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Implementation and Evaluation of IEC 61850-based Distributed Control System for Microgrid Applications

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Introduction

Microgrid technologies are becoming more of a mainstream concept and they are now predominantly getting adopted by the utilities around the globe. Increased deployment of microgrids is creating new challenges and imposing new requirements on microgrid automation systems, such as the ability to implement fast control functions, deal with modified distribution system configurations, and adapt protection systems to changing conditions. Modern microgrids are complex integrated engineering systems that rely heavily on communication technologies to achieve coordinated control. Thus, a critical component to further proliferation of microgrids technology is interoperability, i.e. use of standardized communication interfaces between different systems and components of the microgrid.

This paper presents a resilient, modular and scalable distributed control architecture for microgrid systems which uses distributed agents controlling individual loads, network switches, generators or storage devices to provide intelligent power management and efficient microgrid operation. The communication between the distributed agents is realized by implementing IEC 61850 data models and GOOSE messages. The data models include state representation, measurements at various points, and dispatch requests for reliable operation of microgrid control system. System resiliency is enhanced through implementing distributed agent architecture with no single point of failure.

Finally, data integration process of microgrid control functionality and its operation for various microgrid use cases is validated and demonstrated through microgrid hardware controller-in-the-loop simulation setup. The hardware testbed includes: (1) A typical microgrid power system simulation model implemented on PLC based simulation platform; (2) A physical distributed microgrid control system with IEC 61850 implementation.

An example use case for black start and planned islanding are presented where the system should achieve optimal control as composed of numerous distributed control actions of asset dispatch, load management, power transfer, and islanding while ensuring delivering secure and selective microgrid operation.

Microgrids Overview

A microgrid is considered an integrated system consisting of distributed energy resources (DERs) including generation and storage, and multiple electrical loads operating within clearly defined electrical boundaries

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that acts as a single controllable entity with respect to the grid [1]. They may be made up of many different generation and storage mixes and grid connectivity formats, as well as cover a vast range of sizes. A typical microgrid may have a structure and components as shown in Figure 1. In many respects, microgrids are smaller versions of a traditional power grid. However, microgrids differ from traditional electrical grids by providing optimum energy utilization between power generation and load, resulting in increased power supply reliability. Microgrids can incorporate renewable power, reduce costs and enhance reliability. Today they can also be used as black start resource or to bolster the grid during periods of heavy demand. As a result, microgrids are increasingly being adopted. Significant cost reductions of renewable distributed generation such as solar photovoltaics (PV) and wind, along with the development of efficient energy storage technologies and the availability of affordable wide-area communication infrastructure, have helped make microgrids more feasible and adaptable technology.

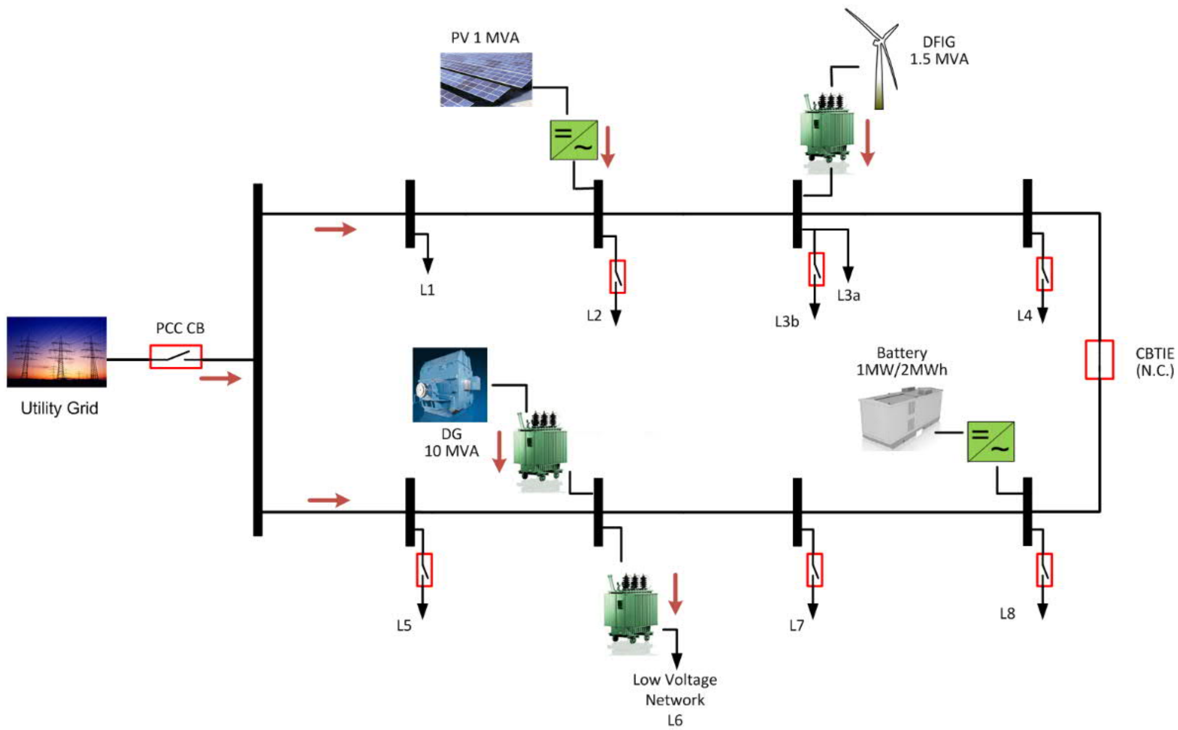

Figure 1: Typical microgrid structure and components [2]

A microgrid control system performs dynamic control over energy sources, enabling autonomous and automatic self-healing operations. During normal or peak usage, or during a primary power grid failure, a microgrid can operate independently of the grid and isolate its local generation and loads without affecting the grid's integrity. Microgrids interoperate with existing power systems and information systems and can feed power back to the grid to support its stable operation. A microgrid control system can enable it to connect and disconnect from the grid to operate in both grid-connected or island-mode and is generally intended to manage power balance connected distribution network. There are several operational modes of the microgrid or transitions from one to another [3]:

- 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
- Reconfiguration function, where the microgrid boundaries may change based on system conditions (e.g., faults)

As shown in Figure 1, a typical microgrid power system may consists of: Generators (diesel, gas, etc.); Wind generation; Solar photovoltaic generation; Other renewable technologies such as geothermal generation; Distribution feeders; Main grid connection/interconnector switch; Energy storage devices (flywheels, batteries, etc.); Demand managed devices; Industrial controllable loads; Commercial/residential loads (air conditioners, pool pumps, etc.). All these individual devices need to be integrated to interact as a strong and powerful system. There are two ways of interaction between these devices: electrical connection and communication between the devices.

IEC 61850 Communications

Microgrids rely heavily on communication technologies to achieve coordinated control between devices potentially from multiple vendors. 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 which are interconnected in bulk with the utility power system the different communication technologies present major technical difficulties, implementation and maintenance costs. Thus, a critical component to further proliferation of microgrids technology is interoperability, i.e. use of standardized communication interfaces between different systems and components of the microgrid. To provide intelligent power management and efficient microgrid operation, the communication between the distributed agents can be realized by implementing IEC 61850 data models and GOOSE messages. The system can implement fast distributed control, which would have been impossible to accomplish with older communications protocols (such as Modbus), or even with local or remote I/O. Additionally, using IEC 61850 communications for microgrid control helps to reduce the engineering and commissioning time because they eliminate the need for complex I/O wiring.

Furthermore, 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 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 semantic models representing DER include logical nodes for generation, storage and loads. Generation devices are further classified as photovoltaics, combined heat and power (CHP), wind, reciprocating engines, and fuel cells. The Logical Node related to Energy Storage Systems are defined in detail in IEC 61850-90-9 [5]. IEC 61850 DER information model utilizes UML modeling approach and builds on top of the existing IEC 61850-7-4 logical nodes where possible, and defines DER specific logical nodes as required for the new use cases.

Microgrid Control System: Central Controller vs. Distributed Controller

The microgrid control system implements control algorithms that maximize the renewable input to microgrids or accomplish other operational goals as defined by the microgrid operator, while assuring robustness and stability of the power system. In broader classification of the architecture of microgrid control systems, there are mainly two different approaches that can be identified: centralized [6], distributed [7]. In a fully centralized control architecture all the information is communicated from the field control devices to a master controller and the decision is made at a single point. On the other hand, in a distributed control architecture, each unit is controlled by its local controller with control schemes achieved by means of a hierarchical control scheme consisting of three control levels: primary, secondary, and tertiary[8]. However, it has been recognized that a central control system has several downsides in a microgrid environment:

- A failure of the central master controller can be catastrophic
- Redundancy of central master is often very expensive
- Large hardware requirements for a central master controller (memory and CPU)
- System maintenance requires complete shutdowns
- Scalability and expansion are expensive and complex tasks
- System relies more on security as attacks on a central controller would be catastrophic
- Modification requires lots of testing
- Limited options for network redundancy
- Works against the nature of a microgrid which is often distributed

The distributed controller employs control system which is local to the various electrical devices. The idea is that every node (generator, wind turbine, etc.) is autonomous. But all these nodes together build a network of peers that represents the whole power system. To overcome the shortfalls of the central decision-making engine (master controller) the peers communicate together. With communication they can make the correct control decision in every situation. The communication in such a distributed environment works through exchanging peer-to-peer messages between the individual controllers. The advantages of having the control system distributed and split up in individual peers are:

- Each electrical device can be fitted with a separate, less complex controller that:
    - Mirrors the already existing redundancy of electrical devices back to the control system level. If one generator controller fails, it appears to the system as if one generator has failed, therefore the next generator starts as replacement
    - Is easy to maintain. Parts of the system can be shut down while the rest of the system continues to operate independently. Upgrades and updates can happen on one diesel generator while the rest of the power station is still operating in automatic
- The failure of one controller doesn't have catastrophic impact since replacement capacity can be brought online immediately
- The system is more scalable and extendable, not limited to on-board I/O of central master controller
- It is a more cost-effective solution
- Due to modularity in nature, it is easier to maintain and upgrade an existing installation
- Communication redundancy can be easily achieved
- Each node is autonomous and yet closely integrated with its peers

Distributed Microgrid Controller System Architecture

The microgrid controller system described here is based on modular and scalable microgrid integration platform, e-mesh Control, which uses distributed agents controlling individual loads, network switches, generators or storage devices to provide intelligent power management and efficient microgrid operation. This solution is designed to enable high penetration of renewable power generation in wind-diesel and solar-diesel power systems couple with energy storage devices, maximizes fuel savings and enables the microgrid to automatically connect to or disconnect from the utility grid without interrupting critical loads.

e-mesh Control system is based on networked architecture of distributed controllers, with individual controller responsible for a specific component within a microgrid. Each controller controls its associated individual generator or load only. However, it publishes information about its power generated or consumed, its generation or load type, its status and its availability to the network, visible to all other controllers on the network. Based on this information and type-specific application algorithms on each controller the total system acts in a coordinated manner without the need of a single master controller. It has a predefined controller hardware configuration with type-specific firmware application. Figure 2 illustrates e-mesh Control Architecture. The naming convention for the controllers is provided in Table 1.

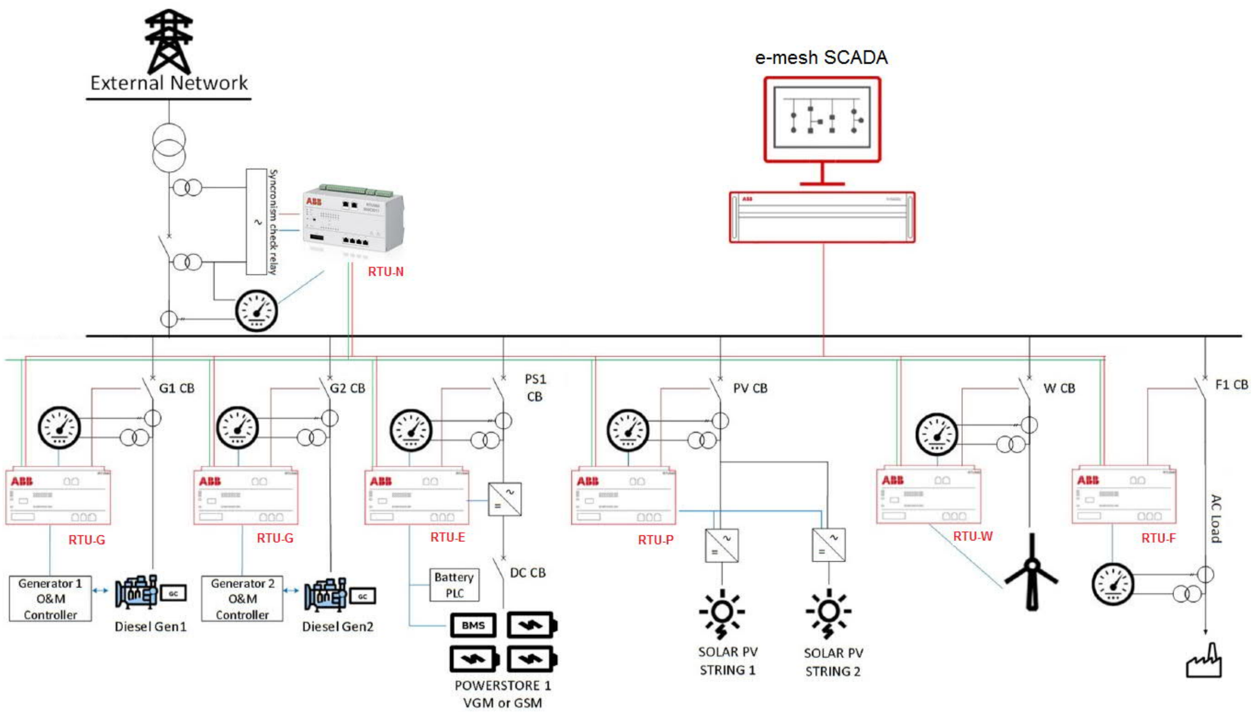

Figure 2: e-mesh Control System Architecture

Table 1: Naming convention for distributed controllers

Supervisory DER Controller	Description
Diesel/Gas generator (RTU-G)	To control, monitor and interface to diesel generators
Distribution Feeder (RTU-F)	To control, monitor and interface to feeders and their protection relays
Photovoltaic Solar (RTU-P)	To control, monitor and interface to solar array inverters
Single/Multiple Load (RTU-L)	To control, monitor and interface to large loads like crushers, boilers, etc.
Energy Storage System (RTU-E)	To control, monitor and interface to the energy storage devices like flywheels and batteries
Network connection of Microgrid (RTU-N)	To control, monitor and interface to other microgrids or larger grids
Wind Turbine (RTU-W)	To control, monitor and interface to wind turbines

All the controllers communicate relevant information through peer-to-peer messages with each other to achieve microgrid controller objective, for example a single device like a photovoltaic control and monitoring system (RTU-P) is not able to do much without other components of the e-mesh control system. It requires visibility to diesel generators and other plant equipment to schedule and control the PV array.

The e-mesh Control integration and communication with main microgrid components like wind turbines, diesel generator controllers, solar and battery inverters is manufacturer independent. In this paper the peer-to-peer communication between the distributed controllers is realized by implementing IEC 61850 data models and GOOSE messages. The main objectives of the networked architecture and non-proprietary communication interface used by the e-mesh Control System are:

- Standardization of how generators and loads are managed in the microgrid
- Every generator and load can connect to the microgrid independent of size or make
- Every generator and load have local intelligence to control its output
- Generators and loads can be added or removed without the need to change other controllers
- Use of nonproprietary industrial communication systems

Implementation of IEC61850 Communications

Figure 3 shows the data flow signals passing to other controllers via IEC61850 interface. To decrease the time required for field events to be reached from the foreseen controllers, it is possible to redirect a signal directly from the acquired one configuring the IEC61850 dedicated tabs for the signals. This is particularly useful for status and measurements data that do not need to be processed internally by the application. In case, the source of the data is a variable generated in the logic or a field signal that should not be shared within a pressing time requirement, the communication can go through the RTU Logic. This allows to manage the signal only in one controller, and the treated values are sent to the other RTUs. GOOSE messages contain data objects representing measurements, DER status and other variables necessary for the implementation of the distributed control algorithms. Table 2 and Table 3 illustrate the signal mapping of RTU-G Logic variables and corresponding field data with IEC61850 GGIO Logical Node (LN).

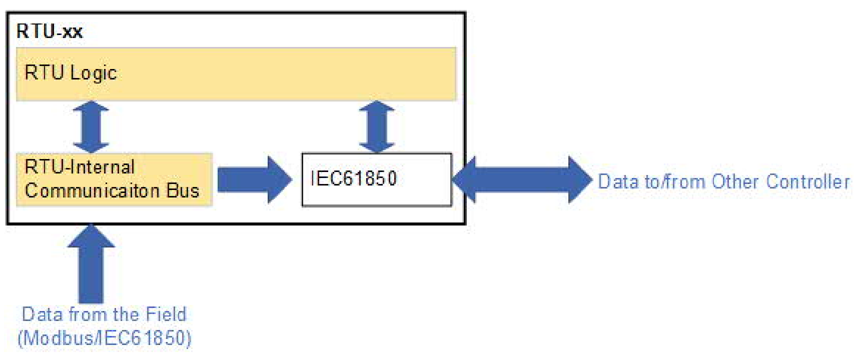

Figure 3: Data flow for signals passing to other controllers

Table 2: Signal mapping of RTU-G monitoring, control and status variables with IEC61850 GGIO Logical Node

RTU-G Parameter Name	Logical Device Instance Name	Logical Node Group	Logical Node Prefix : for GGIO	Logical Node Class	Logical Node Instance	Signal Data Object Name	Signal Data Attribute Name
External Active Power	LD0	LN_Generic_IO	SP16	GGIO	1	Ind1	stVal
External Reactive Power	LD0	LN_Generic_IO	SP16	GGIO	1	Ind2	stVal
Grid Forming Active Status	LD0	LN_Generic_IO	SP16	GGIO	1	Ind3	stVal
Grid Following Active Status	LD0	LN_Generic_IO	SP16	GGIO	1	Ind4	stVal
Device is Healthy	LD0	LN_Generic_IO	SP16	GGIO	1	Ind5	stVal
Comms Lost Status	LD0	LN_Generic_IO	SP16	GGIO	1	Ind6	stVal
Generator Load-sharing Maximum Power	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn1	mag.f
Generator Minimum Active Power	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn2	mag.f
Generator Nominal Active Power Maximum Limit	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn3	mag.f
Generator Nominal Active Power Minimum Limit	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn4	mag.f
Total Generator Actual Overload Active Power	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn5	mag.f
Total Generator Maximum Nominal Reactive Power	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn6	mag.f
Total Generator Minimum Nominal Reactive Power	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn7	mag.f
Actual Nominal Apparent Power	LD0	LN_Generic_IO	MV8	GGIO	1	AnIn8	mag.f
Generator Spinning Reserve for Black Start	LD0	LN_Generic_IO	MV8	GGIO	2	AnIn1	mag.f
ES SOC Percentage to start Generator	LD0	LN_Generic_IO	MV8	GGIO	2	AnIn2	mag.f
ES SOC Percentage to stop Generator	LD0	LN_Generic_IO	MV8	GGIO	2	AnIn3	mag.f
Generator Schedule Enable	LD0	LN_Generic_IO	SP16	GGIO	1	Ind7	stVal

Table 3: Signal mapping of RTU-G Field Data with IEC61850 GGIO Logical Node

RTU-G Data from Field parameter Name	Logical Device Instance Name	Logical Node Group	Logical Node Prefix : for GGIO	Logical Node Class	Logical Node Instance	Signal Data Object Name	Signal Data Attribute Name
Voltage	LD0	LN_Generic_IO	MV8	GGIO	3	AnIn1	mag.f
Active Power	LD0	LN_Generic_IO	MV8	GGIO	3	AnIn2	mag.f
Reactive Power	LD0	LN_Generic_IO	MV8	GGIO	3	AnIn3	mag.f
Frequency	LD0	LN_Generic_IO	MV8	GGIO	3	AnIn4	mag.f
Online Status	LD0	LN_Generic_IO	SP16	GGIO	4	Ind1	stVal

Simulation Testbed

This section provides a simulation testbed setup for testing the IEC61850 configuration and functionality in a microgrid environment for the system shown in Figure 4: Power system simulator setup. The system is based on 13.5 kV/60Hz medium voltage grid with various microgrid components. Table 4 provides the simulation testbed components, their ratings and specifications. As part of the testbed an RTU based e-mesh simulator (emcMGSim) provides microgrid field behavior for automation test environment at secondary controller level. It doesn't include a complete power flow analysis but provides an average time response of the microgrid's power system over a period of 100ms. It also provides an adjustable Primary

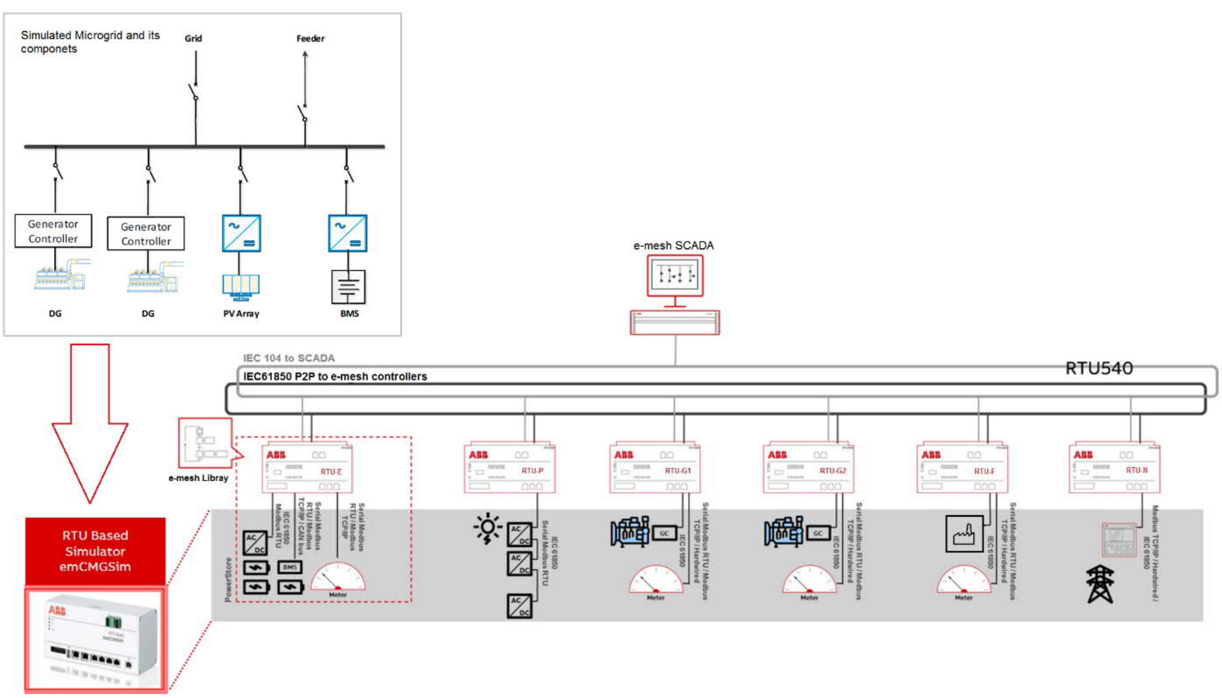

Figure 4: Power system simulator setup

Control response along with emulation of field devices such as power meters and circuit breakers. The emcMGSim simulator accepts Modbus TCP interface up to assets of for each type except for Grid.

Table 4: Microgrid system simulated testbed component ratings and specifications

RTU	e-mesh Unit	Power System Simulator
Generator Controller	RTU-G1	10 MVA Diesel Generator
Generator Controller	RTU-G2	10 MVA Diesel Generator
Photovoltaic Controller	RTU-P	600 kW Inverter based PV Plant
Battery Energy Storage Controller	RTU-E	1 MVA Inverter based BES System
Feeder Controller	RTU-F	Variable Load
Network Controller	RTU-N	External network and Microgrid Point of Common Coupling (PCC)

The Simulator is composed by several software components one for each functional unit: Generator; Battery Energy Storage System (BESS); Renewables (Photovoltaic and Wind); Feeder and Grid. The Generator functional unit allows to have two operating modes: Isochronous (No secondary controller regulation) and droop mode (with secondary controller frequency and voltage regulation), it accepts frequency and voltage reference from secondary controller and a droop regulation is applied with drop of 0.05 both for frequency and voltage. Figure 5 provides Generator functional unit natural response. The BESS functional unit battery energy system behavior with state of charge management and VSI regulation mode and accepts frequency and voltage references. The Renewable with PV functional unit allows to manage a PV plant giving the capability to set actual irradiances as a percentage of nominal power and can accepts P and Q limitation set point. The Feeder functional unit provides the capability to set active and reactive of actual load values, allowing to test and simulate different use cases. Finally, the Grid functional unit calculates actual Microgrid frequency and voltage based on the differences between active power and reactive power contribution of functional units and the load, by adding a user-definable Inertia for each of the DER. It also simulates and allows transition from Islanded to Grid-connected with a synchro check relays simulation.

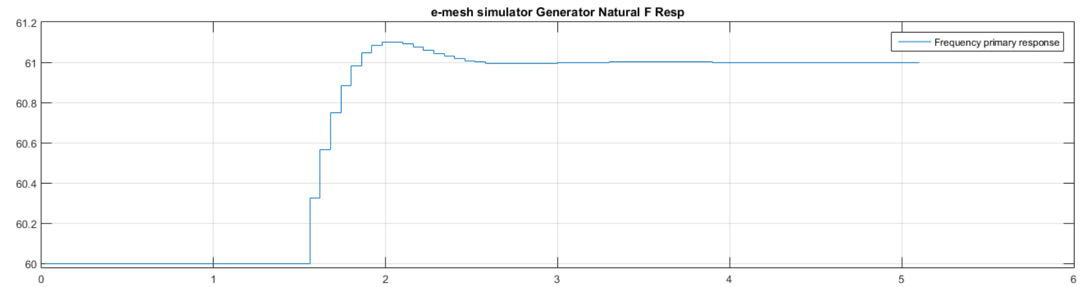

Figure 5: Generator functional unit natural response

Validation of data integration process and control functionality of the distributed microgrid is realized by a laboratory testbed setup with hardware components discussed above. Figure 6 provides the hardware controller-in-the-loop testbed setup configured with IEC61850 communication. The hardware testbed includes all the e-mesh functional units listed in Table 4, emcMGSim and also e-mesh Controller for SCADA interface. This setup was used for testing control functions and microgrid use case presented below.

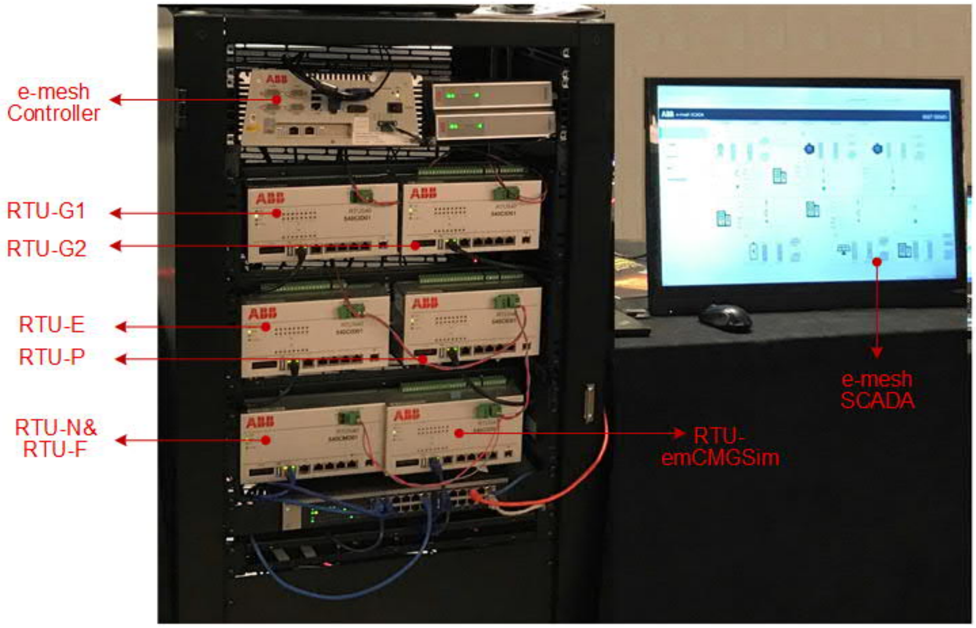

Figure 6: Laboratory testbed setup for microgrid use case

Case study results

Figure 7 shows the controller-in-the-loop simulation results for Microgrid operating sequence with Blackstart followed by Islanding scenario. The graphs indicate proper system response and stable operating condition of microgrid during various mode transitions. Here the communication, to obtain measurements and statuses information, between e-mesh controller functional units are realized via IEC 61850 GOOSE messages.

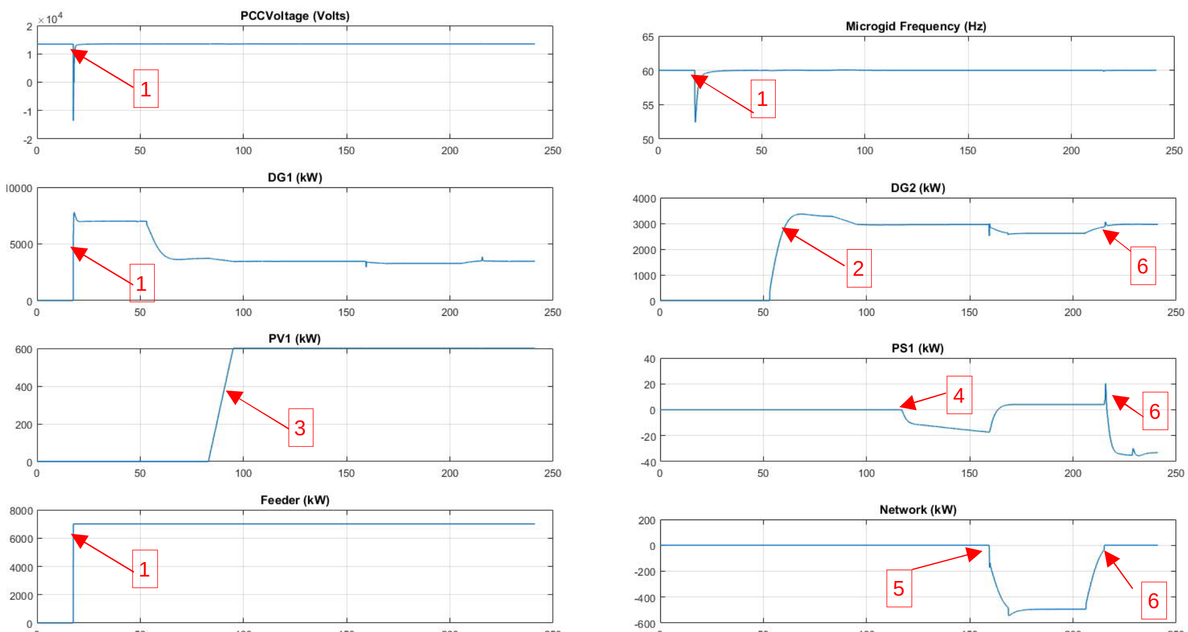

Figure 7: Microgrid Blackstart and Islanding scenario

The microgrid components are not active in the initial system condition. To start the sequence, the system proceeds with black start by energizing each microgrid component one-by-one until all the devices are connected to the microgrid. At this point the microgrid operates in islanded mode and then goes to grid-connected mode and once the system stabilizes it will go into a planned islanded mode of operation. Following sequence gives more about the operation scenario:

1. The Diesel Generator, DG-1 is energized and it provides all the real and reactive power required by the feeder load
2. The DG-2 is energized. As it ramps up the power required by the feeder is shared between DG-1 & DG-2, according to the droop regulation.
3. PV inverter is energized and it slowly ramps-up with a fixed ramp rate until its rated power. As it ramps up, the power required by the feeder is shared among all the active DERs. Here, the PV is operating under 100% irradiance and producing maximum possible output power.
4. BESS is energized. Depending on the state-of-charge (SOC) at the time of energization the BESS either output the power (discharging) or consume power (charging). Here in this case it starts in charging mode. At this point all the microgrid components are active and system is in islanded mode.
5. Microgrid transition into grid connected mode. Figure 8 provides the e-mesh SCADA snapshot showing operation state of grid-conned microgrid.
6. Once the system is stabilized it will transition into planned islanded mode of operation. Figure 9 provides the e-mesh SCADA snapshot showing operation state of islanded microgrid.

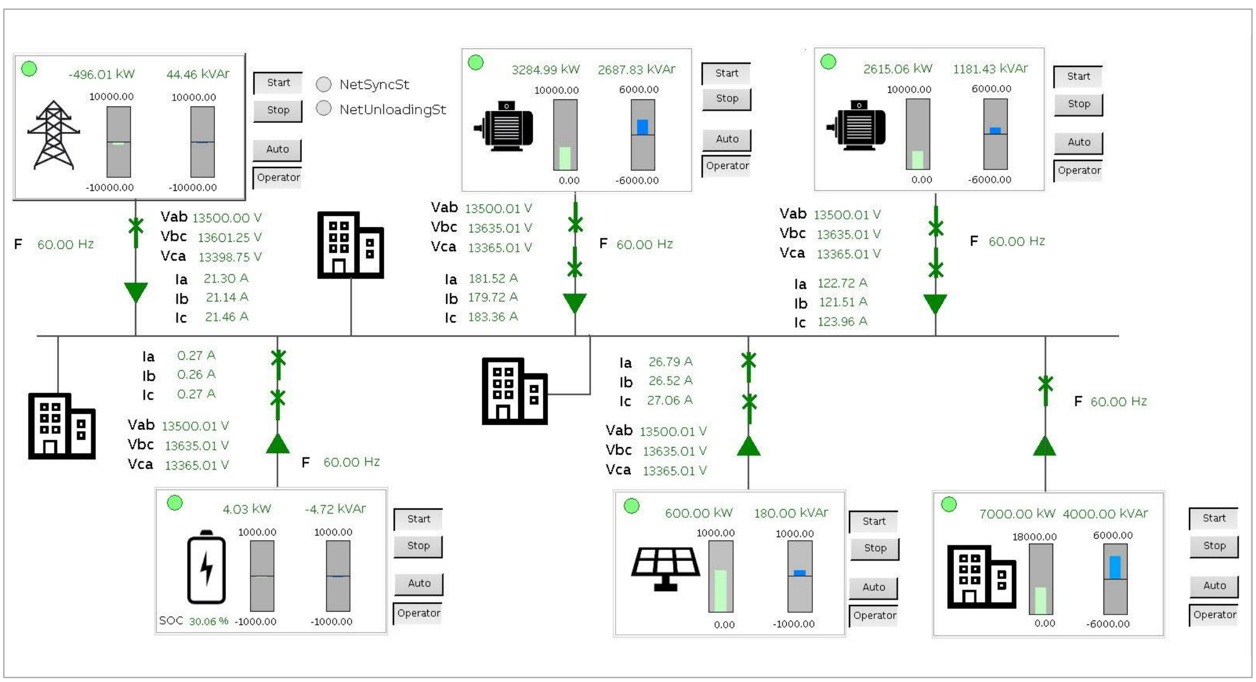

Figure 8: e-mesh SCADA HMI showing Grid connected mode

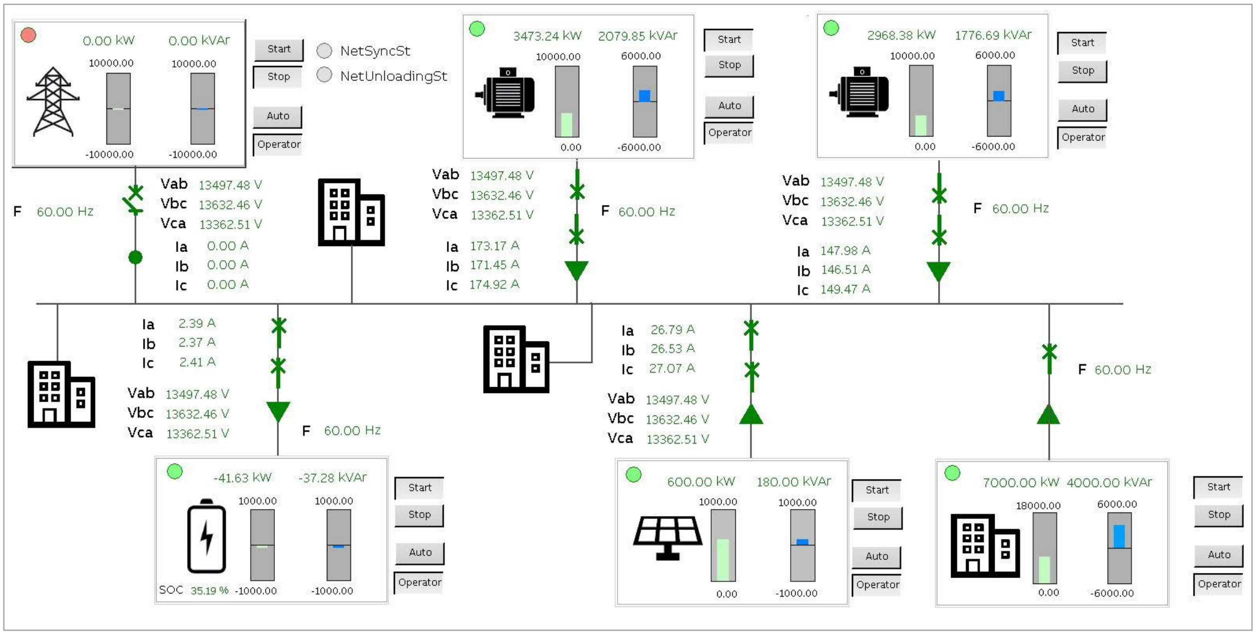

Figure 9: e-mesh SCADA HMI showing planned islanded mode of operation

Conclusions

The microgrid market is rapidly developing around the world in a variety of application segments. Now the Microgrids technology is no longer in a demonstration pilot stage they are making their presence to commercial projects driven by solid business cases. A recent Navigant Research report has identified over 400 microgrid projects in operation or under development globally. To facilitate further proliferation of microgrids technology use of standardized communication interfaces between different systems and components of the microgrid is necessary. Here in this paper a modular and scalable microgrid control architecture presented which uses distributed agents controlling individual loads, network switches, generators or storage devices to provide intelligent power management and efficient microgrid operation. The communication between the distributed agents is realized by implementing IEC 61850 generic data models and GOOSE messages. As part of future work the data models will be extended to IEC 61850-7-420 standard.

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