Technical Requirements for Customer-End Devices and Communication Network in Implementing Smart Grid Functionalities to LVDC system

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SUMMARY

This paper discusses the technical requirements for intelligent electrical devices (IEDs) of a low-voltage DC (LVDC) distribution system, and for communications and control system at customers' premises. In a smart LVDC system, the power electronic converters are natural IEDs and central parts of the control architecture regulating the operation of the local system and active resources, such as demand, production and storing, to meet the needs of the power system control, markets and customers. In large-scale, utilizing LVDC technology does not change the fact that demand flexibility is one of the most valuable resources, and thus, demand response (DR) important functionality of the SG. But, the LVDC distribution provides basis for the infrastructure aiming on activating the customer-end resources on energy markets. To bring the customers as part of the active electricity markets, intelligent controlling devices (ICDs) are required. In case of LVDC distribution, the customer interface ICDs are integrated with the customer-end inverters (CEI), giving them a triple role; 1) a controlled voltage/current source; 2) IED in local LVDC network participating on system control and monitoring; 3) ICD responsible of coordinated load control. Furthermore, the CEI (ICDs) are responsible for providing advanced metering infrastructure (AMI) for network operators. Thus, it is needed to have certain data processing performance and interfaces to connect with surrounding information systems, and to control the customer's loads. The CEI supplies 230/400 VAC to the loads in customer premises. The range distance of the load devices in the customer-end AC (or DC in some cases) network from the output of the CEI is in maximum around tens of meters. Thus, in addition to ICD in the CEI, communication network in customer-end AC grid and additional controller at the customer utility box are required to enable the smart functionalities. Furthermore, the communication network on the customer-end AC grid is connected to the upper communication network on the LVDC distribution grid level. The main objective of the paper is to propose and describe the selection procedure of applicable ICDs, and the communication technology and network architecture for the customer-end network of the LVDC system.

KEYWORDS

Low-voltage direct current (LVDC), smart grid (SG), electricity markets, demand side management (DSM), load control

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1. INTRODUCTION

Today, power distribution networks are heading toward smart grids (SG), globally. The transition in Europe is driven mainly by the societal needs and the EU energy policy objectives. Novel smart grids in Europe should constitute a competitive and liberalized environment with the energy producers, micro-generation facilities and modern electricity distribution systems. In addition, according to Directive 2009/28/EC, which promotes the growth of renewable energy generation, the power supply of the SGs will mostly depend on renewable energy resources. Accordingly, the EU has set the '20-20-20' target; 20% of Greenhouse gas emissions compared with 1990 levels must be decreased, 20% improvement in the EU's overall energy efficiency must be achieved, and 20% growth in the share of energy obtained from renewable energy sources must be gained, all by the year 2020 [1].

These objectives have partly changed the electricity production scheme. Today the power flow is not anymore only from the centralized primary power plants to the customers, while the number of distributed generation (DG) units or decentralized connections of renewable energy technologies, such as wind turbines, and photovoltaic cells in the consumers at the ends of electricity distribution systems has increased. In addition, with electrical energy storages (eES), which are becoming more common in modern smart grids, the electrical power can be stored for the electricity blackout, to sustain the distribution grids during faults and in island modes. To control the power flow in the grids, and provide uninterrupted energy supply to the customers, information and communication technology (ICT) systems on the distribution grids have become a necessity. Information about the status of the distribution grid, behaviour of the customers, and statuses of the DG and eES units in the grid, are needed to be collected to the master of the grid and to the remote data bases of the distribution and transmission system operators (DSO, TSO) [2]. With this information, the efficiency, reliability, and the flexibility of the electricity production and distribution can be improved, as one major focuses of the SG principles. Furthermore, the energy consumption peaks can be equalized by the DGs and eESs.

The deep integration of ICT systems with power distribution grids is a main cornerstone in implementing SGs. A second foundation stone are the smart functionalities implemented on the intelligent devices in the grids exploiting the available ICT. The electrical energy consumption and production data from the customers are collected and analyzed, and this information is used for instance for demand-side management (DSM). DSM is essential for optimizing the power consumption, and minimizing the cost of power supply in SGs. Further, monitoring and controlling the grids to provide continuous and reliable power distribution for the customers is needed.

General demands for novel SGs listed above are also required and needed to be implemented on the low-voltage direct current (LVDC) electricity distribution system, which is the studied SG concept. An LVDC field installation grid with its main properties and functionalities is presented in [3] and [4]. Power line communication (PLC) based data transmission concept based on commonly used Internet protocol (IP) for the LVDC research site is studied in [5]. The communication concept is only proposed for the DC grid between the power electronic converters. However, the communication network has to be extended on the customer-end AC grids for customer load control as part of the main functionality of the SG concept. Beside the communications, ICDs are needed on the customer premises and on the DG units, which will be installed on the LVDC research site as the next milestones. Thus, in this paper the technical requirements for the ICDs and the communication network for the ends of the LVDC field grid are discussed. Furthermore, the complete ICT system for the LVDC system is proposed. The structure of the paper is the following. First, the LVDC system and SG functionalities, which are or will be implemented in the LVDC research site are presented. Those partly determine or guide the selection of applicable ICDs and communication solutions for the system. Accordingly in the next section, the smart devices, network architecture and communication technology for the customer-end AC grids and for the DG/eES units are discussed. Finally the paper is summarized in the conclusion Section.

2. LVDC SMART GRID CONCEPT

The basic idea behind the LVDC electricity distribution system is that low-voltage DC with apply of power electronic devices are used in the electricity distribution. The concept of the LVDC distribution system, and the architecture and dimensions of the LVDC field installation grid is illustrated in Figure 1 a [4]. The medium-voltage 20 kV AC is transformed into low-voltage AC, which is rectified to, and delivered with +750 VDC, 0 V and −750 VDC voltage levels to the customers in a bipolar LVDC system. DC power is supplied with LV underground cables (UGC) to the customer-end inverters (CEIs). The CEIs convert the DC to standard 230/400 VAC, which is supplied to the customer loads through a three-phase customer-end AC grid [4].

The LVDC system provides certain advantages to the electricity distribution. According to [6], the highest DC voltage level still rated as low-voltage is 1500 VDC, and with that DC level, approximately four times more power can be distributed [7], and around seven times longer distribution distances as a function of voltage drop can be covered by using the same UGC network used in the low-voltage AC distribution [8]. Furthermore, the effects of short-time faults in the MV grid are not experienced by the customers, because of the energy storage capacitors implemented in the DC grid and at the CEIs. As a result, high-quality AC voltage can still be delivered to the customers during such faults. In addition, direct connection of distributed generation (DG) units and electrical energy storages (eES), such as solar panels and battery banks to the DC grid is an advantage; synchronization of them with the DC is not required [5]. Accordingly, the DC grid can sustain itself as an island grid and remain functional when the connection to MV grid is not available. To be able to do this, SG functionalities, such as grid active on-line monitoring have to be integrated on the LVDC system, and thus ICDs, and communication network are required. The concept of the ICT system with the main SG functionalities on the LVDC research site is illustrated in Fig 1(b). The grid converter (GC) and each CEI are equipped with embedded PC (EPC) and communication interface (CI).

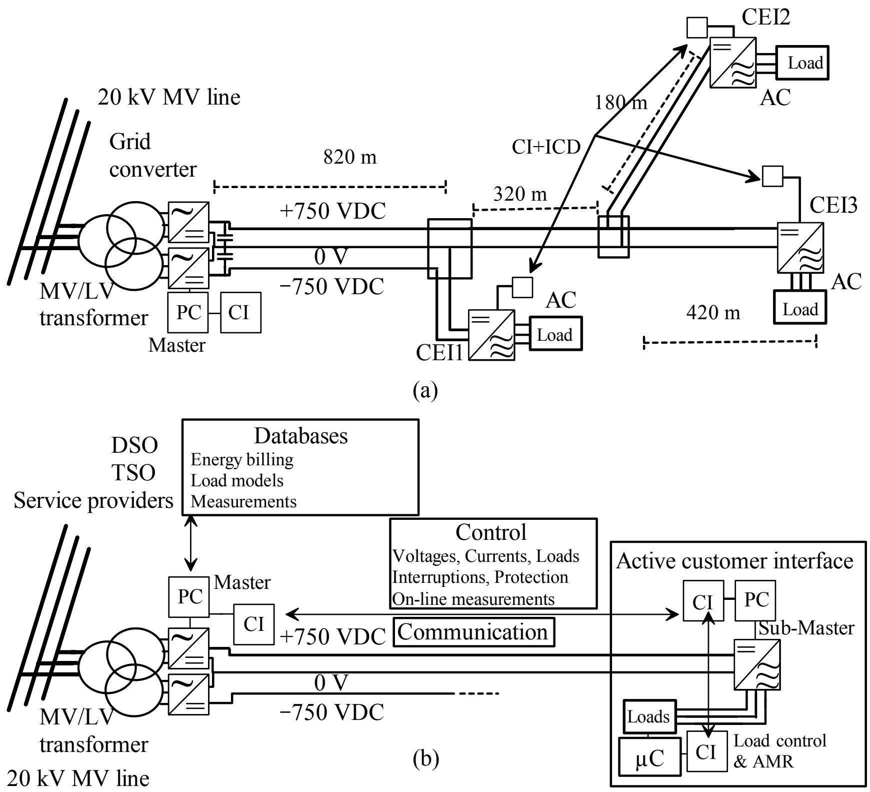

Figure 1. Concept of LVDC distribution system installed as a research site with the ICT system implemented on the DC grid [4] (a), and on the whole LVDC system (b). Embedded PC at the GC is the master of the LVDC communication network, and is interconnected with the sub-master at the CEI through communication interface (CI). There is a subnetwork formed under the CEI AC grid; CI, communication network and intelligent controlling device (ICD) is also needed in the customer AC grid.

2.1 LVDC ICT System

'Active customer interface' (ACI) (or gateway) term, presented in [9], is applied in the LVDC system. ACI concept interconnects the usage of modern power electronics in electricity distribution, AMI technology and two-way communication between the remote data bases and applications of the DSO, service providers and energy market players to form a SG platform. Thus, ICDs are required at the GC and each CEI. Further, communication network is needed between the ICDs on the DC grid.

The LVDC SG concept is implemented in a 1/0.4 kV AC public electricity distribution network operated by the Finnish DSO Järvi-Suomen Energia Oy and owned by the energy company Suur-Savon Sähkö Oy. The LVDC research site is implemented in co-operation with Suur-Savon Sähkö Oy and it is located in Suomenniemi, Finland. The structure and dimensions of the LVDC research site is depicted in Figure 1a [4]. The structure and architecture of the LVDC system mainly determine and affect the choosing procedure of the suitable communication technology and the network architecture in the system. In addition, the selection and minimum requirements for the ICDs and communication technology in the LVDC system are defined by the LVDC SG functionalities. At the moment, the communication network is IP-based and implemented with multi-core optic fibre between the GC and CEIs, and installed next to the UGC DC network. The communication interfaces in this case are Ethernet switch at the GC, which comprise Ethernet-to-fibre slots, and Ethernet-to-fibre converters at each CEIs. The ICD at the GC and each CEI are implemented with Linux-based EPCs, and those are interconnected through the UG optic fibre network. The LVDC ICT system is illustrated in Figure 2.

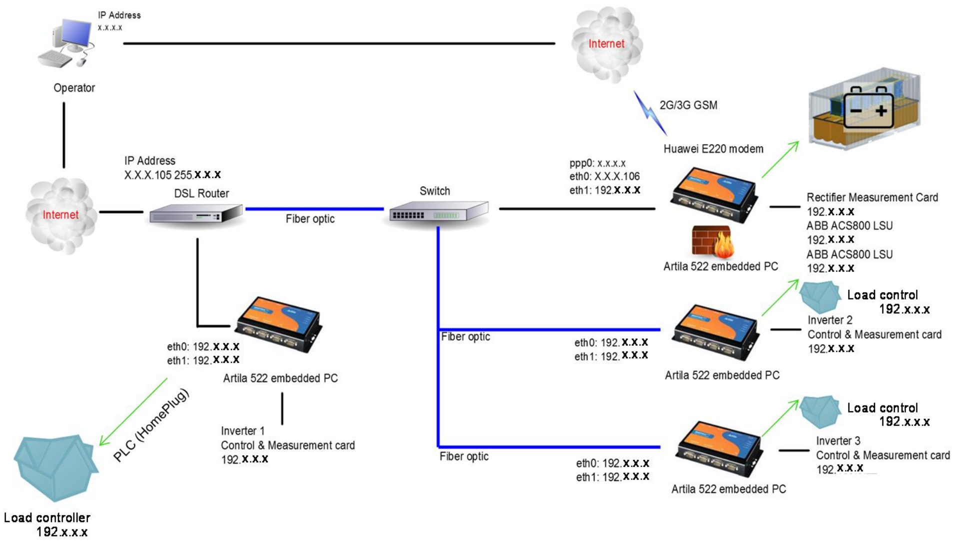

Figure 2. Communication network architecture and ICDs in the LVDC research site.

2.2 Information flows

The flexible and highly reconfigurable platform for testing and comparisons of ICT technologies and concepts in real smart distribution network environment was one of the aims in the LVDC network research site development. The EPCs based on open source Debian Linux distribution and efficient ARM processors are used for ICT system implementation. This forms flexible environment for efficient application development using open source GNU toolchain. The applications can be written, for instance, using C and Python. The web portal, for instance is powered by open source licenced and efficient, secure lighttpd web server. The availability of the open source protocols, such as CANopen and Modbus/TCP, and drivers and libraries, for instance SocketCAN and libmodbus, improve the connectivity with third party devices connected to the network.

The Linux-based EPCs and Ethernet-enabled DSP-based measurement cards in the CEI form flexible solution for measurement data acquisition, storage, processing, and transfer [4]. The CEIs of the research site imply measurements of voltage and currents on AC and DC sides, which are sampled, by data acquisition solution, at 2 kHz. The corresponding RMS values are calculated for a period of two seconds. Moreover, the DSP measurement card allows additional signal processing, such as FFT, and therefore harmonic content up to 2.5 kHz is calculated. Therefore the instantaneous values, the RMS values and the harmonic content are transferred from the CEI DSP to the EPC for further processing. On the EPC power quality indices according to IEEE 1549-2010 are calculated. The data is transferred to network master EPC (Figure 1), for storage and reporting on the network web-portal. The master EPC, which is located on the GC, imply similar to CEI functionalities. The measuring point of the voltages and currents are the GC DC and AC sides on both poles of bipolar LVDC network. The instantaneous and RMS values, and FFT spectrums are transferred to master EPC for processing, storage and reporting.

To implement data transmission over Ethernet, the custom protocol, based on fixed size TCP/IP packets, is developed. The protocol is designed to meet the physical link bandwidth. In a case of the LVDC research site, the measurement card DSP serial communication interface limits the payload side and the sampling data rate of the instantaneous values. Therefore instantaneous measurement data transmission rate is set to 2 kHz. The protocol datagrams and those sizes are overviewed in Table 1.

Table 1. Application protocol datagrams in the DC grid between the EPCs in the GC and CEIs.

Name	Payload size, bit	DSP SCI stream, bps	Maximum throughput, bps	Ethernet TCP/IP frames, bit	TCP/IP Ethernet stream, bps	Transmission rate
Inverter control card datagram	384 584 16 480	777 408	921 600	592 792 16 896	1 194 032	2 kHz 2 Hz 0.5 Hz
Rectifier measurement card datagram	448 608 16 448	905 440	921 600	656 816 16 864	1 322 064	2 kHz 2 Hz 0.5 Hz
Client control datagram	80		921 600	576	1 152 000	2 kHz
Client application datagram	872 16 472		100M	1080 16888	2 168 444	2 kHz 0.5 Hz
Server control datagram	88		100M	576	1 152 000	2 kHz

The instantaneous data is buffered at the CEI EPCs. On fault, 2 kHz sampled five seconds measurement window containing instantaneous values of the voltage and current on DC and AC sides of the CEI, is saved on local storage. Therefore, recording of high-resolution waveforms before and after a fault is implemented. The fault data is consolidated on the master, script engine is taking care of transferring the fault data over SFTP protocol. The described measurements with the statuses of the connected devices are presented on the web-based portal of the LVDC system, which is monitoring the system functionality. Furthermore, the web-based portal allows remote control of network connected devices forming remote control functionality. High-resolution measurement data enable fault diagnostics. This allows remote diagnostics of the LVDC network behaviour. Power quality monitoring on the DC network improves possibilities of the LVDC network condition monitoring. Furthermore, power quality monitoring functionality deliver power quality indices according to the IEEE standard 1459-2010 for single-phase loads in the customer-end LVAC networks, and enable power quality monitoring. Moreover, this allows nonintrusive customer load identification.

DR functionality on LVDC network, especially control over customer loads, is feasible, due to the bidirectional communication between CEI and network master unit. Moreover, the battery energy storage system (BESS) integration on the DC network will further improve this functionality. However, due to the nature of LVDC system as a prototype and test setup, the ICDs and data signals over the communication network could be enhanced and optimized. Moreover, the present LVDC ICT system only covers the DC grid, but due to the structure of the LVDC system, the communications and ICDs are also required in the CEI-fed AC grids. Thus, to consummate the ICT system with complete coverage on the LVDC system it is required to extend the network on the CEI AC grids. In addition, elementary ICD, such as microcontroller (μC) is needed inside each customer premises. This is necessary for customer load control and AMR data as a part of DR and DSM.

3. IMPLEMENTATION OF ACI IN LVDC SYSTEM

3.1 Intelligent controlling devices and communication network architecture

Based on the features of the SG functionalities that are and will be implemented on the LVDC system, the selection of ICDs, and the communication technology and network for the LVDC grid ends can be determined. As initial background information, the communication network in the customer-end AC grids and for the DG units is proposed to be IP based as the communication network in the DC grid, and between the LVDC system and the web portal. This would provide the extendibility and compatibility, and straightforward interconnection between the SG applications and communication networks in the DC grid and in the customer AC grids. Furthermore, the first requirement for the ICD, which will be implemented on the customer utility box for load control in the customer-end AC grid, is that there has to be an Ethernet port. In addition, with this architecture, each CEI forms an IP subnetwork under it, while the IP-based network between the CEI and the rectifying bridge GC on the DC grid is the main IP network. For the interconnection between the main IP network and the CEI subnetworks, an Ethernet switch (ES) is required to each CEI. At the moment, there are EPCs at each CEI, which are equipped with two Ethernet ports, of which other is reserved for the connection to main IP network in the DC grid, and the other for connecting the DSP of the CEI (Figure 2) [4]. Thus, additional ES is required to extend and provide the IP-based network to the customer AC grid.

Moreover, for the technical device for implementation of customer load control, for instance, relay controller board (RCB) is one solution; group of customer loads, such as lighting, heating, cooling, boilers etc. are connected to relay output. Thus, load groups can be controlled on or off with single relay outputs. There are several commercial relay control boards available that come with for instance serial ports (RS-232, RS-485 etc.), or with different bus types i.e. CAN, I2C. Thus, the ICD at the customer utility box, which can be simple and low-cost µC inside the customer premise has to have at least one Ethernet port to connect the CEI EPC and one serial port for controlling the customer loads via the relay control board. With this way, load control signals on IP from the remote data bases via the LVDC ICT system to the customer loads can be established. Moreover, measurements have to be carried out inside the customer premise regarding the customer load conditions, including inside and outside, and household water temperatures etc. All the sensor data collected have to be analyzed locally in the µC, or relayed to the CEI EPC via the communication network, where further decisions and actions are made. Thus, these pose some additional interface and calculation performance requirements for the µC. The schematic of the ICT system in the CEI AC grid, including the DC and AC current/voltage measurements by the CEI DSP, and sensor information inside customer property measured by the µC is illustrated in Figure 3. Based on the requirements listed above, the computational performance and memory requirements of the µC inside the customer utility box are modest; simple running program for the functionality and only essential and short sensor data and control messages between the CEI, sensors and the relay controller board.

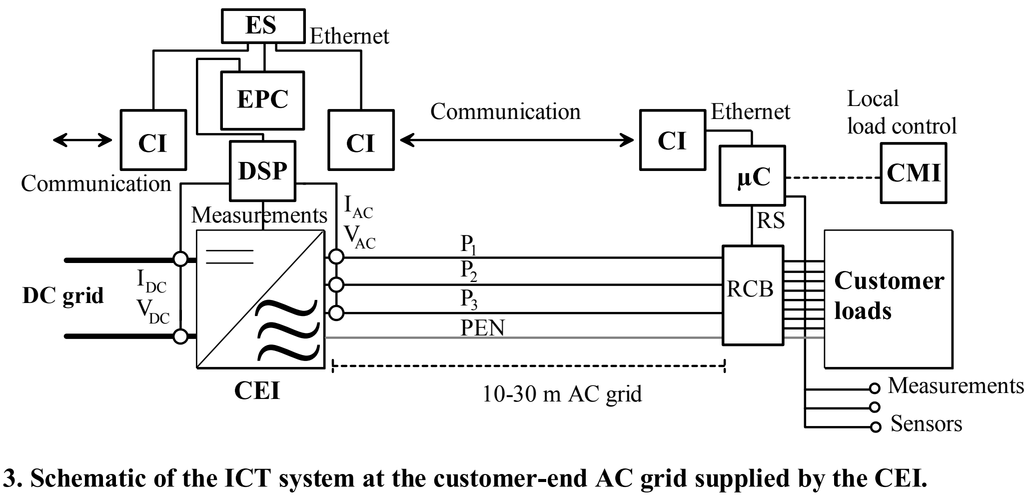

Figure 3. Schematic of the ICT system at the customer-end AC grid supplied by the CEI.

With this ICT system setup, the customer loads are brought under the SG concept as part of DSM and load control. However, some method has to be provided for the customers so that whenever they want they can easily restrict or disable the load control functionality. In the LVDC research site, this can be done through the LVDC web portal; for instance separate web portal with end-customer authorization, where only the loads from the list of controllable loads can be abled or disabled by the customer. In practice, load control by the customer could be provided and executed through some customer-management interface (CMI) (inside the customer premise), which is also used for customer home-automation system integration. The µC connected to RCB could take input from the CMI for instance via wireless or bus connection, as illustrated in Figure 2. Thus, customers can locally and easily change the load control states. This is essential for the flexibility of the SG concept.

Moreover, ICD and communication network are required for the BESS, which is planned to be installed next to the grid converter. Thus, similar EPC as in the GC and each CEI is proposed for the ICD unit and monitoring of the whole battery bank, and it will be interconnected (distance around 5 m) to the GC EPC with Ethernet cable via the manageable Ethernet switch inside the GC [4]. By this way, fast and secure interconnection between the EPCs is achieved.

3.2 Suitable communication technologies

The customer load control application does not require high data rates or low latencies, but is one of the main functionality in SGs. Thus, low-cost, reliable and IP-based communication solution for the customer-end network can be considered as the main requirement. There are low-cost licence-free wireless sensor networks, or wired, such as power line communication technologies available for the home or neighbour area networks (HAN, NAN). Wireless communication technologies for smart grids and their applications are presented for instance in [10], and opportunities and challenges of wireless sensor networks in SGs in [11]. The problem encountered with wireless technologies are the frequency spectrum allocation issues and licence costs, which vary almost in every country. The problem with licence-free wireless frequency bands, such as 2.4 GHz Wi-Fi band, is that the transmission powers are limited, and other applications, which apply the same licence-free bands, can interfere with each other. Furthermore, the wireless signals may have penetration problems, when the customer utility boxes are installed inside at customer premises. All these have a negative effect on the reliability concerns. If wireless solution is chosen, two wireless network transceivers are required to form a communication network under each customer-end AV grid.

Power line communications (PLC) is attractive for and commonly used in smart grids [12]. PLC provides low-cost data transmission medium for SG applications; communication networks exists wherever there is power lines or cables. To form a PLC channel over power lines, PLC modems, as the end devices, and PLC couplers, which separate the PLC modems from, and inject the PLC signal to the power grid. PLC is divided into narrowband (NB) and broadband (BB) PLC by the applied frequency band, of which NB PLC is considered more applicable for electricity distribution systems, especially in the ‘last mile’ connections. Power line communication is proposed, and its applicability as the main communication solution for the LVDC system is studied in [5] and [13]. New G3-PLC compliant NB PLC modems based on ITU-T G.9903 PLC transceivers [14] have been introduced to be used in Europe by Devolo, a leading manufacturer of the PLC technology. Devolo’s G3-PLC modems, which apply frequency band between 150–500 kHz [15], and are EMC compliant with regulations in the European Commission EMC directive [16][15], have been tested in the LVDC field grid between the GC and CEIs [13], and in the customer-end AC grid. According to the data transmission test results, G3-PLC modems are applicable communication technology for the customer AC grid, providing IP-based gateways and access network with low data rates through the AC grid. Two PLC modems including couplers are required to each customer-end AC grid. Thus, NB PLC could one solution for the communication network between the CEI and µC at the customer loads.

3.3 Future ICT development

The nature of the SG applications implemented between the GC and CEI in the LVDC research site, and operated from the GC, such as grid monitoring, is that relatively large amount of data with strict latencies (under tens of milliseconds) are sent between the converters due to the fact that the LVDC system discussed here is a prototype and test setup for LVDC distribution. This is the main reason why the communication network on the DC grid is implemented with optic fibre (OF), which presents high performance, high reliable and interference resistant wideband communication medium [4]. At the moment the SG functionalities between converters in the LVDC field grid rely mainly on the GC EPC (as the grid master) and large amount of data is sent between the converters. However, the EPCs as high-performance distributed intelligence units at the grid ends provide possibility to move into more distributed ICT system, where the communication between the converters could be minimized (only essential control and monitor data), and more SG functionality responsibilities would be distributed to the CEI EPCs. Thus for example, the applicability of the G3-PLC as the main communication media between the converters, and as the base technology of the LVDC ICT system could be tested.

4. CONCLUSION

In this paper, technical requirements for the intelligent controlling devices (ICDs) and communication network in the customer ends of the LVDC system are proposed, completing the whole LVDC ICT system. IP based communication network on the customer end grids, interconnecting the ICDs and providing easy and simple extendibility of the LVDC ICT system is presented. The main technical and performance requirements for the ICDs in the grid ends are discussed. The demands for communication capacities by the SG functionalities integrated on the LVDC field installation system are evaluated. Low data rates without strict latency requirements in the customer AC grid are concluded. Wireless and narrowband (NB) power line communication (PLC) technologies as the communication media for the SG applications in the customer end AC grids are suggested. As future work, to optimize and develop the LVDC ICT system operation, the data transmitted between the ICDs at the GC and CEIs in the DC grid will be compressed and reduced, and the complete LVDC ICT system proposed in this study covering the DC and customer AC grids will be implemented and tested with current DC grid OF network and, for instance with PLC. Thus, the reliability and applicability of the PLC-based network for the proposed LVDC ICT system is tested in practice.

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