Data modelling of converters for the automation and monitoring of MTDC grids

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Abstract: Multi-terminal DC (MTDC) grids based on voltage source converters (VSCs) are a promising option to integrate the increasing share of generation from the distributed energy resources (DERs) both in the transmission and distribution grids. However, in the broader use of VSCs for the transmission and distribution grid, there is an absence of a standardised data model for the VSC. In this work, the authors propose an IEC 61850 based data model for VSCs and an existing IEC 61850 model is extended for the dual-active bridge (DAB) converter as an interlink between various DC terminals and the modular multilevel converter (MMC). Furthermore, a generic data modelling guideline is proposed for intelligent electronic devices (IEDs), which are responsible for the interoperability among converters in the MTDC grid. The implementation of the real-time monitoring system of a hybrid AC-DC MTDC grid with the proposed IED is presented as an exemplary case. Through experimental tests of this MTDC grid, it is shown that the proposed IED meets the latency requirements for P2 through P6 class of monitoring, protection, and control applications according to the IEC 61850 standard. The automation architecture presented in this work is also validated for interoperability within the MTDC grid.

1 Introduction

MTDC transmission is increasingly considered a viable solution for various power distribution applications. In the connection of large off-shore wind farms to the onshore AC grid, they can power for longer distances to multiple connection points on shore [1]. A pan-European multi-terminal HVDC super grid has been proposed to interconnect various European countries and the regions close to their borders [2] to reduce the spinning reserve requirement and the cost of electric power generation. Although there are existing point-to-point connections, there are proposed multi-terminal grids (MTDC) [3] since MTDC configuration offers more flexibility and reliability to the operator due to the bi-directional capability in the converters [4]. The bi-directional flow of power in the converter makes the DC system more flexible because, at the event of deficiency or surplus of power in the electrical network, the power between the nodes is redistributed [1, 5]. However, the power redistribution is only possible, if the converters are interoperable in the DC electrical network or hybrid AC–DC electrical network. Therefore, schemes for automating AC and DC grids are designed so that the converters are interoperable in the same automation architecture.

The smart grid architecture model (SGAM) provides a method to use a structured approach for designing the automation architecture [6]. The SGAM suggests a methodology to facilitate interoperability by dividing an automated grid into five layers. The IEC 61850 standard series is widely used for substation automation, and the standard can be mapped onto three interoperable SGAM layers, which are communication layer, information layer, and a function layer. The IEC 61850 standard series was introduced to facilitate the interoperability of the automation devices, modular expansion, and upgrading of the substation automation design [6, 7]. This is achieved through the standardised data modelling framework and communication services. However, the data models defined in the initial standard series correspond to the components within a typical ac substation. In the later editions, data models for the devices automating the distributed energy resources (DER) control were also included [8]. There have been few attempts to virtualise the converter with bi-directional capabilities based on IEC 61850 standard in literature [9, 10]. Although the authors have used the data model from the existing IEC 61850 standard to represent regulation of dc grids, they have only considered uni-directional power flow. The data model in the literature [9, 10] represents the change of direct current to alternating current using a power inverter, which is represented by IEC 61850 logical node (ZINV) and converting the alternating current to direct current again using a rectifier, which is represented by IEC 61850 node (ZRCT). Although standard IEC 61850 has a logical converter model of an inverter (ZINV) and rectifier (ZRCT), it lacks the bi-directional property required for the converter. A standardised data model of the converter would make converters from different manufacturers interoperable with the control centre and also facilitate smooth integration of DC grid with AC grid since IEC 61850 is an existing substation automation standard for AC grid.

In this study, two converter topologies have been considered for data modelling of a converter: the modular multilevel converter (MMC) topology and the dual-active bridge (DAB) topology. The DAB topology is a DC–DC converter used in MTDC grids for various applications like load sharing, integration of photo-voltaic panels, and energy storage devices [11, 12]. The MMC topology-based converters are AC–DC converters, which are widely used as voltage source converters for HVDC applications [13]. The authors provide the generic design of the intelligent electronic device (IED) for automating the converter operation. The specific extension of the current logical node ZCON for representing the converter controller modes and data models for bi-directional converters (DAB and MMC) is proposed. Further, the data model has been implemented in a laboratory setup for monitoring and control of converters. The laboratory setup consists of four nodes: three nodes are DAB converters and one node is interfaced to the grid with three-level neutral-point clamped (3L-NPC) converter. The demonstrator grid is used to emulate events such as power flow...
2 Substation automation with IEC 61850: background

The IEC 61850 standard series was first designed for the substation automation. It primarily provides the basic data models for all physical components deployed within the substation and DER controllers. The data models facilitate a logical representation of the physical component implemented in the substation. The data model enables a generic microprocessor-based device with standard I/Os, known as IED to host these logical representations of the physical tools. They are hence providing interoperability between all the substation automation devices. The essential functional IEDs are defined as the logical nodes (LNs), and the different parameters required for the function are modelled as the data objects with their attributes. A set of LNs is grouped under a single logical device (LD) instance that is hosted within a dedicated IED. The data modelling structure is summarised in Fig. 1. Each IED could support multiple LDs with multiple LNs, thus enabling the virtualisation of various devices in one IED. The data model of a transformer in a DC–DC converter is depicted in Fig. 2. The transformer is depicted with the logical nodes YPTR along with three data attributes of the transformer such as over-time (OvITm), status value (statVal), and start time (strTime).

Furthermore, the standard also prescribes specific transfer times that the IEDs and the communication infrastructure should comply with the monitoring, control, and protection applications [16]. The standardised communication services are mapped onto specific protocols for notifying emergency status changes, streaming transducer data (from instrument transformers) and regular measurement and control updates. The mappings mentioned above are done onto the generic object-oriented substation event (GOOSE) messages, sampled value (SV), and manufacturing message specification (MMS) protocols, respectively. The MMS protocol service can be used over wide area network (WAN), thus making it a viable option for an AC–DC hybrid grid, since hybrid grids could span over a large geographical area.

The automation architecture for a converter in substation has been presented in [17] and the data models for network topology, switch status, and power flow between the station are described. However, the data models are not used for MTDC applications. Whereas in [18], DERs are automated with controllers, which are not interoperable with other devices. Thus, standard IEC 61850 for MTDC grid provides data models and function templates for information exchange in the substation. The IEC 61850 data model of battery, DER, and parts of the converters has been used to represent automation architecture of the grid. In the following papers [9, 10], the bi-directional converter is represented using inverter represented by ZINV logical node, rectifier represented by ZRCT logical node and the DC measurement represented by MMDC logical node. However, the misrepresentation of the converter data model can be attributed to the standard itself. The latest extension of the standard IEC 61850 7-420 defines data models for different types of power electronic-based converter controllers. However, they specifically address the functionalities of DER management systems, DER generation systems, types of DERs, and their auxiliary systems but the DER in the standard is falsely represented as ZINV and ZRCT. The converter data model and converter applications are currently described in part IEC 61850-90-7, the data models to represent the different operation modes of the DER interfacing ‘inverters’ are defined. However, the data models are defined for specific DER integration for AC grids and they cannot be directly used to represent DC–DC converters (such as DAB Topology) or the AC–DC converters (such as MMC topology) that are used in MTDC grids. The data models currently defined for DER operation are not sufficient to represent the physical topological configuration of the converters and the different control modes that are required for the operation of the MTDC grid, which differ from the standard operational modes of DERs integrated to AC grids.

3 Design considerations for converter data models for grid operation

The converter in a hybrid AC–DC MTDC grid would be responsible for bi-directional power flow between its connected
nodes. Furthermore, the standard control modes of the DERs differ from MTDC-grid converters. The latter must support DC voltage control modes, such as master-slave control and droop control [19]. In order to realise these control functionalities, the converter controllers have to exchange their current operation states either with one another (in distributed control strategy) or to a central controller (hierarchical control strategies). Hence, these operation states have to be represented virtually as data models with the IED interfacing the converter controller, irrespective of the manufacturer of the converter or controller, would enable all converters in the grid interoperable. The requirements for the detailed design of the data models are discussed in the upcoming sub-sections.

3.1 Specifications of converter control in MTDC grids

The monitoring of the nodal DC voltage in MTDC grids is necessary for power flow scheduling. The DC voltage measurement also indicates imbalance due to converter surges [19]. The DC voltage can either be controlled with a current-based control or power-based control [20–22]. Thus, the monitoring of the DC voltage is necessary as the voltage varies with changes in the power flow in the DC grid. The basic control scheme strategies and the parameters are briefly explained below. The logical node in the IED would incorporate these parameters as data attributes:

i. **Voltage Droop Control**: The DC voltage droop control scheme for DC networks is equivalent to the frequency droop control principle in AC grids, where the load-dependent frequency variation is used as input signal in the control system to adjust the power. The converters adapt their active powers set points simultaneously to regulate the DC voltage according to their droop characteristic. There are two droop control approaches, which are voltage-current (U-I) and the voltage-power (U-P) characteristics, represented by (1) and (2). The U-P characteristics droop is advantageous from a system operator viewpoint, since the power flows of each terminal can be directly regulated [22]. The droop constant $K_{dc}$ determines the relation between voltage and current deviations. The variable with subscript 0 represents the set point value i.e. $\Delta U_{dc} = U_{dc} - U_{dc,0}$. $\Delta I_{dc} = I_{dc} - I_{dc,0}$ and $\Delta P_{dc} = P_{dc} - P_{dc,0}$.

The slope of the $I-U$ or $P-U$ characteristic is determined by droop constant $K_{dc}$ as shown in the (1) and (2) below.

$$\Delta I_{dc} = (1/K_{dc})\Delta U_{dc}$$

(1)

$$\Delta P_{dc} = (1/K_{dc})\Delta U_{dc}$$

(2)

ii. **Constant Current/Power Control**: The droop constant equal to infinity, thereby not change the current/power whenever the DC voltage changes. The converter will maintain the current/power injection constant, irrespective of the value of the DC voltage at its DC bus.

iii. **Constant Voltage (Zero Droop Constant)**: The constant voltage control can be represented as a horizontal curve in the $I-V$ or $P-V$. The converter tries to maintain the voltage constant with power injection. It is normally used in with other control modes.

iv. **Master Slave Control**: The master converter maintains the voltage according to the set point. The master converter is referred to as the slack bus, and the slave controllers maintain the complex power constant by absorption or injection at a point of common coupling.

The control schemes above have limited values for individual converters depending upon the control schemes. The limits are essential parameters, which are defined in the logical node as data attributes. The limits of the converter, which are considered in the logical node, are introduced below [19]:

i. **DC voltage limits**: The DC voltage has an upper and a lower limit. The voltage rating of the converter determines the upper limit. The lower limit is more complex as it is based on a limitation of the injection voltage.

ii. **Current limit**: The current range of the parameter depends on the thermal capability of the converter at the different converter components and supports the schemes for both converter and grid protection.

4 Extended IEC 61850 data model for converters

The data models for the DC–DC converter is based on DAB topology since it is widely used in MTDC grids [11, 12]. The data model for the AC–DC converter is based on MMC topology. The MMC topology is predominantly used in HVDC application [13], and the data attribute of the number of sub-modules is necessary for monitoring and control application of the MMC converter. Although in the next section, the demonstrator grid uses 3L-NPC topology-based converter. The MMC data model can be used for the 3L-NPC topology-based AC–DC converter by selecting data attributes from the data model. The ZCON logical node defined in the IEC 61850-7-420 is adopted as the logical base node and is extended with additional data objects. Fig. 3 represents a full physical mapping of the MTDC grid to the logical nodes, where the green depicts the AC grid and blue depicts the DC grid. The different logical nodes for representing the physical components are briefly explained below.

i. **XSWI**: The logical node to represent switches without short-circuit breaking capability, for example, disconnectors, air break switches, and ground switches.

ii. **CSWI**: The logical node used for representing the circuit breaker controller and the switch controller.

iii. **XCBR**: The logical node to represent the circuit breaker.

iv. **MMDC**: The logical node used for representing the DC measurements.

v. **TVTR**: The logical node to represent a voltage transformer.

vi. **VTTC**: The logical node to represent the current transformer.

vii. **LLN0**: The logical node that defines, in particular, the communication objects and the log of the virtual device.

viii. **LPHT**: The logical node to represent the physical device and communication properties, which is identical for all logical devices.

ix. **ZCON**: The logical node represents converter controller attributes, namely the rated power, input and output limits for both current and voltage, power/voltage/current output set points and control modes.

x. **YPTR**: The logical node to represent the power transformer. Especially to represent the high-frequency transformer for DAB converter. This logical node would not be present for IEDs representing the MMC.

xi. **FFIL**: The logical node to represent the different filter configurations.

xii. **PIOC**: The logical node for instantaneous over-current protection.

xiii. **PTOC**: The logical node for over-current protection.

xiv. **XVOC**: The logical node for voltage protection.

xv. **MMXU**: The logical node used for representing the DC measurements.

4.1 Proposed data model extensions for ZCON

In IEC 61850, the logical nodes are further represented with the necessary data attributes. The data attributes are classified according to status information, measured information and control [23]. The classification of the data attributes is termed as common data classes (CDC) in the IEC 61850 standard. The parameters such as control, measurements and current limits introduced in the previous section are represented according to the CDC present in the IEC 61850-7-3 standard. CDCs define the structure and data
type of the data object. The hierarchical data model extensions to represent bi-directional converters are depicted in Fig. 4.

i. **SwHz**: The data attribute represents a nominal switching frequency. It is modelled with data attributes of analogue setting (ASG) CDC.

ii. **PSang**: The data attribute represents the phase angle between the primary and secondary side. The phase angle is an essential factor to be monitored since it decides the direction of power flow in the converter. The data attribute is exclusive for DAB. The data attribute is modelled with data attribute of ASG CDC.

iii. **SubMoCnt**: The data attribute represents the number of sub-modules present in the MMC converter. This data attribute is exclusive to the MMC converter, and it decides the voltage level for the MMC converter. This is modelled with data attribute of ASG CDC.

iv. **PQVLimSet**: The data attribute represents the active, and reactive power curve limits set points. It is modelled with data attributes curve Shaping setting (CSG) CDC.

v. **CtrlMod**: The data attribute represents the control mode for the DC grid control with a value given below. It is modelled with data attributes enumerated status setting (ENG) CDC.
   (a) 0 = Unknown
   (b) 1 = Master-Slave mode
   (c) 2 = Droop control mode
   (d) 3 = Deadband control mode
   (e) 4 = Undeadband control mode
   (f) 5 = Voltage margin control mode

vi. **MsCtrlMod**: The data attribute represents that which converter is the master and which converters operate as slaves. This is notified with a value below. It is modelled with data attributes ENG CDC.
   (a) 1 = Master
   (b) 2 = Slave

vii. **DrpConst**: The data attribute represents the droop coefficients for DC grid voltage-based power sharing between the converters. It is modelled with data attributes of ASG CDC.

viii. **Bndctr**: The data attribute represents, the band for the specific droop control of converters for voltage-based power sharing. It is modelled with data attributes of ASG CDC.

ix. **InDALim**: The data attribute represents the input DC current limit. It is modelled with data attributes of ASG CDC.

x. **InAVLim**: The data attribute represents the input AC voltage limit. It is modelled with data attributes of ASG CDC.

xi. **OutAALim**: The data attribute represents the output AC current limit. It is modelled with data attributes of ASG CDC.

xii. **OutAVLim**: The data attribute represents the output AC voltage limit. It is modelled with data attributes of ASG CDC.

5 **Demonstrator GRID using the proposed IED model**

A laboratory MTDC grid based on voltage source converters is constructed and operated using the proposed IED model. The schematic is shown in Fig. 5 and the picture of the laboratory grid is shown in Fig. 6. The demonstrator grid has a bipolar configuration operated at a voltage of ±190 V. The MTDC grid has four terminals corresponding to four converters as listed in Table 1.
6 Test case and experimental results

The automation platform is based on the IEC 61850 standard and used for monitoring scenarios in the MTDC test grid. The scenarios in the MTDC test grid emulate events in the existing distribution and transmission grids. The scenarios also depict the IEC 61850 conformance testing [14, 15]. The scenarios are classified into two categories according to the IEC 61850 conformance testing, i.e. hierarchy and communication profiles.

The IED has been used to monitor the set points of a single converter in the first scenario. In the second scenario, the phase angle of the MTDC test grid is changed, and two converters in the MTDC test are monitored. The IED has deployed the ZCON data model and it is used to change the set points in the converter and control the direction of the power flow between two converters.

The first scenario shows that the IEC 61850 data model of the converter facilitates interoperability between the converter and the communication between the AIXcontrol router and Merkurbox is with a proprietary protocol.

**Bay level:** The bay unit is responsible for measurement, protection, and control of the substation. In the automation architecture, the IED is responsible for measurement and system-level control function. The IED is implemented on NI-compact reconfigurable input output (RIO) processor (NIcRIO-9024) with driver for IEC 61850 MMS protocol. The NIcRIO is equipped with inputs and outputs for both digital and analogue signals. The MMS server hosts the data models of the DAB converter and facilitates the standard IEC 61850 MMS communication services. The field programmable gate arrays (FPGA) are programmed for synchronous measurement acquisition from the analogue I/Os and asynchronous set-point updates. It is the FPGA that bridges the I/Os of the NIcRIO with the processor. The measurements are read synchronously, which are subsequently associated with the data objects of the MMXU/MMDC logical nodes hosted in the MMS server. Similarly, the control set-point updates made on the data objects of the extended ZCON logical node for DAB are asynchronously read by the FPGA from the processor and appropriate signal outputs are provided through the I/Os. The FPGA programming, the configuration of the MMS server, and the association of the I/O signals to the data objects are done using the Labview interface. Although in this study, the IED-converter is configured as an MMS server, with the substation configuration language (SCL) files defining the data model of the DAB converter. The SCL file is independent upon the hardware architecture since the IED would interact with the external system based on the IEC 61850 data model structure. The automation architecture for monitoring the laboratory MTDC grid is shown in Fig. 7. The IED is containing the logical nodes and ZCON, MMXU and MMDC are deployed in the MTDC grid.

The SCL file defines the automation and interaction of the IED with the external system. The IED is configured as an MMS server, with the SCL file defining the data model of the DAB converter presented in the previous section. The measurements are read synchronously and subsequently associated with the data objects of the MMXU/MMDC logical nodes hosted in the MMS server. Similarly, the control set-point updates made on the data objects of the extended ZCON logical node for DAB are asynchronously read by the NIcRIO, and appropriate signal outputs are provided through the I/Os. The NIcRIO programming, the configuration of the MMS server, and the association of the I/O signals to the data objects are done through the Labview interface. Fig. 8 is an image of the components in process level and bay level connected through the AIXcontrol router.

** iii. Station level:** In the demonstrator grid, the station level consists of a computer with IEC 61850 software package installed, hence the computer functions as an MMS client for the IED in the bay level. The supervisory interface is programmed in Labview. Fig. 9 is a snapshot of the screen.

The AC–DC converter connects the MTDC laboratory grid to the public AC grid and regulates the DC bus voltage in the grid-connected mode operation. The AC–DC converter is a commercial 3L SKiiP28SM107E3V1 Evaluation Inverter from Semikron [24], while the DAB converters connecting the PV and batteries are laboratory prototypes. The DC–DC converter labelled as 2 in Fig. 5 facilitates power injection from the solar panels to the MTDC laboratory setup, meanwhile performing the maximum-power-point tracking (MPPT) for the connected photovoltaic (PV) panels. The DC–DC converter 3 in the diagram is connected to a battery. It is responsible for the charging and discharging of the battery emulating a flexible energy storage system. The data attributes PSang represents the bi-directional flow of power since the bi-directional power flow cannot be monitored with the existing logical nodes. The DC–DC bus converter 4 is connected to either passive or electronic loads. With this MTDC demonstrator grid, connected operation and islanded mode operation, can be tested.

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Topology</th>
<th>Power rating, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AC–DC converter</td>
<td>3L-NPC converter</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>DC–DC MPPT converter</td>
<td>DAB</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>DC–DC battery charger</td>
<td>DAB</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>DC–DC bus converter</td>
<td>DAB</td>
<td>2</td>
</tr>
</tbody>
</table>

**Table 1 Overview of the MTDC grid**

Fig. 6 Picture of the MTDC grid

The automation structure for the MTDC laboratory grid has been developed according to the IEC 61850 compliance tests, which would be tested in the next section. According to IEC 61850-9-2, the substation is divided into three distinct levels:

1. **Process level:** The local control of the converter is done by an FPGA-based controller, Merkurbox from AIXControl. The Merkurbox converts the analogue quantities to digitalised quantities. The communication between the Merkurbox and the bay level is through a FPGA-based AIXcontrol router. The...
The second test scenario shows that the IEC 61850 data model provides a standardised communication platform between two converters for bi-directional power flow.

6.1 Vertical interoperability in demonstrator grid

In the MTDC grid, the AC–DC converter needs to regulate the DC voltage [25, 26] at the respective DC-link to control the power flow between the nodes. The voltage regulation of multiple nodes should be possible from a remote control centre by setting corresponding set points. The scenario exhibits a client-server profile-based interoperability test since there is a pre-existing process bus LAN connection between the IED and the converter controller. The scenario also shows that the automation architecture is vertically interoperable between devices at the bay level and station level. The scenario highlights the importance of standard data model in a MTDC grid, where multiple converters are required to be monitored at the control centre. The data attributes, such as SwHz, PQVLimSet, CtrlMod, MscrtMod, Drpconst, OutWSet, OutDVLim, InDALim, and OutDALim, are sent by the IED to the control centre for monitoring, where the IED is configured as an MMS server, and the control centre is the MMS client. The set-point voltage is sequentially stepped down and stepped up at the DC-link. Initially, the MMS client monitors the data attributes until a default set-voltage of 380 is reached at 7.20 as seen in Fig. 10. In Figs. 10–12, $U_{dc}$ is the measured DC voltage obtained from the logical node MMDC, and OutDVLim data attribute is the reference voltage from the control station. In the voltage step-down process, the output DC voltage limit, OutDVLim, is changed from 380 to a new reference voltage of 360 at the DC-link. The change in the DC-link voltage is realised in 48. The voltage step-down scenario is plotted in Fig. 11. In the voltage step-up process, the output DC voltage limit, OutDVLim, at AC–DC converter is 360, and a new reference is set from the MMS client, which changes the voltage to 380 at the converter. The voltage step-up in the DC-link voltage is realised in 47. The IED collected measured voltage at the DC-link and plotted in Fig. 12. The horizontal interoperability tests are plotted in Labview without the graphical interface as seen in Fig. 10. The proposed IED in the automation architecture has a transmission delay of <10. The transmission delay according to section 11.1.3 from IEC 61850-5 considers acquisition delay and processing delay within the LAN infrastructure. Furthermore, the standard classifies the power system applications into six transfer time (TT) classes according to their latency. The transmission latency of the automation architecture is compared with the six TT classes in the standard, which is a common practice for newly proposed IEC 61850 architecture [18, 27, 28]. Since the automation architecture has a transmission delay <10, the data model can be used for TT5, TT4, TT3, TT2, TT1, and T0 applications, such as status changes, fast and slow automatic interactions, and operator commands.
Conclusions

One of the primary functions of a DC–DC converter is bidirectional power flow between the connected nodes. In a DAB, the power is regulated by changing the phase shift angle between the primary and the secondary side of the converter [13, 29]. The bi-directional power flow scenario shows that the automation architecture complies with peer-to-peer interoperability test and horizontal interoperability test. The scenario consists of a point-to-point virtual connection over the process bus Ethernet LAN. The architecture complies with peer-to-peer interoperability test and horizontal interoperability test. The scenario is also an example of devices connected at bay level communicating via peer-to-peer profiles.

The AC–DC converter 1 (Table 1) performs a voltage source converter. The set-point reference power of the phase shift angle (PSang data attribute) of the DC–DC converter is changed from 0 to ±30°, which indicates charging or discharging of a 48 battery storage system with the power flow of 0, 1.5, and −1.5 during load changes. The DC-link voltage is regulated 380 with disturbances ±5 V during load changes.

7 Conclusions

To ensure interoperability of the converters in the MTDC grids, the authors present a generic modelling scheme for the IED-converters. Furthermore, IEC 61850 data model extensions have been suggested for incorporating converters such as DAB and MMC topology in MTDC grids. The proposed IED-converter is implemented with Ni-cRIO from national instruments. A real-time monitoring platform employing IED-converter with other IEDs for AC grids is set up. Furthermore, the latency characterisation of the measurement acquisition chain is presented. The results show that the IED could meet the latency requirements of P2 to P6 class of monitoring, protection, and control application.

8 Acknowledgment

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9 References

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Fig. 12 Zoom-in of the sent reference value and collected measurement value of the DC-link voltage at the IED during a step up

Fig. 13 Measured DC-link voltage and ac grid current during load power step changes

6.2 Horizontal interoperability in demonstrator grid

One of the primary functions of a DC–DC converter is bidirectional power flow between the connected nodes. In a DAB, the power is regulated by changing the phase shift angle between the primary and the secondary side of the converter [13, 29]. The bi-directional power flow scenario shows that the automation architecture complies with peer-to-peer interoperability test and horizontal interoperability test. The scenario consists of a point-to-point virtual connection over the process bus Ethernet LAN. The change of phase angle at a node triggers a shift of power flow in the other node. The scenario is also an example of devices connected at bay level communicating via peer-to-peer profiles.


