EE) of LVDC electricity distribution system. The focus of the paper is on the development trends and the dependencies of the system EE. In the paper, the prospects of development of LVDC electricity distribution EE is presented using quantitative results and the system development challenges are discussed. Moreover, the impacts of microgrid infrastructure developments on the LVDC system efficiency are covered. With assumptions on presented infrastructure developments, future LVDC system will be able to improve the EE of energy distribution.

1. INTRODUCTION TO LVDC SYSTEMS

The basic concept of the low-voltage DC (LVDC) distribution system was introduced as a replacement for lateral medium-voltage branch lines and low-voltage network in rural area distribution [1]. The proposed concept has been proven to have techno-economic potential [2], and current trends indicate that worldwide electricity distribution networks are experiencing a transformation towards the application of DC at both the generation and consumption level [3].

Today, driven by the assigned targets in the EU energy policy (Energy Efficiency Directive 2012/27/EU), steps to improve the EE of the existing networks are to be made by distribution system operators. Therefore, also the EE of the LVDC system should be seriously considered. The EE of the first implementation of the LVDC system is low due to the efficiency of customer-end inverters (CEI) on the partial loads [4], the related challenges are addressed using computational approach in [5]. To improve the EE of the LVDC system, following approaches are under consideration in order to optimize the EE of the system:

- Voltage level optimisation
- Usage of the modern, high efficiency switching components
- Usage of the more efficient converter structures
- Usage of the Battery Energy Storage Systems
- Usage of residential DC supply

In [6], it is shown that the integration of distributed generation into a DC microgrid can improve the efficiency of the energy distribution. Moreover, the energy storage could be used more efficiently in LVDC systems, due to possibility of direct connection of the energy storage to DC network and therefore elimination of the losses on conversion during charging and discharging of the storage [7].

In previous research [19], it was concluded that conversion efficiency in the loads of the DC microgrid (400V) has to be higher than 94.4% to have lower total losses compared to an AC microgrid (200V) with assumption of constant efficiencies of AC/DC and DC/DC conversions. Also the grid converter is found to be important factor. The losses in the AC and DC microgrid systems for residential complex were compared in [20], the whole losses of the DC system are around 15% lower than that of the ac system for a year. Efficiency analysis of low-voltage DC distribution systems (325V) [21] showed that the losses in the mixed AC/DC system are about 1% higher than in the AC system. The authors in [22] state, that despite of fact that the conduction losses in the DC grid (325V) are half of those in the AC grid, these losses only amount to about 0.3% of the useful power. Also they concluded that the distribution of electrical energy by means of a DC grid calls for very efficient AC/DC and DC/DC converters; especially at partial loading.

In this paper the LVDC system efficiency is computed in a quantitative manner for the different network case scenarios. Calculations are based on the AMR measurements of the network customers. The annual EE indices are estimated for LVDC system with described EE optimisation approaches applied.

2. EFFECTS OF TOPOLOGY AND COMPONENT DEVELOPMENTS ON LVDC ENERGY EFFICIENCY

The network cases are based on part of an actual distribution network, which is a traditional 20 kV medium-voltage (MV) and 400 V low-voltage (LV) AC distribution network in Finland region. The network model is built on the database data provided by a Finish electricity distribution company Elenia. One year AMR measurement data of network customers is used in calculation. The case networks are illustrated in Fig. 1 and Fig. 2. Numerical description on case networks is given in Table 1.

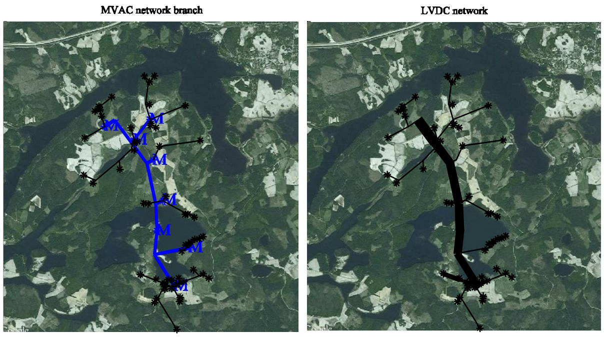

Fig. 1. Case network 1 (rural network)

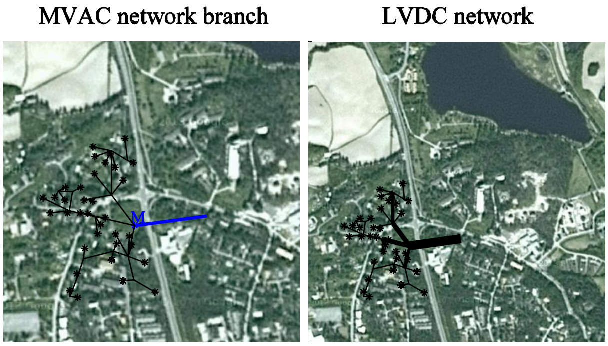

Fig. 2. Case network 2 (city network).

The computed estimate on the EE of the AC distribution is presented in Table 1. In the presented AC distribution efficiency, energy losses of the external power supplies of the end-user electronic devices are not considered.

Table. 1. Description of the network cases.

Network case	1	2
Number of customers	56	87
Annual energy consumption [MWh]	530	513
Peak power hours [h]	2800	2750
MV/LV transformers	8	1
MVAC total length [km]	5	0.2
LVAC total length [km]	12	2.2
AC distribution EE [%]	94.07	98.5
DC distribution EE (conduction losses only) [%]	96.45%	99.68%

Voltage level optimisation

Existing DC distribution system have been built with different voltage levels such as 325, 380, 400, 600, 750 and 1500 VDC in bipolar and unipolar configurations [21] [19] [24][9]. By utilizing the maximum 1.5 kV voltage level, defined by the low-voltage directive (LVDC 73/23/ECC), and the international standard IEC 60038, more efficient transmission and distribution is achieved in low-voltage distribution system than with lower voltage levels. Therefore, this paper covers only the EE of the ±750 VDC bipolar LVDC distribution system. The computational result on DC distribution EE presented in Table 1, emphasizes that usage of full range voltage for the DC distribution is optimal in terms of EE. In comparison with MVAC and LVAC distribution, LVDC distribution provides improved efficiency and eliminates the need for additional distribution (MV/LV) transformers.

Prove of concept (Milestone 1)

To prove the concept of the LVDC rural-area distribution, based on the use of power electronics, an LVDC network supplying four residential houses was built in eastern Finland. The CEIs in the LVDC network are based on IGBT-bridge and 50Hz isolation transformer [24]. Such galvanic isolation results in physically bulky and expensive CEI [8]. Furthermore, EE is low, due to high switching losses on IGBT bridge and no-load losses of the isolation transformer [4][5]. The annual EE of such system will be just 71.8%, with 26.8% of energy losses on the CEIs only. Therefore, the efficiency of a DC/AC conversion is a major challenge.

Galvanic isolation (Milestone 2)

A high-frequency DC/DC converter-based galvanic isolation could improve the efficiencies of the CEI and the LVDC system. For the LVDC distribution system, the implementation of the galvanically isolating DC/DC converter for the customer-end isolation is proposed in [8]. By replacing the 50 Hz isolation transformer with a DC/DC converter, significant improvement in EE can be achieved. According to calculations, based on DC/DC converter efficiency curve reported in [23], EE of the system is increased to 83% and energy losses on CEI are reduced to 14.3%.

High efficient components and topology (Milestone 3)

The changes in converter topology could improve CEI efficiency. For instance in publication [9] the reported measured efficiency for LVDC system is 92.5–94%, with usage of the three-level NPC converters. Furthermore, the use of modern wide bandgap (WBG) semiconductors such as Silicone Carbide (SiC) and Gallium Nitride (GaN) has enabled the converter systems to reach efficiencies up to 99 % [10][11]. Utilization of the WBG devices in the CEI would therefore significantly reduce the switching losses of the CEI. SiC switches in DC/DC converter are also reported to increase DC/DC stage efficiency to 99.1% [18]. Together with SiC inverter efficiency curve reported in [12], the EE of the case LVDC system increased to 90.1% and the losses of the CEI decrease to 7.8%.

Modularity (Milestone 4)

Major improvement could be made to system EE by increasing the partial load efficiency of the converter. The modular topology of the CEI could in theory allow operation near maximum efficiency and therefore improve the EE of the CEI [13] and the LVDC system. To decrease the losses of the DC/AC conversion, a MOSFET-based Modular Multilevel Converter (MMC) is proposed in [14].

Furthermore, in publication [15] is reported for the soft switched triangular current mode (TCM) T-Type inverter to improve the European efficiency [25] to 99.1% at expense of higher system complexity. For the LVDC system, the modular topology is proposed in [13][14][16].

3. COMPUTATION RESULTS

The computation methodology used in the paper is presented in [5]. The result of the computation presented in this paper is the annual EE of an LVDC system, with standard 230/400V three-phase LVAC supply of the customers. The computation results on system EE and energy losses on CEI are concluded in Table 2 and illustrated in Fig. 3 and Fig. 4.

Table 2. Computation results

N	Milestone	1	2	3	4
1	System Energy Efficiency[%]	79,28	84,34	87,14	91,40
	Energy loss on CEIs [%]	15,75	10,33	7,44	2,99
2	System Energy Efficiency [%]	71,86	83,98	90,24	94,15
	Energy loss on CEIs [%]	26,80	14,26	7,78	3,75

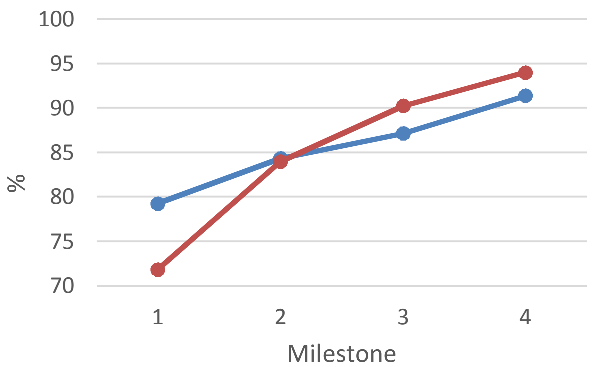

Fig. 3. LVDC system energy efficiency.

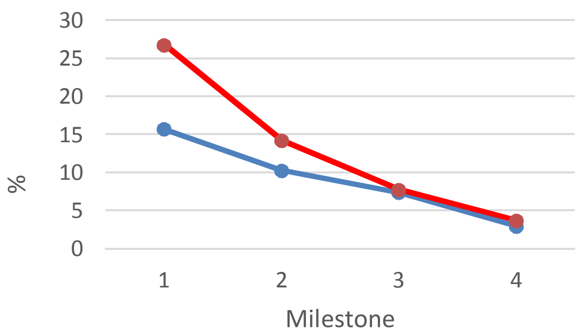

Fig. 4. Energy loss on CEI.

The results of EE computation (Fig. 3) are showing the improvements of the LVDC distribution EE in the next development milestones. The second milestone, the galvanic isolation by DC/DC converter according to results will reduce energy loss on CEI by 30%. Moreover, replacement of the isolation transformer with isolated DC/DC converter, will remarkably reduce size and weight of CEI. High efficient switching components with corresponding modular topologies of converter will increase EE, but the complexity and cost of CEI will also increase. This milestone is highly dependent on power electronic component developments and availability of the solutions on the market. Moreover, as CEI is a component of distribution network, detailed techno-economic studies and optimisation, such as presented in [8][16], are necessary. Overall, the more efficient switching components and modular topology of CEI are expected to give 10–20% improvement in EE of the LVDC system over first milestone. For the further improvements of the system EE, infrastructure developments are required.

4. EFFECTS OF INFRASTRUCTURE DEVELOPMENTS ON LVDC ENERGY EFFICIENCY

Distributed Generation (DG)

The number of the network connected, small scale generation units is increasing. These are residential roof photovoltaic panels (PV), district combined heat and power (CHP) plants, and small-scale wind turbines. The distributed sources are interfaced with network with power electronics, i.e. converters. With LVDC system, the connection of DG to distribution network will require DC/DC grid converter, and therefore could be more energy efficient due to no need of DC/AC grid converter stage. Furthermore, the LVDC system capacity will allow more DG to be connected to low-voltage networks. In comparison, in case of DG connected to MV network, the energy route to end-customer, imply a step-up transformer and MV/LV distribution transformer, and therefore overall EE of such system will be reduced.

Battery Energy Storage Systems

Today, battery energy storage systems are making the way to the distribution systems. Usage optimisation and feasibility of investment are questions of the great importance. In AC microgrids, for BESS the interfacing using AC/DC converter will be needed. For the MV network connected energy storage, the step-up transformer is required, therefore EE of storage system is reduced. In LVDC distribution network the BESS could be connected directly to DC network as in publications [7][17] is shown. Such integration is more efficient than in AC microgrids or traditional AC networks, in which the interfacing DC/AC converter is required.

Customer-end DC supply

The DC supply can be used at customer-end premises to supply numerous appliances [26]. Therefore, upon widening and advancing of DC technology, could be expected that residential appliances will accept DC current supply. For the case LVDC technology, this reduces the peak load of the DC/AC stage of the CEI due to the fact that common residential appliances with high power and energy consumption, such as direct electrical heating, heat pump, air conditioner, washing machines/dishwashers will be supplied using DC. Besides, home appliances today already natively operate on DC. In such case, only galvanic isolation stage and voltage reduction are required to power DC loads of residential building. With high efficient DC/DC converters [18], energy losses on CEI (Fig. 4) can be reduced further and overall system EE improved. The residential DC allows to remove rectifying stage from end-user appliances, for external AC power supplies, Lawrence Berkeley National Laboratory (LBNL) estimated average efficiency of 68% [27]. Therefore, with DC supply overall EE will be increased, as for instance in [20], is concluded. And, as reported in [27], reduction of the conversion losses on appliances is expected to reduce from an average loss of about 32% in current LVAC systems down to 10% with DC grid within a building.

5. CONCLUSIONS

The EE of the 1.5kV LVDC distribution systems for the selected network cases were computed and the results were presented. Despite of low EE of the first implementation of the system, the computation results show remarkable improvements in the system EE with more efficient power electronic topologies and efficient power electronic components. The inclusion of directly connected energy storage to the system will further improve the EE of the system and will present clear advantage over AC microgrid. The direct DC usage on customer premises will remove the need for inefficient external AC power supplies from end-user appliances and therefore improve further the EE of energy distribution. The conclusion is that future LVDC system will be able to improve the EE of distribution networks.

Acknowledgments

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