Interoperability and Interchangeability for Microgrid Protection Systems using IEC 61850 Standard

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***Abstract*—Microgrids have been proposed in an effort to handle the impact of distributed generators (DGs) and make conventional grids suitable for large scale deployments of DGs. However, the introduction of microgrids brings some challenges such as the protection of a microgrid and its entities. Due to the existence of generators at all levels of the distribution system, the fault currents vary substantially. Furthermore, grid connected and islanded modes introduce two different sets of fault currents. Consequently, the traditional fixed current relay protection schemes need to be improved. Several adaptive protection schemes have been developed in the literature. These protection approaches, despite addressing protection challenges, require extensive communication and control. In order to achieve a standard way of modeling this communication infrastructure power engineers have been using IEC 61850 and its extensions, such as IEC 61850-7-420. As a result, it has been found out that several concepts such as interoperability and interchangeability have to be considered in networks designed with IEC communication standards. This paper studies the modeling structure in IEC 61850 standard and some challenges associated with it. Then, IEC 61850 based modeling of a novel adaptive microgrid protection scheme is given in detail. The challenges and potential pitfalls related to virtualization of power system in IEC modeling world are analyzed. Finally, some insights are shared on the required steps that shall be taken to unleash capabilities of microgrids in current smart network era.**

***Index Terms*— Substation Automation, Communication in Power Networks, Smartgrid Communications, Adaptive Protection, Plug and Play in Smartgrids**

I. Introduction

It is a known fact that rising penetration of DG does have adverse impact on the grid structure and its operation. The microgrid concept is a solution proposed to control the impact of DG and make conventional grids more suitable for large scale deployment of DG [1]. Microgrids are capable of coordinating and managing DGs in a decentralized way, thus reducing the need for the centralized coordination and management of such systems.

Dynamic behavior of microgrid components makes it hard to design a traditional management strategy. Moreover, microgrids are intended to expand and receive new deployments. This also requires novel management strategies, including automation. Protection of microgrids is one of the fields that require a thorough revision, since the traditional protection schemes tailored for passive power networks with high inertia are not valid for active microgrids which are likely to change more often [1]. Consequently, new adaptive protection schemes have been proposed, which track the state of the microgrid and adjust protection parameters [2, 3].

This highlights the need for of reliable communication infrastructure coupled with the power grid. A standard approach is required since it is possible to find many different types of DGs, interconnections, electronics interfaces. There are several standardization and universalization works performed by several bodies. The ultimate objective is to standardize certain aspects of DGs and microgrids while there is no technology or design constraint stipulated to hinder the versatility of these concepts [4].

Microgrids will become more complex with the introduction of communication devices and systems. For this reason, International Electrotechnical Commission (IEC) IEC61850 released in 2003 for the first time a communication standard for a substation automation system, and in the same token, it has been used for other purposes [5]. With a vision of controlling DGs it has been extended beyond 10 years. The first release, IEC 61400-25 was about the communication in wind power. Two more extensions IEC61850-7-410 [6] on hydroelectric power plants and IEC61850-7-420 [3] on DERs logical nodes have also been published.

The wide-spread acceptance of IEC61850 was hindered by practical issues such as interoperability and interchangeability. This stems from the fact that IEC61850 limits the number of mandatory data objects and attributes; and it gives the freedom of selection of implemented services to the supplier of the device [7]. This is done to support innovation and flexibility but the downside is challenging nature of interoperability. Consequently, although it is promised by IEC61850 standard, interoperability is far from being granted and stands as a block for the wide-spread acceptance of the standard.

Based on the afore-mentioned facts this paper focuses on the implementation of IEC61850 in adaptive microgrid protection systems and the associated challenges such as interoperability and interchangeability. The organization of this paper is as follows: Section (II) gives an insight about multi-vendor equipment and plug and play (PnP) in power grids; Section (III) details an adaptive protection system and its modeling with IEC standards. Section (IV) gives the developed PnP framework and Section (V) draws the conclusions.

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II. MULTI-VENDOR EQUIPMENT AND PNP IN SMARTGRIDS

Traditional electrical networks include equipment manufactured by different vendors. Some may belong to the same manufacturer yet carry different model numbers and features. Therefore, it is very important that the communication between this equipment is sustained for proper operation of microgrids. However, the large majority of power grids have been turn-key solutions from one vendor with maximum one IED from another manufacturer. Major vendors have set up their system verification centers. However, the know-how built up in this manner is exclusive to the major vendors and independent system integrators have no access [8].

Consequently, the endeavor to use IEC61850 based multi-vendor networks requires users to become experts of this standard. This is due to the fact that although IEC61850 standard promises interoperability between devices from different vendors, it does not guarantee it. As it will be explained in the next section, ambiguous definitions in the standard lead to issues in interoperability.

A. Plug-and-Play Concept in Smartgrids

Plug-and-play (PnP) has been implemented in communication and computer networks where a device, most of the time, can be connected to the network and operate without any preliminary arrangements. Considering the active and ever-changing nature of microgrids, PnP is highly desirable for power network elements. This necessitates achieving interoperability between these elements which are manufactured by several manufacturers. Interoperability means the ability of two or more IEDs from different vendors to exchange information and use that information for correct execution of specified functions. Interoperability is not a simple data transfer; it realizes information exchange between two or more devices of similar intelligence. It is required that the receiver understand the syntax (structure) of the data as well as its meaning which corresponds to the semantics in the context of the process and of its tasks. In some cases it may be possible to replace a device supplied by one manufacturer with a device supplied by another manufacturer without the need to make any changes to the rest of the system. This is called interchangeability [7].

Although sustained interoperability in power utility communication is the main objective of IEC61850, the truth is that certain factors prevent this from happening. Majority of the users expect that IEC61850 conformant devices should be interoperable without any issues. Contrary to this belief, the literature shows that conformance with IEC61850 standard only reduces the number of interoperability issues, but it does not eliminate them [8]. Furthermore, IEC61850 standard only defines a conformance test in IEC61850-10 [9] but it is silent about what procedures shall be maintained to ensure operability.

It may sound weird to the first-time readers that a communication standard aimed at providing interoperability has some interoperability issues. In order to put this in perspective, it is important to identify the reasons. As shown in Figure 1, the fundamental reason lying underneath is the flexible nature of the standard. Some of the definitions are made in an ambiguous fashion and majority of the attributes are classified as `optional` rather than `mandatory` to support different kinds of devices provided by different suppliers. Therefore, the majority of the Logical Node (LN) content may not exist or may not be mapped. Furthermore, it is not stipulated by the standard which LNs shall be present in a device. As a result depending on the interpretation of the engineers, same IEDs may have different LNs and same LNs may have different data content.

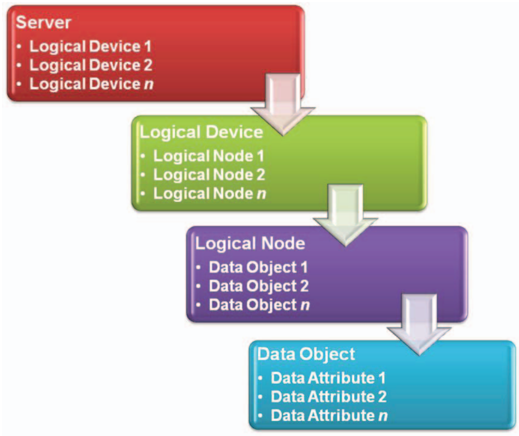

Fig. 1. IEC61850 Data Model

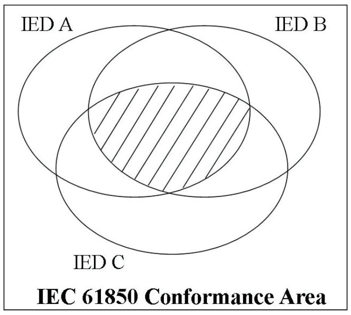

Fig. 2. Representation of Different IEDs in compliance with IEC61850

Figure 2, shows three different IEDs which are modeled in compliance with IEC61850 standard. Non-intersecting portion of each device can be interpreted as an `optional` attribute or function implemented only in that particular IED. The hatched area shows the common conformance area utilized in all of the IEDs. Any attribute or function implemented outside this area would result in interoperability problems between these IEDs, all of which are included in the boundaries of IEC61850 conformance area, i.e. all of them are IEC61850 conformant. The opposite argument is also correct: if the implementation of these IEDs is restricted to the hatched area only, then interoperability would be achieved. Experience gained through some implementations sheds more light on what factors might cause this problem [10].

From the above discussions it is evident that in order to overcome these challenges, a comprehensive interoperability approach is required. This will help end-users select the devices and tools that will be used in a substation for automation, control and/or protection.

III. ADAPTIVE MICROGRID PROTECTION SYSTEM MODELED WITH IEC 61850 AND 7-420 EXTENSION

In order to suit the dynamic structure of microgrids and their versatile operation conditions an alternative protection strategy is proposed as shown in Figure 3. The central controller communicates with every single relay and DG in the microgrid on interruption basis. The communication with relays is necessary to update the operating currents of the relays and to detect the direction of fault currents and thus isolate the fault properly. The protection unit communicates with DGs to record their status as ON/OFF, the rated current IratedDGx and the fault current contribution IfaultDGx. The data map of microgrid controller is as shown in Table I. Each component is stored with the related control variables. The very first variable of the central unit is the operating condition of the microgrid. Once the microgrid is islanded or re-connected to the grid status of the relay R1 is handled as an interruption in the system. New operating fault currents of relays are calculated by considering the fault contribution of the grid, i.e. IfaultGRID and updated.

Distributed generators are monitored and two different current values are stored, accordingly. In Table I, the status of DG3 shows that it is not in operation. This may be due to maintenance, the intermittent nature of RE resources (no sun or wind) or the excess local generation. In case the local consumption increases and DG3 is put into operation, it immediately sends an interruption signal to the central protection unit. The new fault current contribution IfaultDG3 is updated in relay operating currents. Similarly, if DG2 is shut down for a certain reason it will report to the central unit, its status bit will be changed to 0 and new fault current calculations will be performed without IfaultDG2. Electric Vehicles (EVs) are handled as DGs provided that they operate in Vehicle-to-Grid (V2G) mode. In this case, they are treated as inverter interfaced generators with ratings of the inverter. Using V2GModeEVj as a multiplier ensure that only EVs that operate in V2G, and will contribute fault current, are taken into account. For a particular relay the trigger current (the current level that causes the relay to trip) is calculated as shown in Equation (1).

$$\begin{aligned} I_{relay} &= \left(Ifault_{Grid} \times OperatingMode \right) \\ &+ \sum_{i=1}^{m} \left(k_i \times Ifault_{DG_i} \times Status_{DG_i} \right) \\ &+ \sum_{j=1}^{n} \left(k_j \times Ifault_{EV_j} \times V2GMode_{EV_j} \right) \end{aligned} \tag{1}$$

where m and n are the total number of DGs and EVs in the microgrid, respectively; ki and kj are the impact factors of ith DG and jth EV on the fault current of relay; IfaultDGi, IfaultEVj Status and V2GMode are as described above. If the microgrid is operating in islanded mode then the grid's fault contribution will be multiplied with Operating Mode bit which is equal to 0. Likewise the fault contribution of a DG which is not in operation will be annulled by its status bit.

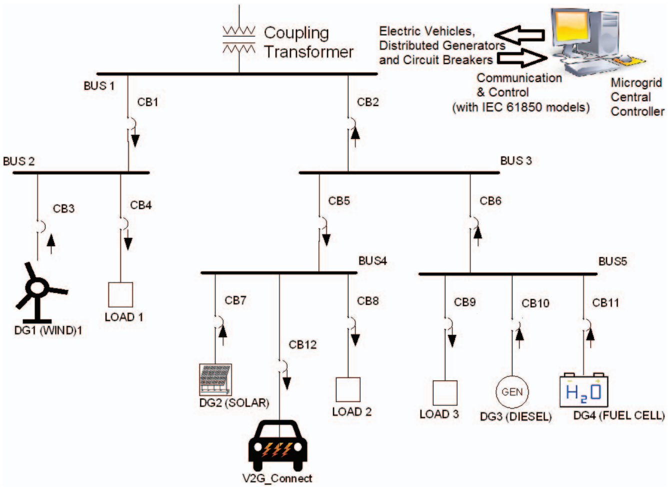

Fig. 3. Adaptive Microgrid Protection System Topology

Table I. Data Maps in the Microgrid Central Controller

	Grid-Connected	Islanded	
Operating Mode	1	0	
Grid Fault	$Ifault_{GRID}$		
Relays	Trigger Current	Fault Detection	Time delay
R1	I_{R1}	0 (No)	t_1
R2	I_{R2}	0 (No)	t_2
R3	I_{R3}	1 (Yes)	t_3
…			
DGs	Irated	$Ifault_{DGx}$	Status
DG1	I_{DG1}	$Ifault_{DG1}$	1 (ON)
DG2	I_{DG2}	$Ifault_{DG2}$	1 (ON)
DG3	I_{DG3}	$Ifault_{DG3}$	0 (OFF)
DG4	I_{DG4}	$Ifault_{DG4}$	1 (ON)
….			
EVs	Irated	$Ifault_{EVx}$	V2G Mode
EV1	I_{EV1}	$Ifault_{EV1}$	1 (ON)
EV2	I_{EV2}	$Ifault_{EV2}$	0 (OFF)
EV3	I_{EV3}	$Ifault_{EV3}$	1 (ON)
…			

In small microgrids it may be assumed that the distances between components are small and the fault contribution of a certain DG will be the same for all parts of the microgrid. In this case the equation may be simplified by taking k = 1. Details of calculating parameter k and time delays, t_{relay}, for proper selectivity can be found in [11]. DG's fault contribution can be determined by means of simulation studies and with experimental work, or assumed to be 1.5 and 5 times $I_{ratedDG}$ for inverter-interfaced and reciprocating DGs. Should this approach be implemented, new DG deployments can be made without making fundamental changes in the protection system. They can be treated as plug-and-play devices once their rated currents and fault contributions are reported to the microgrid central controller.

The central protection unit follows a simple interruption based algorithm. A new deployment or change in "status" and "V2GMode" signals, new fault currents sent to relays. Relays operate independently to open the connections. Once the current flowing over the relay exceeds the trigger current relays sends a signal to set the fault detection bit (as R3). If the fault is not cleared by any other relay inside the delay time, i.e. t_{relay}, that particular relay opens the circuit to isolate the fault (in the diagram R1). These time delays are set to ensure proper selectivity in the system. Obviously central relays such as R1 and R2 have larger time delays than those of located in branches such as R4 and R8. In complex systems time delays may be rearranged and updated in relays along with operating fault currents.

A. Modeling in the Communication World

In this section, the components of the proposed microgrid system have been modeled by using the LNs defined in the IEC 61850 and its recent extension for DERs IEC 61850-7-420. Initially, relays and distributed generators have been modeled by equipping them with communication modules which are essential for the realization of the proposed scheme. Detailed explanations of the models can be found in [3] and [12], this section only focuses on parts related to protection system. Figure 4 shows the new model designed for relays. It shows how the various appropriate functions for the relay could be modelled using the LNs proposed in the IEC 61850 standard.

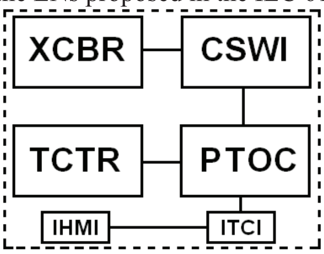

Fig. 4. Relay LD incorporating various functions modeled with LNs

In the relay model, *IHMI* and ITCI provide the interface for remote control and communication purposes. According to the proposed protection systems, there are two key parameters for the proper operation of relays: operating fault current I_{relay} and the time delay for selectivity t_{relay}. Once these parameters are calculated by the MCPU, they are sent to each individual relay through *IHMI-ITCI* interface. These critical values are stored in *PTOC* which detects AC over-current flow in a predetermined direction. Therefore, the detection threshold I_{relay} is stored in *PTOC*. The time delay t_{relay}, which represents the delay applied on detection signal sent to *CSWI*, is also stored inside *PTOC*. *CSWI* is used to send a trigger signal to the *XCBR*, circuit breaker, in case an over-current signal is received from *PTOC*. It is worthy to note here that in modeling the relay, instead of logical node *PIOC*, which detected instantaneous over-current or rate-of-rise, *PTOC* which has the capability to detect fault currents according to their directions, is utilized. This modification is required since fault currents may flow in both directions in microgrids. Furthermore, the relay model is equipped with a remote command and control module (CCM) to update operating fault currents and time delays calculated by the MCPU. This relay model is used for all relays regardless of their positions as load/DG connecting or inter-bus relays.

For a proper communication to be achieved in the network, DGs need to be modeled in accordance with IEC 61850-7-420 and equipped with a communication module which will report the DG status, rated current and DG type. Due to their distinct features each DG type is modeled individually. Figure 5 shows the reciprocating engine and wind turbine (WT) model. In this figure, *MFUL*, *DFLV* represent the fuel characteristics and the delivery system of the fuel. *MFUL* can be set to wind to model WTs. In this section, this structure is used to model DG3, diesel generator, and DG4, wind turbine.

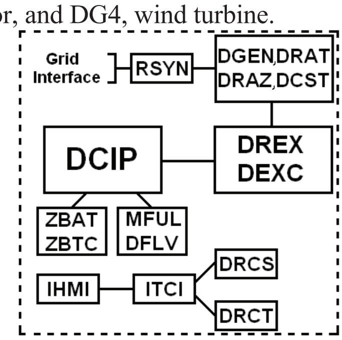

Fig. 5. Reciprocating Engine and Wind Turbine Information Model

The remote communication and control is achieved by *IHMI* and *ITCI* interface. *ITCI* unit is connected to *DRCS* and *DRCT* which represent DER controller status and DER controller characteristics, respectively. The "status" parameter can be extracted from *DRCS*. The data *DRCS.ModOnConn* indicates whether the DG is \`On and Connected\`. When the DG is in operation, i.e. it is ON, and connected, then *DRCS.ModOnConn* is set \`True\`. The data *DRCS.ModOffAval* and *DRCS.ModOffUnav* indicate whether the DG is \`OFF but available to start\` or \`OFF and not available to start\`. In either case the DG will be OFF and will not contribute any fault current. Therefore, if *DRCS.ModOffAval* or *DRCS.ModOffUnav* is set \`True\` it means the D is not in operation. *StatusDG*, the signal which is used to represent whether a particular DG is on or off, can be extracted from values of *DRCS.ModOnConn*, *DRCS.ModOffAval* and *DRCS.ModOffUnav*. This can be represented with the logical expression given in (2):

$$StatusDG = (DRCS.ModOnConn \;\&\; (DRCS.ModOffAval \vee DRCS.ModOffUnav)! \quad (2)$$

DG type, required for fault current estimation, is listed in *DRCT.DERtyp*. It is set to 2 to represent rotating machines so that a factor of 5 shall be used in estimating fault current of the DG. The rated operating current of the DG can be extracted from *DRCT*. *DRCT.MaxWLim* represents the maximum power rating of the generator. From rated current, the fault current can be extracted as in (3):

$$IfaultDG = (DRCT.MaxWLim/\text{Voltage}) * 5 \quad (3)$$

Alternatively, DRAT block might be useful in supplying the fault current of the DG. The two parameters *DRAT.FltARtg* and *DRAT.MaxFltRtg* represent the maximum fault and short circuit currents of the generator. The only drawback is that these parameters are listed as \`Optional\` in the LN, *DRAT*, and may be omitted. The other parameters used above, are all listed as \`Mandatory\` in their respective LN.

Figure 6 depicts the modeling of Fuel Cell and PV panels, DG4 and DG2, respectively. It also shows how the various data, data attributes for a Fuel cell LD can be modelled using the LN models defined in IEC 61850. The major difference between the two, other than their characteristics, is the inclusion of fuel system, *MFUL* and *DFLV*.

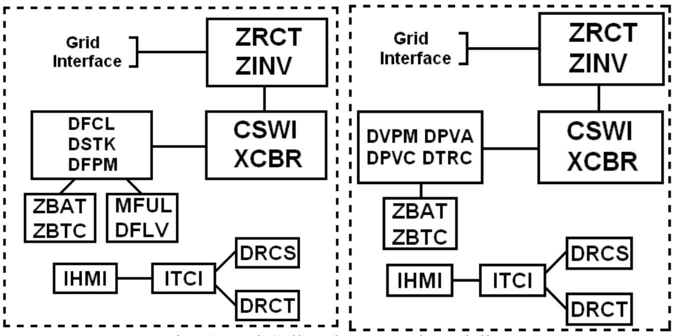

Fig. 6. Fuel Cell and PV Panel Modeling

For both generators, *ZBAT*, *ZBTC* represent the battery, if any, used in the control and/or operation. *CSWI* and *XCBR* represent the DC switch between the fuel cell and the inverter. The inverter which inverts DC input to AC output according to microgrid voltage and frequency requirements and ensures synchronization is modeled with *ZRCT* and *ZINV*. *ZRCT* is used in modeling rectifiers which converts generator output AC to intermediate DC. Properties can be set in detail such as types of commutation, isolation, voltage regulation, conversion (AC-DC, AC-AC-DC, AC-DC-DC), cooling method, AC system and filter types. Furthermore, current and voltage limits can also be set. *ZINV* is used in modeling inverters which converts DC input (either directly from a generator or intermediate DC fed by *ZRCT*) to AC. Properties can be set in detail such as switch type, cooling method, type of commutation, isolation, switching frequency and current connect mode. Furthermore, current and voltage limits can also be set. The remote control and communication module is exactly the same with reciprocating engines. *IHMI* and *ITCI* provide a control interface while critical values are extracted from *DRCT* and *DRCS*. DG status can be extracted similar to the logical expression given in (2).

The DG type listed in *DRCT.DERtyp* is set to 3/4 to represent fuel cell/PV. A factor of 1.5 shall be used for inverter-interface DGs. The rated operating current of the DG can be extracted from *DRCT*. *DRCT.MaxWLim* represents the maximum power rating of the generator. From the rated current the fault current can be extracted as in (4):

$$IfaultDG = (DRCT.MaxWLim/Voltage) * 1.5 \qquad (4)$$

Alternatively, *ZINV* block might be useful in supplying the fault current of the DG. The parameter *ZINV.Wrtg* represents the maximum power rating of the inverter. This value can be used instead of *DRCT.MaxWLim* in (4). This replacement does not improve the accuracy, since the same calculation is carried out, and this parameter is listed as `Optional` in the Logical Node, *ZINV*. For PV, module short circuit current listed in *DPVM*, i.e. *DPVM.MdulSrtCctA*, can be directly used by the MCPU instead of estimation. This improves the accuracy however, the parameter *DPVM.MdulSrtCctA* is listed as `Optional` in the Logical Node, DPVM and it might be omitted for some systems.

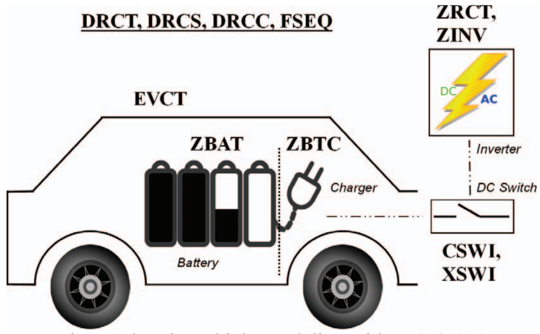

Fig. 7. Electric Vehicle Modeling with IEC 61850

EVs are modeled according to the *EVCT* class developed in [12] as shown in Figure 7. DRCT class is expanded to include EV, ***DRCT.DERtyp*** is set to 6. Fault current contribution is calculated as in (4) since EVs include a battery and an inverter-interface. EVs only give power to the system if V2GMode is ON. This can be extracted from ***EVCT.V2Gstatus=True***. The central controller Data Maps is shown in Table II based on IEC 61850 modeling.

Table II. Data Maps with IEC 61850 Models and Data Attributes

Relays	Trigger Current	Fault Detection	Time delay
R1	I_{R1}	XCBR.Pos = ON	CSWI
R2	I_{R2}	XCBR.Pos = ON	CSWI
R3	I_{R3}	XCBR.Pos = OFF	CSWI
DGs	DG Type	$Ifault_{DGx}$	Status
DG1	DRCT.DERtyp = 2	(DRCT.MaxWLim/Voltage) * 5	DRCS.ModOnConn = True
DG2	DRCT.DERtyp = 4	(DRCT.MaxWLim/Voltage) * 1.5	DRCS.ModOnConn = True
DG3	DRCT.DERtyp = 2	(DRCT.MaxWLim/Voltage) * 5	DRCS.ModOnConn = False
DG4	DRCT.DERtyp = 3	(DRCT.MaxWLim/Voltage) * 1.5	DRCS.ModOnConn = True
EVs	DG Type	$Ifault_{EVx}$	V2G Mode
EV1	DRCT.DERtyp = 6	(DRCT.MaxWLim/Voltage) * 1.5	EVCT.V2Gstatus= True
EV2	DRCT.DERtyp = 6	(DRCT.MaxWLim/Voltage) * 1.5	EVCT.V2Gstatus= False
EV3	DRCT.DERtyp = 6	(DRCT.MaxWLim/Voltage) * 1.5	EVCT.V2Gstatus= True

IV. Interoperability Framework for Adaptive Microgrid Protection System

As explained in section 2, conformance does not guarantee interoperability. To ensure an IEC61850 based power network would function as expected additional steps are required. The gaps caused by the flexibility of the standard and ambiguous definitions thereof shall be double checked. The conformance test stipulated by IEC61850-10 only involves the tested device and the test setup. However, the actual implementation setup in the substation may have impact on the communication interface and its performance. Conformance testing does not fully cover communication latency, time synchronization and performance tests. Considering the excess number of IEDs which conform to IEC61850 standard, the various interpretations by different vendors, possible variations, and interoperability tests shall be handled on project-to-project basis. It is not realistic to suggest an interoperability test which verifies all derivatives of factors causing issues in interoperability.

Accordingly, a full Interoperability Framework has to be implemented which also includes interoperability testing. The test can be based on a model setup and can check interactions between different devices from a single vendor as well as from different vendors. The Framework steps and their objectives are summarized in Table III.

Table III. Interoperability Framework for Microgrid Protection

Step #	Description	Objective
1	Avoiding "Optional" Data Attributes in LNs, prefer "Mandatory"	Minimizing data mismatches between devices
2	Detection of operation limitations by devices such as; i) Only Unbuffered Reports ii) Character limitations in IDs iii) Connection Behavior	Restricted device is bound to have an error while others can operate in both regions, safe operation requires following the limits in the system
3	Proper Documentation of the Model	Proprietary Models are closed and interoperability efforts are blocked. Clear model documentation is required.
4	Equipment Inventory	Detailed inventory includes equipment from same vendor with different model numbers, and equipment from different vendors fulfilling the same task
5	Gradual Integration	Instead of a single step integration of the entire system , step-by-step integration allows for easier problem detection
6	Parameter Extraction	For Adaptive Protection System, 3 parameters are crucial, their extraction from each DG has to be tested
7	Relay Update and Operation	For Adaptive Protection System, 2 parameters sent to relays have to be tested
8	InterOperability Test	Before deploying a new equipment in the system as Hardware in the loop test (HIL)

The important point in this framework is to minimize ambiguous definitions and to document them when they are utilized. In this fashion, it is possible to track them and adjust the system and future deployments accordingly. The operation limitations set by the devices, due to memory or design, can be lethal. The operation parameters, such as GOOSE headers or device IDs, have to be set according to the most restricted device. Documentation of the device models and LN, DA details are crucial to healthy operation in the system. The challenge is proprietary models which manufacturers keep confidential and do not disseminate.

Gradual Integration helps detect errors as they occur while Parameter Extraction and Relay update steps deal with the exclusive operation of the Adaptive Microgrid Protection System explained above. A new deployment or a device replacement has to be preceded by a HIL test where the device is connected to a representative setup for running at least steps 6 and 7. To sum up, the interoperability test should be used as a part of a larger and tedious process. Several steps shall be carefully taken to ensure interoperability of the IEDs in an easy and efficient manner.

V. Conclusions

Microgrids offer novel protection challenges which necessitate implementation of innovative schemes that are adaptive and situation-aware. Communication is indispensable in these schemes to monitor and control. To accommodate different equipment in a single system, standard communication with IEC 61850 is established. This is aimed at achieving a common language in power grid where different devices from different vendors work at the same time. However, ambiguity and flexibility in IEC 61850 may lead to interoperability issues.

In order to investigate these concepts, in this paper, an adaptive microgrid protection system and its IEC 61850 modeling have been given in detail. Furthermore, possible interoperability problems and the ways to mitigate them have been given. When implemented, these will facilitate Plug-and-Play concept in microgrids.

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