Topic #: 14

Nested Microgrids for Increased Grid Resiliency

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Introduction

The article presents a control and communication architecture for interconnecting multiple microgrids by leveraging IEC 61850 data models with distributed energy resources (DER) extensions, IEC Common Information Model (CIM) and Open Field Message Bus (OpenFMB) frameworks. An example use case for planned islanding in the nested microgrid scenario is also provided.

To accommodate high DER penetration, future distribution grids will require numerous interconnections between DER providers, facilities and aggregators, possibly not under utility control, and utility grids. Microgrids provide an attractive framework to achieve this goal, and additionally can deliver grid resiliency in their ability to island from the grid, or by operating as nested microgrids. The term “nested microgrids” is used to refer to an ecosystem of cooperating but autonomous microgrids with points of interconnections to the utility and to peer microgrids. Nested microgrids enable flexible response to natural disasters, as well as the ability to reconstitute the system from the component microgrids, while maintaining at least critical loads served to the degree possible.

Participants in this ecosystem need to exchange information at varying degrees of granularity and under varying assumptions of trust. Information that passes across points of cyber and physical coupling may include state representation, measurements at various points, and dispatch requests. The system should achieve optimal control as composed of numerous distributed control actions of asset dispatch, load management, and islanding while ensuring public safety by delivering secure and selective protection functionality. Interoperability is accomplished by implementing standards for asset self-description that also comprehend dynamic properties of assets, e.g. current state of charge in the case of a battery energy storage system.

Each microgrid service area implements its own stability, protection/control and energy management functions. These functions are implemented by the microgrid control system, which may be centralized or distributed, and is integrated with protection relays and DER controllers. The service area can be completely separated from the main grid, both electrically and from the cyber standpoint. Additionally, each microgrid service area can be further partitioned to pockets or sub-microgrids where individual DER can be preconfigured to operate independently supplying its designated critical loads. The nested microgrid control system must have the intelligence to determine if a system condition has met its sub-microgrid operation condition, and make transitions to the various operation modes as needed considering all possible nested microgrid topologies.

[1] The work described here was performed as an account of work sponsored by an agency of the United States Government with funding from the Dept. of Energy (DOE) under Cooperative Agreement DE-OE0000831. The views expressed are those of the authors. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Microgrid Requirements

This section summarized generic microgrid requirements as outlined in [1] with extensions that are necessary to implement nested microgrids use cases. According to the US DOE definition, a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode and is generally intended to balance supply and demand. It always contains a distribution network which has to be managed.

There are several operational modes of the microgrid or transitions from one to another:

- Islanded mode
- Grid Connected mode
- Transition from grid-connected to islanded mode
  - in emergency/fault situation of the area electric power system
  - in cases of a strategic request (i.e., military microgrid)
- Transition from islanded to grid-connected mode
  - Typically on request through utility SCADA
- Microgrid black start including connection to the grid
- Microgrid shutdown
- Nested microgrids self-healing or reconfiguration function, where the microgrid boundaries may change based on system conditions (e.g., faults)

Dispatch in grid-connected and islanded modes as well as transitions between the two are also covered in the IEEE Standards 2030.7/2030.8 for specification and testing of microgrid controllers [2], [3].

Figure 1 gives an example for the conceptual structure of a microgrid including the basic actors. A key extension is the ability to interface with the peer nested microgrid management system.

Table 1 provides the list of typical use cases as defined in [1] for a single microgrid / DER management system with extensions for a multiple microgrid operation. Basic microgrid use cases are 1 through 8. Uses cases 9-17 are more advanced and may require features that are not available in conventional utility protocols and data models. Using the extended IEC 61850 object models for DER in conjunction with OpenFMB framework mapped to DDS/SDN helps to implement the advanced microgrid use cases.

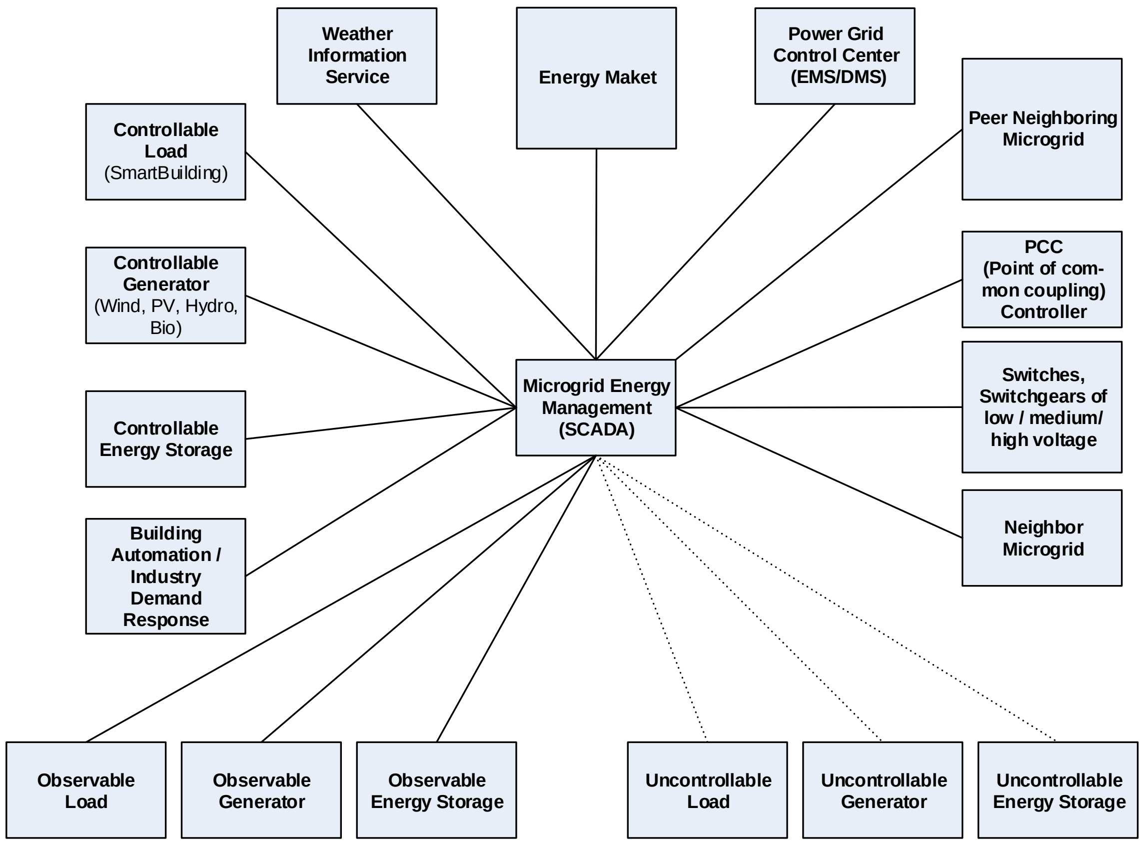

Figure 1 – Nested Microgrids Architecture

Table 1 – Microgrid Use Case List

Use case #	Use case name	Description	Actors
1	Microgrid Monitoring/SCADA - DER status - Measurements - Forecast /history	The DER/microgrid controllers provide information to DER Management System in a spontaneous / cyclic mode and per request.	Microgrid Operator
2	Dispatch	Control generation and loads in a microgrid to maintain stable operation (energy management function), economic dispatch, and in grid-connected mode	Microgrid Operator
3	Exchange of schedules for operation	Exchange DER schedules	Utility
4	Ancillary network and balancing services	Microgrid provides ancillary and balancing services to the utility	Utility
5	Monitoring of power quality information	According to IEEE 1547 power quality should be monitored for responsibility, corresponding to the interconnection agreements	Microgrid Operator
6	Direct control in microgrid	It should be possible to control switches, modes, analog set-points, etc. directly. This includes voltage/frequency control, protection coordination.	Microgrid Operator

Use case #	Use case name	Description	Actors
7	State transitions (islanded/ grid-connected)	Islanding decisions may be given from the operator or may come from the POI device. Paralleling decisions are given by the operator. The microgrid can automatically implement the decision i.e. execute steps like voltage, frequency and phase adaptation and give a signal to the PCC device to close the breaker when all necessary conditions are met.	Microgrid Operator, POI device
8	Black start	In black start use case the microgrid can started from the scratch. Two functions are needed: local black start of the microgrid (leading to island operation) and reconnection to main grid	Microgrid Operator
9	Auto-configuration	When new devices (e.g. DER or intelligent appliances) or sub-systems (e.g. Home/Building Energy Management Systems) are installed in or at the edge of the microgrid they automatically configure themselves (also frequently denoted as Plug & Play). The Microgrid operator can access the devices in a secure and trusted manner.	DER Unit, Microgrid DER Management
10	Registration of DER owned by the DER owner at the Microgrid DER Management	DER owner likes to offer the services of the DER unit (e.g. supplying energy) to Microgrid Operator. Before doing so the DER unit has to be registered at the registry of the Microgrid DER Management. In the registry the technical profile of the DER (performance, characteristics, forecast) will be provided. Access rights are defined based on contractual agreements which define the level of monitoring and control of the DER unit from the Microgrid Management system.	DER Unit, Microgrid DER Management
11	Deregistering	If the DER does not want to be registered in the registry proxy. It stops to provide its services to this microgrid.	DER Unit, Microgrid DER Management
12	Discovery of DER controller for auto-configuration	After registration the VPP/Microgrid operator can access to the registry proxy to search and then to communicate to the devices in a secure and trusted manner.	DER Unit, Microgrid DER Management, Microgrid Operator
13	Discovery of DER in registry proxy	The devices can describe their capabilities to the VPP/Microgrid DER Management and specify their services (performance and power characteristics).	DER unit, DER Management
14	Discovery for DER Management in a secure network environment by broadcast services (no firewall blocks the communication link)	Devices advertise their services to DER Management system. Search functions for control points to find devices of interest (e.g. VPP needs DER with a certain profile, for example independent from weather conditions).	DER Unit, DER Management, Microgrid operator

Use case #	Use case name	Description	Actors
15	Dynamic system management	Software update (firmware / application / configuration data); software version supervision	DER Unit, DER Management, Microgrid operator
16	System Characteristics Exchange	Static and dynamic attributes of microgrid assets such as aggregated capacity, state of charge of battery, and system state estimates need to be exchanged between neighboring microgrid management systems and/or DSO DER Management System.	Microgrid DER management, DSO DER Management
17	Self-healing	Status and control command exchanges between neighboring microgrids to support reconfiguration to accomplish specific operational goals, e.g. improve voltage profiles and minimize losses in normal operating mode, planned islanding or detect permanent faults, isolate and reconfigure the system during disturbances	Microgrid DER management, DSO DER Management

IEC 61850 DER Information Model

The manufacturers of DER devices have developed their own proprietary communication technology and protocols as well as applied traditional point-based utility communications protocols, e.g. Sunspec Modbus or DNP3. However, as utilities, aggregators, and other energy service providers start to manage DER devices that are interconnected in bulk with the utility power system, the different communication technologies present major technical difficulties, implementation and maintenance costs. Additionally, point based protocols do not include any semantic information, making integration of products from multiple vendors rather difficult. Consequently, the need to have a standard that defines semantics-based communication and control interfaces for all DER devices led to the development of the IEC 61850-7-420 standard [4]. This standard defines new IEC 61850 information models that can be used in the exchange of information among controllers of distributed energy resources.

The IEC 61850 semantic model uses the concepts of logical nodes, which are container classes that hold the data relating to one device or function. The semantic models representing DER include Logical Nodes for generation, storage and loads. Generation devices are further classified as photovoltaics, combined heat and power (CHP), reciprocating engines, and fuel cells. The Logical Nodes related to energy storage systems are defined in detail in IEC 61850-90-9 [5]. The IEC 61850-7-420 information model utilizes UML modeling approach and builds on top of the existing IEC 61850-7-4 logical nodes where possible, and also defines DER specific logical nodes as required for the new use cases. Figure 2 shows the different Logical Nodes that are defined in IEC 61850-7-420 Edition 2. This sections provides an overview and a brief description of the DER management logical nodes.

Abstract DER Logical Nodes

The new IEC 61850-7-420 Edition 2 Abstract Logical Nodes are created with the UML class structure diagrams and extensively use generalization and inheritance properties to build a hierarchy from the most basic to comprehensive objects. The Abstract Logical Nodes hold data objects that are common to at least two specific logical nodes, which inherit these data objects. Abstract logical nodes cannot be instantiated, i.e. they may not be used as stand-alone concrete instances in a data model. The Abstract Logical Nodes are briefly summarized as follows, for more details refer to [4].

- **DERResourceLN** defines an identifier DERId of the resource within a system using the resource. Different DERIds may be defined for different system users.
- **DERStateAbstractLN** DER State Machine Logical Node supports the generic DER State Machine interface. The controllable states are on, off, cease to energize, return to service and disconnection during normal and emergency conditions, blocking, standby and test operation modes.

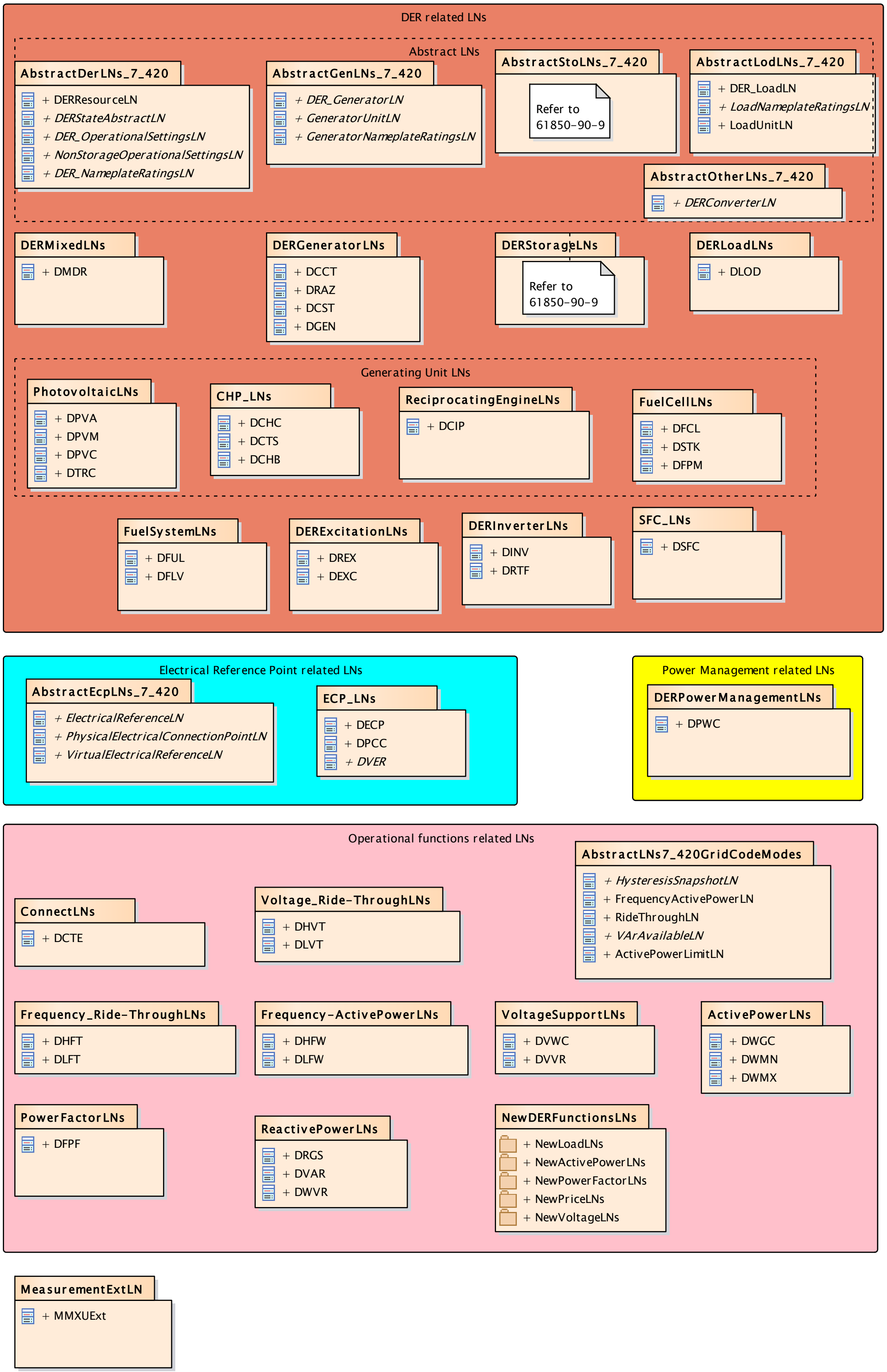

Figure 2 – Logical Nodes defined in IEC 61850 7-420 Edition 2 [4]

- **DER_OperationalSettingsLN** includes the operational settings that apply to any type of DER, including single DER units, aggregated DER units, and virtual DER. Measured and controlled values include among others the available capability, and DER behavior in islanded mode setting used to switch to isochronous control mode in order to control the voltage and frequency, for instance in microgrid operation.
- **NonStorageOperationalSettingsLN** includes the operational ratings for generators and adds setpoints for ramp rates, minimum/maximum voltage operating ranges, maximum apparent and reactive power, as well as reference for reactive power setpoints.
- **DER_NameplateRatingsLN** defines the DER nameplate ratings that apply for all types of DERs, including generators, storage, and load.
- **ElectricalReferenceLN** defines the identity of electrical reference point for the Electrical Connection Point.
- **PhysicalElectricalConnectionPointLN** contains the physical characteristics of the Electrical Connection Point.
- **VirtualElectricalReferenceLN** this ECP abstract logical node contains the operational characteristics of virtual ECPs.
- **DER_GeneratorLN** defines the actual connected and operational state of a DER generating unit, including aggregations of generating units.
- **GeneratorUnitLN** defines available data objects for a particular DER generating unit. It is mostly composed of inherited objects from other classes.
- **GeneratorNameplateRatingsLN** as the name implies defines the generation nameplate ratings for DER of type generator.
- **DER_LoadLN**, **LoadNameplateRatingsLN**, and **LoadUnitLN** are logical nodes related to loads and have the structure that is similar to the corresponding generator LNs. Similarly, these LNs are composed mostly of inherited objects from the base classes.
- **DERConverterLN** is the abstract logical node class holding common attributes of the DER-specific converter logical nodes

Abstract Energy Storage Logical Nodes

These logical nodes are defined in a separate technical report [5], and currently are not part of the IEC 61850-7-420 model. Figure 3 shows the abstract classes diagram for energy storage related logical nodes.

Electrical Connection Point

The Electrical Connection Point (ECP) is defined as a point of electrical connection between one or more DER units and any electric power system (EPS). Usually there is a switch or circuit breaker at this point of connection. There can be more than one ECPs in a DER plant as shown in Figure 4, where ECPs exist between each DER and the local bus (this is also referred to as Point of Connection – PoC), between each group of DER units and the local power system (with load) and between multiple groups of DER units and the utility power system. This terminology is also consistent with the definitions of the revised IEEE 1547-2018 Standard on DER interconnection and interoperability [6].

The new IEC 61850-7-420 edition also introduces the concept of “virtual” ECP that would allow implementing use cases related to Virtual Power Plants.

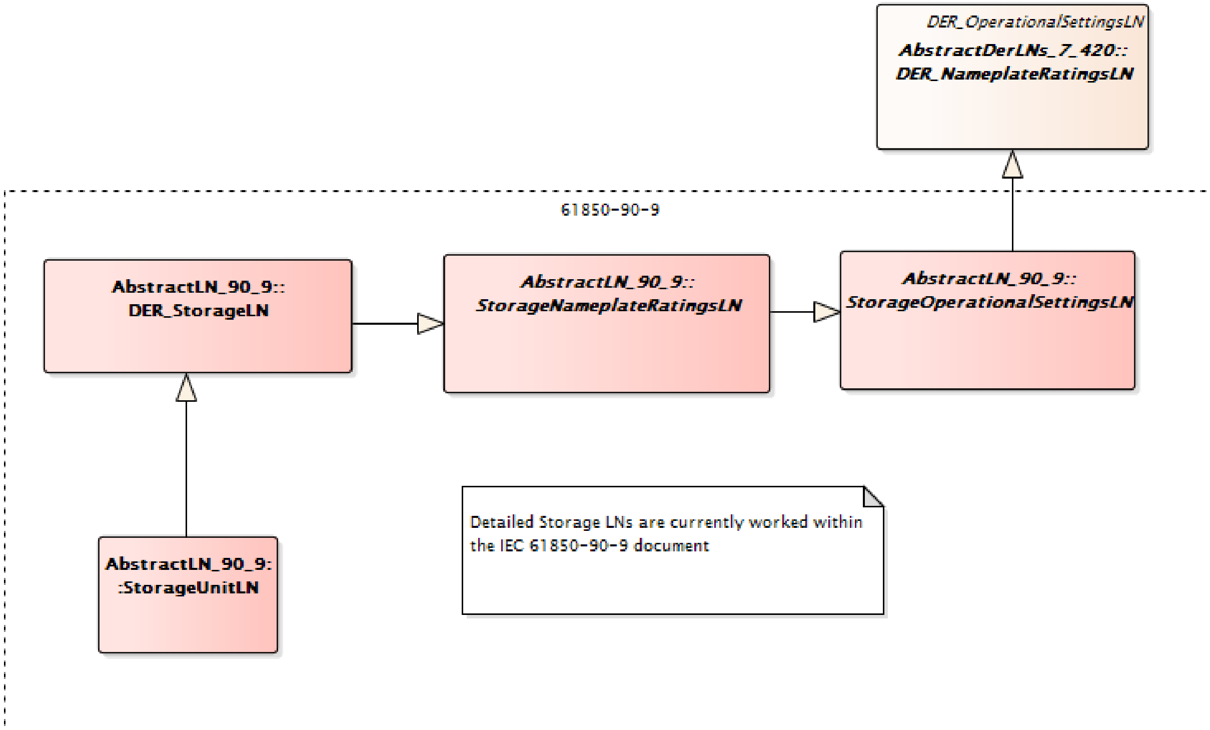

Figure 3 – Energy Storage Abstract Classes [5]

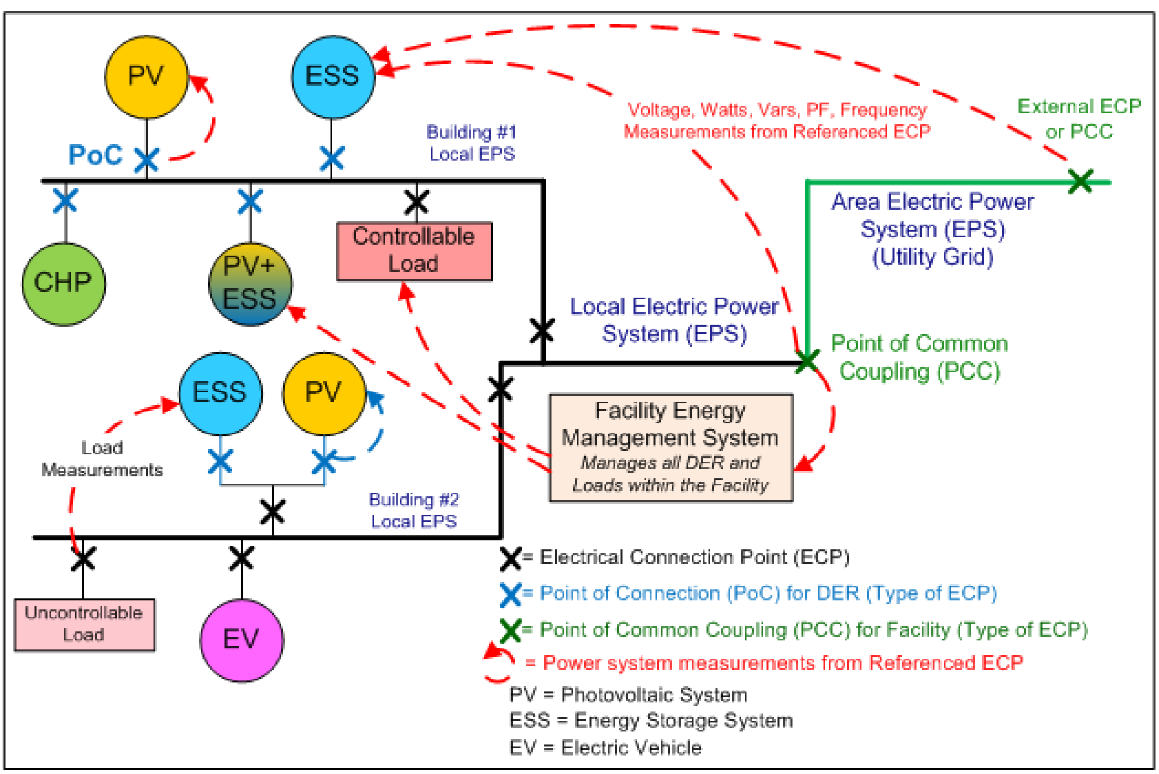

Figure 4 – Electrical Connection Points in a DER Plant [4]

The ECP logical node class defines the characteristics of the DER plant at the electrical connection point (ECP) between one or more DER units and any electric power system including isolated loads, microgrids, and the utility power system. ECP-related logical nodes have changed substantially compared with the first edition and include the following in addition to the abstract common logical node classes, e.g. Functions, Statistics and Domain LN.

- **DECP** models the operational characteristics of the physical ECP including the nameplate, identity, type, settings (nominal voltage, frequency) as well as measurement as pointers to MMXU and MMXN data objects. Note that the specific ECP logical nodes may inherit properties of the abstract ECP classes described in the next section.
- **DPCC** models the point of common coupling and contains the operational characteristics of the Electrical Connection Point between the local EPS and the area EPS.
- **DVER** abstract logical node contains the operational characteristics of the Electrical Connection Point (ECP), including "nameplate" or static information (identity, type), settings (nominal voltage, frequency), and measurements (pointers to MMXU and MMXN data objects). This applies specifically to 'virtual' ECP reference.

Power Management

The power management function is associated with one or more DER resources, electrical reference points, and operational functions within its jurisdiction. A power management function may act as the controller of a single DER, a facility energy management system, a plant management system, a microgrid management system, an aggregator management system, or a utility management system. The power management logical node class is:

- **DPWC** includes requested setpoints for active power reactive power, cease to energize command, as well as references to DER resource, Electrical Reference Point and Operational Functions LNs.

DER Generator

The DER generator logical device describes the generator characteristics of the DER unit or "composed" DER units. The DER generator functional model describes the generator characteristics of the DER unit. The LNs in the DER generator functional model globally inherit abstract LNs. The specific logical node classes defined for the DER generator logical device are:

- **DCCT** provides the data for economic dispatch application, such as marginal operational cost, and cost to start/stop and ramp the DER.
- **DRAZ** defines the DER advanced generator ratings, including dynamic modeling parameters, e.g. transient and sub-transient impedances and time constants.
- **DCST** provides the related economic information on generator operating characteristics/costs.
- **DGEN** defines the actual connected and operational state of a DER generating unit, including aggregations of generating units.

Reciprocating Engine

A reciprocating engine is an engine that utilizes one or more pressure-driven pistons in order to convert back-and-forth motion into a rotating motion. The most common form of reciprocating engine used to generate electricity is the diesel engine, which is used in combination with an electric generator to form a diesel generator. The logical node class defined for the reciprocating engine logical device is:

- **DCIP** reflects the characteristics required for remote monitoring and control of reciprocating engine functions and states

Fuel Cell

A fuel cell is an electrochemical energy conversion device producing electricity from external supplies of fuel (on the anode side) and oxidant (on the cathode side). The logical node classes defined for the fuel cell logical device are:

- **DFCL** reflects those data required for remote monitoring of critical functions and states of the fuel cell.
- **DSTK** models the characteristics of a stack of fuel cells that are stacked together to provide the desired voltage level.
- **DFPM** reflects data objects that are required for remote monitoring of the fuel processing module processing used to extract hydrogen from other types of fuels.

Photovoltaic

A photovoltaic (PV) system which directly converts solar energy into electricity. The logical node classes defined for the photovoltaic logical device are:

- **DPVA** describes the configuration of the PV array. The logical node may be used to provide configuration information on the number of strings and panels or the number of sub-arrays in parallel.
- **DPVM** describes the photovoltaic characteristics of a PV module.
- **DPVC** reflects the information required for remote monitoring of critical photovoltaic functions and states.
- **DTRC** provides overall information on the tracking system.

Combined Heat and Power

Combined heat and power (CHP) covers multiple types of generation systems involving heat in the production of electricity. The logical node classes defined for the combined heat and power logical device are:

- **DCHC** provides overall information of the CHP system, including identification of the types of equipment within the CHP system, usage issues, and constraints affecting the overall CHP system, and other parameters associated with the CHP system as a whole.
- **DCTS** describes characteristics of the CHP thermal storage. This logical node applies both to heat storage and to coolant storage, and is used for measurements of heat exchanges.
- **DCHB** describes the characteristics of the CHP boiler system.

DER Fuel System

The fuel system logical device describe the characteristics of the system of fuel for different prime movers. The logical node classes defined for the fuel system logical device are:

- **DFUL** models fuel supervision including cost, efficiency, etc.
- **DFLV** describes the delivery system for the fuel including flow rate, temperature and pressure

DER Excitation

The DER excitation comprises the components of a DER that handles the excitation systems used to start the generator. The logical node classes defined for the DER excitation logical device are:

- **DREX** defines the DER excitation ratings
- **DEXC** provides settings and status of the excitation components of DER devices

DER Speed/ Frequency Controller

Some DER generators can have their speed or frequency controlled to affect their energy output. The logical node class defined for the DER speed/frequency controller logical device is:

- **DSFC** defines the characteristics of the speed or frequency controller.

DER Inverter/Converter

Some DER generators require rectifiers, inverters, and other types of converters to change their electrical output into grid-ready AC. The logical node classes defined for the DER inverter/converter logical device are:

- **DINV** defines the characteristics of the inverter, which converts DC to AC. The DC may be the output of the generator or may be the intermediate energy form after a generator's AC output has been rectified.
- **DRTF** defines the characteristics of the rectifier, which converts generator output AC to intermediate DC.

EV

The E-Mobility electric vehicle logical node contains information on an Electric Vehicle Supply Equipment (EVSE) and its AC or DC charging information [8].

- **DEEV** is the LN class for showing EV's charging type and charging status (battery, voltage, and process).

Loads

- **DLOD** is the LN class for aggregated loads resources and consists mostly from the objects inherited from abstract classes.

Operational Functions

The new edition of IEC 61850-7-420 also includes an extensive list of Logical Nodes for operational functions designed to be compliant with the grid codes, both European and IEEE 1547-2018 [6]. These LNs are not listed here; for more details refer to [4]. The operational functions covered are as follows:

- Disconnect / Connect Function
- Cease to Energize / Return to Service Function
- High/Low Voltage Ride-Through (Fault Ride-Through) Operational function
- High/Low Frequency Ride-Through Operational function
- Dynamic Reactive Current Support Operational function
- Frequency Watt Operational function (Frequency Sensitivity Operational function)
- Volt-Watt Operational function
- Fixed (Constant) Power Factor Operational function
- Fixed (Constant) Reactive Power Operational function
- Volt-Var Operational function
- Watt-Var Operational function
- Watt-PF Operational function
- Active Power Limiting Operational function
- Active Power Setting Operational function
- Low Frequency-Watt Emergency Operational function for Demand Side Management (fast load shedding)
- Low Voltage-Watt Emergency Operational function for Demand Side Management
- Monitoring key status, alarm, and measurement values
- Scheduling of Power Settings and Operational functions

OpenFMB data model extensions

To achieve field interoperability, a standards-based approach for field communications and data modeling is necessary. While the semantic models for core power system functions as well as DER extensions are offered by IEC 61850 [4], the OpenFMB framework offers an attractive way to enable peer-to-peer field interoperability particularly when interconnecting heterogeneous communication networks [7]. OpenFMB is an architectural framework for distributed intelligent nodes interacting with each other through loosely coupled, publisher-subscriber messaging for field devices and systems at the grid edge. The reference operational logical architecture of an OpenFMB Node, shown in Figure 5, is composed of three major components, namely the application/adapter layers, interface layer, and a middleware layer. OpenFMB Applications are located within an OpenFMB Node and support grid functions by analyzing data and requesting appropriate actions as needed in the specific use case. OpenFMB Adapters are located within an OpenFMB Node and interface the field message bus with end devices. Their role is to map, enrich, orchestrate, route, and translate information between end devices and the field message bus. They provide uni-directional or bi-directional exchange of information between Data Profiles and other protocols and conventional formats, such as DNP3, Modbus, IEC 61850 GOOSE, C12, XMPP, or others.

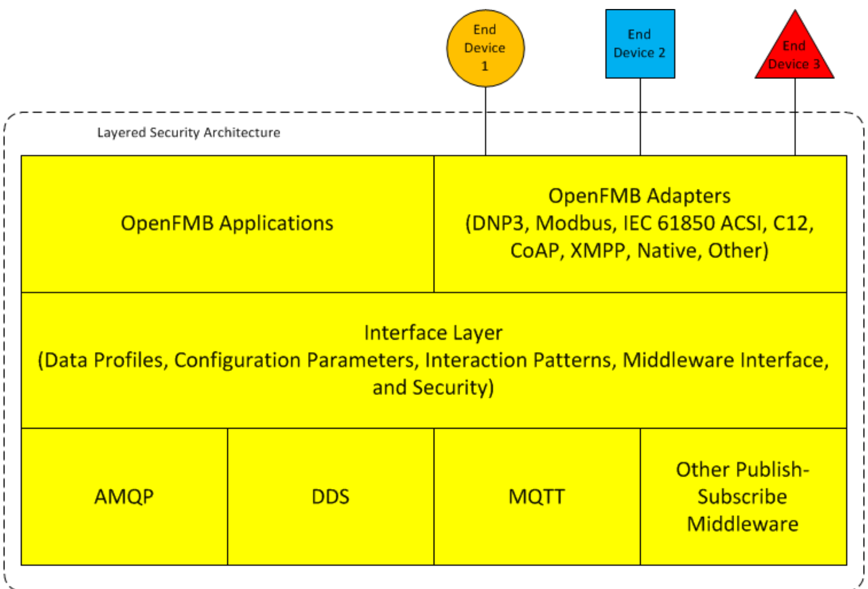

Figure 5 – OpenFMB Operational Logical Architecture [7].

The OpenFMB data model is built on top of the semantic models of IEC 61850, including 61850-7-420 extensions and the IEC 61968/61970 Common Information Model (CIM) components. For instance, Figure 6 shows the OpenFMB profile for discrete breaker control. It is built with the standard XCBR circuit breaker logical node with the attached mRID tags that allow to create unique identifiers for each object.

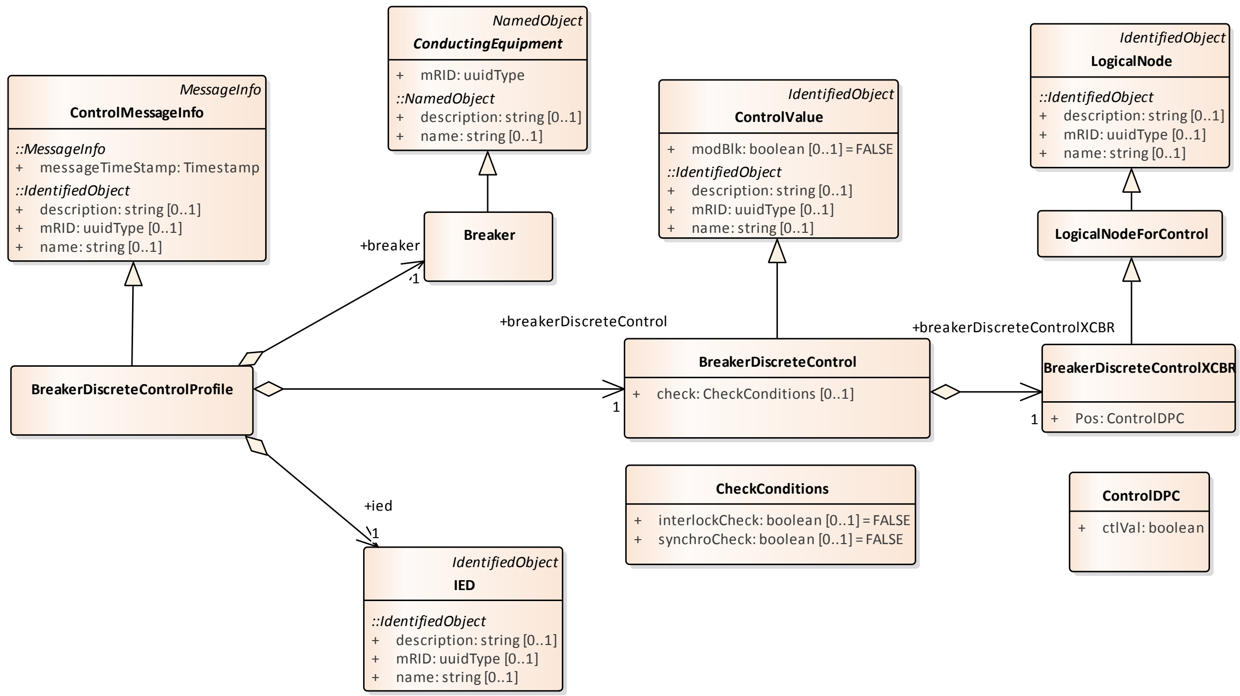

Figure 6 – OpenFMB Breaker Discrete Control Profile.

It also adds ConductingEquipment class from the CIM that allows the breaker status information to be associated with a specific piece of equipment in a network. This capability is very important for mapping the IEC 61850 model to network topology, particularly for multi-microgrid management functionality. This is especially important when the network topology changes dynamically, as with self-healing, reconfiguration and other use cases that support resiliency.

Multi-layered microgrid networks

Based on the microgrid requirements and open standards presented in the previous Section, this Section derives the overall communication architecture for a resilient multi-microgrid distribution system.

Figure 7 shows a conceptual diagram for a nested microgrid system that enables coordinated control through aggregation and integration of multiple microgrids into a utility DMS/DERMS system built on top of open standards described in the previous sections. Note that even though just two microgrids are shown in the figure for simplicity, the assumption is that the same architecture can be generalized to support communication between an arbitrary large number of microgrids. The communication networks can be partitioned as needed by using the Software Defined Networking (SDN) technology. In case of an electrically connected microgrid cluster, the microgrids will operate on the same communications subnetwork; otherwise, they will be operated on different subnetworks with the ability to re-compose the communication network as needed to accommodate distribution network reconfiguration. This architecture adopts and enhances the IEC TC57 WG17 architecture, and also implements the OpenFMB with SDN extensions for Microgrid-to-Microgrid communications.

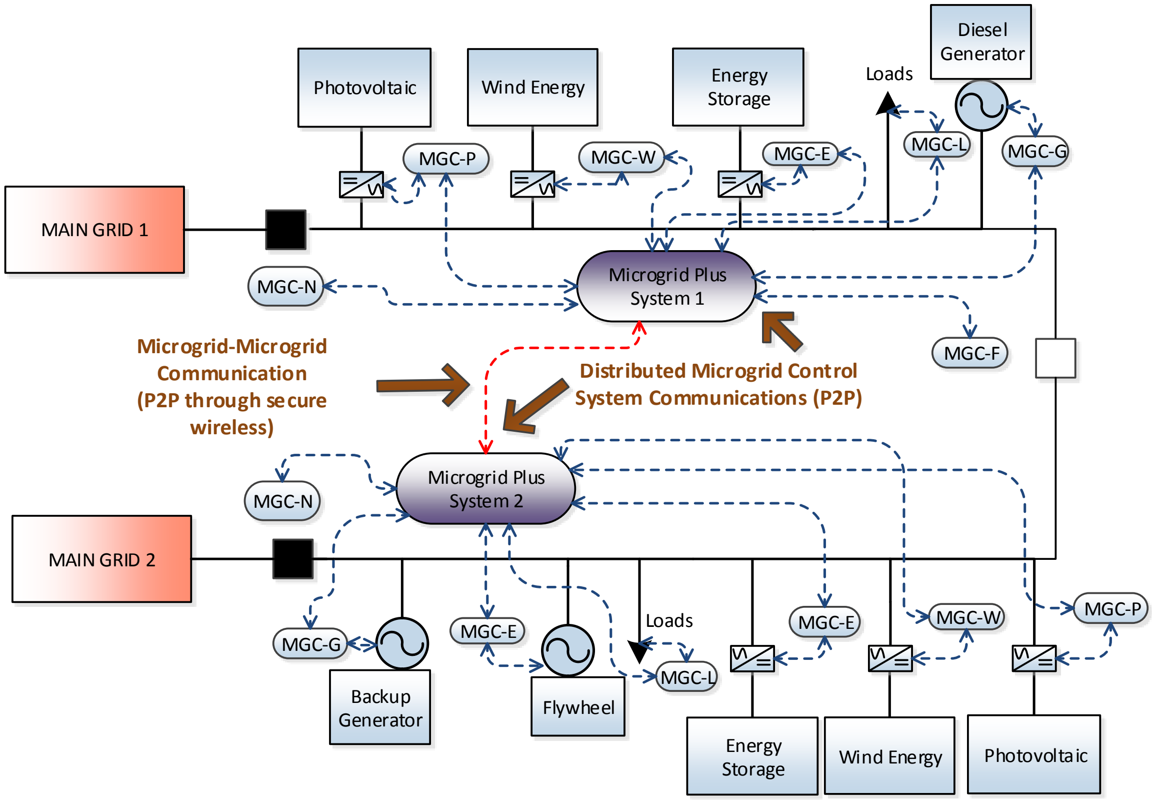

Figure 7 – Multi-layered Resilient Microgrid Network

The example system shown in Figure 7 consists of two medium voltage microgrids connected to two distribution substations in normally open or normally closed loop configuration. Note that for simplicity the DER step-up transformers and protection relays are not shown in this figure. For each microgrid, a Microgrid Plus distributed control system implements the core individual microgrid management functions including DER dispatch, power sharing, intermittency and spinning reserve support, load management, and protection coordination, as well as the other microgrid requirements as specified in the previous section. The Microgrid Plus system consists of a network of MGC controllers, which are supervisory controllers for each DER asset. The distributed architecture is resilient to failure of a single DER/controller. In this setup the MGC controllers of Figure *7* share information with each other via fast peer-to-peer communications, which can be based on IEC 61850 GOOSE or IEC 60870.

Additionally, the individual Microgrid Plus control systems can exchange information with the neighboring microgrid control system through secure wireless communications gateway, e.g., ABB ARG600 4G/LTE Arctic, or TropOS meshed wireless gateways with built-in cybersecurity features, particularly IPSec and VPN.

Secure microgrid-to-microgrid communications are required to implement microgrid self-healing functions for increased system resiliency, as well as cybersecurity features such as compromised node isolation. In terms of the information model, the individual microgrid controllers can implement the IEC 61850 extended DER semantic models, which may also be harmonized with the OpenFMB model in order to support linking the 61850 data model to network topologies.

Mapping of IEC 61850 GOOSE messages to OpenFMB/DDS for microgrid-to-microgrid communications is performed with an IEC 61850 GOOSE-to-OpenFMB adapter developed under the Apache 2 license. Additionally, SDN extensions for OpenFMB/DDS heterogeneous subnetworks, currently in use by many utilities, to be interconnected, as well as implement quality of services and network isolation policies. In the current OpenFMB paradigm DDS communications implement multicast messaging within each network and do not have provisions to interconnect the different subnetworks. SDN routers designed based on an open source OpenFlow SDN implementation is used to convert the above messages to 'unicast' to cross separate subnetwork boundaries. Then the messages can be converted back to multicast again as needed.

Building on top of OpenFMB/DDS with the added SDN layer allows the advanced nested microgrids use cases to be fully realized. For instance, in case of an internal fault in one of the microgrids the distributed microgrid control system can identify the fault location, isolate the faulted segment, and reconfigure the system as needed to minimize the outage effect. Additionally, in case one microgrid is compromised by a cyber-attack, the system will be able to identify the intrusion and isolate the compromised microgrid from the rest of the network.

Simulation Example

This section provides a simulation example for planned islanding functionality in a multi-microgrid environment for the system shown in Figure 8. The numerical simulations are performed in the time domain using the detailed DER models, including switching inverter models with the associated control systems. The system under study represents a generic two-microgrid system with several typical DER units connected to the medium voltage grid at two different substations. The MV grids are modelled as a strong source with an X/R ratio of 7.0 and voltage level of 13.5 kV. Microgrid 1 includes a PV facility, wind generator, energy storage system, and a diesel generators; Microgrid 2 includes energy storage and a large synchronous machine. Both microgrids contain controllable loads that can be used for load management/ load shedding. The figure also shows the basic characteristics of the model components, e.g. voltage level of buses, apparent power of the synchronous generators, and power and energy capacity of BESS. The synchronous generator controllers operate in frequency droop mode according to the new IEEE 1547 requirements, and the energy storage inverters can work as voltage sources; i.e. they can provide voltage and frequency regulation in islanded mode.

In the modeled scenario the tie line breaker is initially closed and a command is issued to island Microgrid 2 from the rest of the system. In this particular case the microgrid control system for Microgrid 2 monitors the tie line power flow in order to minimize it through associated control of its own DER assets, particularly diesel generator. It may also issue a request to microgrid control system of Microgrid 1 to control its assets and loads so that the tie line power flow is reduced to nearly zero in case Microgrid 2 does not have enough capacity on its own. Once the tie line power flow goes within the predefined threshold close to zero, the tie line breaker is opened and the energy storage in Microgrid 2 is switched to voltage source mode to provide the voltage and frequency reference in the islanded mode. Additionally, Microgrid control system 2 performs a load management function according to the actual state of charge of the battery and availability of the diesel generator. Once this is completed the POI 2 breaker is opened and Microgrid 2 enters islanded mode.

As shown in Figure 9 the voltage at the nearest load to the POI (load 5) and the three phase current of the storage during planned islanding remain fairly stable, verifying smooth islanding, and do not violate the requirements of IEEE 1547 or IEEE 2030.7.

Additional use cases that were considered include unintentional Islanding, resynchronization with main grid, resynchronization between two microgrids and a fault detection, isolation and restoration (FDIR) scenario where an internal fault occurs in one of the microgrids and the two microgrid control systems work collectively to detect and isolate the faulted segment. In the FDIR scenario, the system is reconfigured by switching an un-faulted microgrid segment from one microgrid to another.

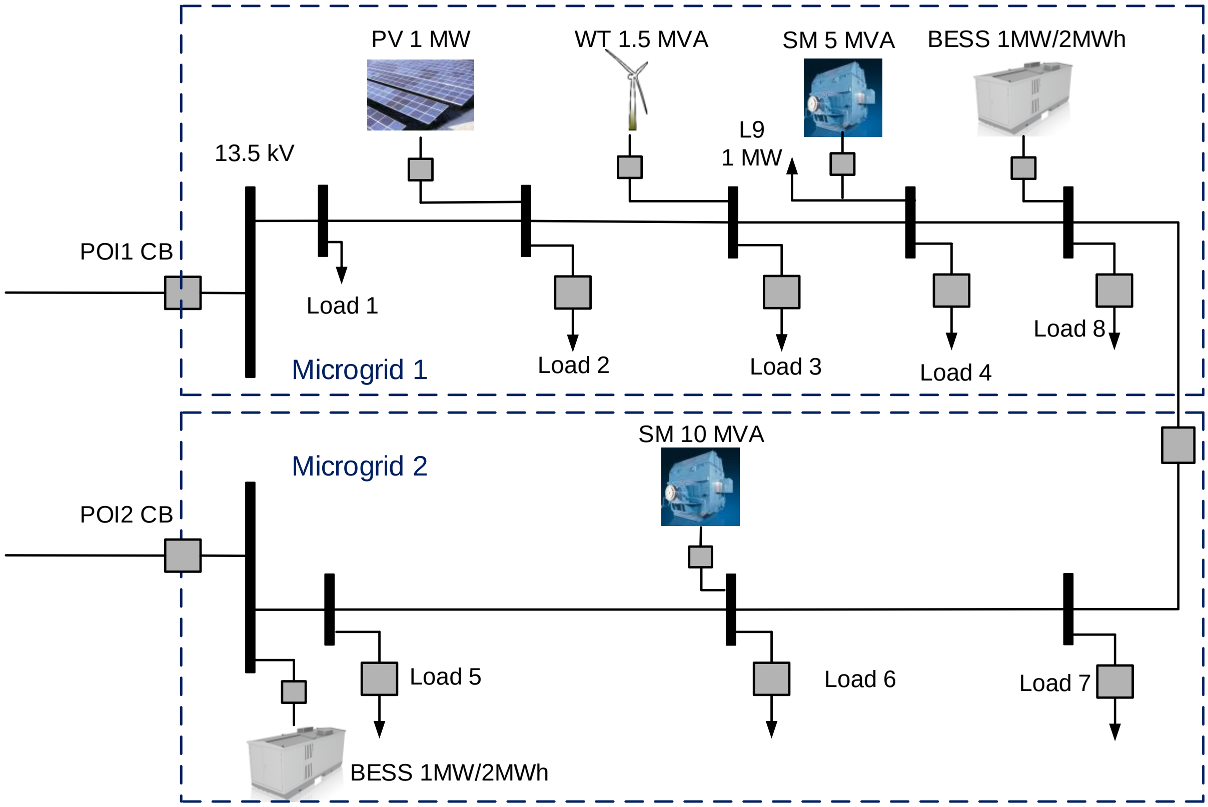

Figure 8 – Multi-microgrid test system

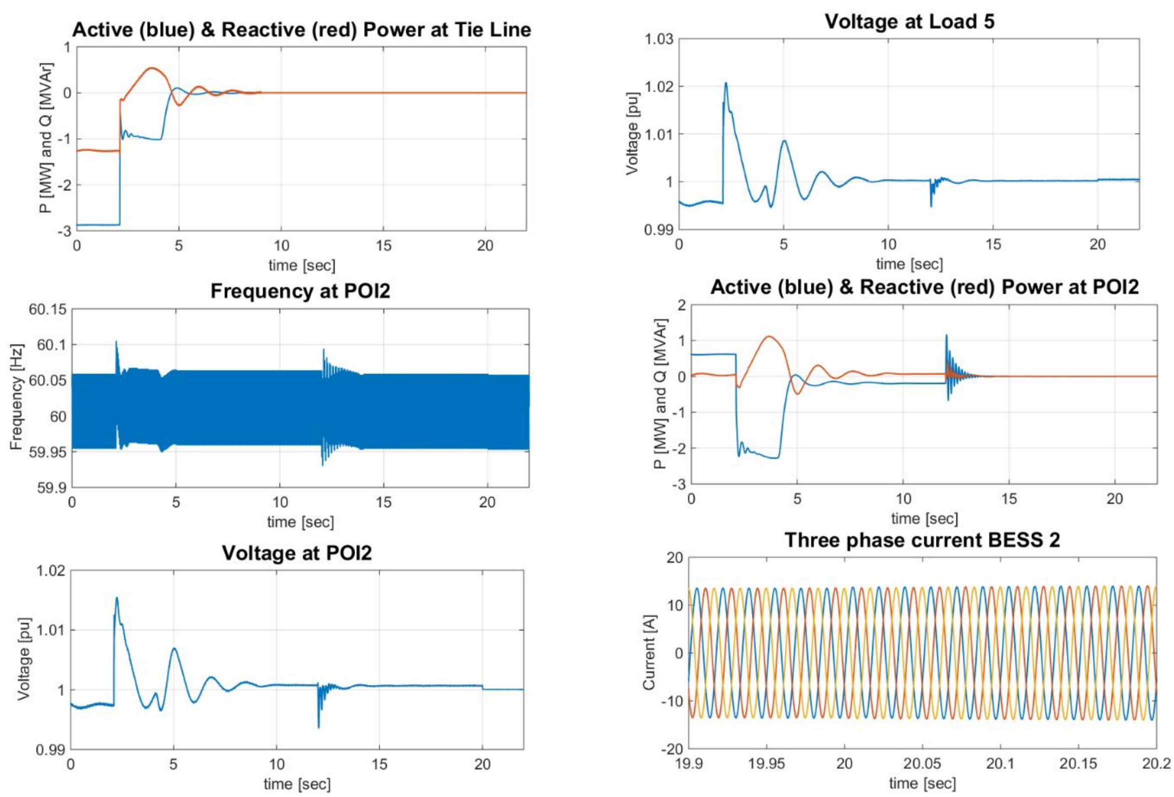

Figure 9 – Nested microgrids simulation results

Conclusions

An ecosystem of cooperating but autonomous microgrids, with points of coupling to the utility and to peer microgrids (nested microgrids) offers an attractive way to enable large scale DER integration at the grid edge. It permits implementing flexible response to natural disasters, as well as the ability to reconstitute the system from the component microgrids, while maintaining at least critical loads served to the degree possible. This article derived a multi-microgrid communication architecture on top of the definitions of IEC Technical Committee 57 Working Group 17 Power system intelligent electronic device communication and associated data models for distributed energy resources and distribution automation, in combination with the OpenFMB Working Group models. A specific simulation example for planned islanding in the nested microgrid environment is also presented.

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