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Microgrid Controller and Advanced Distribution Management System Survey Report

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Michael R. Starke
Drew Herron

July 2016

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OAK RIDGE NATIONAL LABORATORY
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Electrical and Electronic Systems Research Division

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ACRONYMS

ADMS	Advanced Distribution Management System
CSEISMIC	Complete System-level Efficient and Interoperable Solution for Microgrid Integrated Controls
DDS	Data Distribution Service
DER	distributed energy resource
DG	distributed generation
DMS	distribution management system
DOE	US Department of Energy
EMS	energy management system
IEEE	Institute of Electrical and Electronics Engineers
OMS	outage management system
ORNL	Oak Ridge National Laboratory
R&D	research and development
SCADA	supervisory control and data acquisition
UPS	uninterruptible power supply

ABSTRACT

A microgrid controller, which serves as the heart of a microgrid, is responsible for optimally managing the distributed energy resources, energy storage systems, and responsive demand and for ensuring the microgrid is being operated in an efficient, reliable, and resilient way. As the market for microgrids has blossomed in recently years, many vendors have released their own microgrid controllers to meet the various needs of different microgrid clients. However, due to the absence of a recognized standard for such controllers, vendor-supported microgrid controllers have a range of functionalities that are significantly different from each other in many respects. As a result the current state of the industry has been difficult to assess. To remedy this situation the authors conducted a survey of the functions of microgrid controllers developed by vendors and national laboratories. This report presents a clear indication of the state of the microgrid-controller industry based on analysis of the survey results. The results demonstrate that US Department of Energy–funded research in microgrid controllers is unique and not competing with that of industry.

1. INTRODUCTION

1.1 MICROGRIDS

The growth of distributed renewable and/or nonrenewable energy resource installations, emerging utility-scale energy storage, plug-in hybrid electric vehicle use, and demand response is bringing unprecedented opportunities and challenges to the electric distribution system. As these technologies evolve, utilities, end users, manufacturers, and other participants in distribution system operations are actively transforming the utility operational model. In the past, utility systems were able to mostly operate in isolation, but they are now facing a systems-integration challenge with the complex coordination and integration necessary for these distributed resources.

One available approach for integrating these technologies is through a microgrid. As defined by the Microgrid Exchange Group, "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."[1] This definition of a microgrid has been adopted by the US Department of Energy (DOE) as well as the Electric Power Research Institute. Under this definition a microgrid can be regarded as a controllable resource connected to a distribution network.

With a microgrid, power can be imported or exported to the main distribution network depending on the system constraints and the economic incentives (e.g., market tariffs). A microgrid can also provide ancillary services such as voltage support and regulation services in support of the main distribution grid or utility. This is a feature that a conventional end-user system cannot deliver [2, 3]. Furthermore, a microgrid not only provides energy but also improves local reliability, reduces emissions, and contributes to a lower cost for the energy supply by taking advantage of distributed energy resources (DERs), storage devices, and responsive loads [4]. In addition, a microgrid can improve power quality by supporting voltage and reducing voltage dips within the microgrid [5]. These benefits also support the end-use customers and have attracted growing attention from both academia and industry [6].

1.2 MICROGRID CONTROLLER

Achieving the various described benefits from a microgrid requires a coordinated and coherent operation of the microgrid assets including DERs, energy storage systems, and responsive load. To that end a crucial component of today's microgrid is a microgrid controller. The controller must consider forecasted output of renewable distributed generation (DG) and load demand, market tariffs or forecasted electricity and fuel prices, and the technical constraints on the interconnected electrical distribution network and devices to provide the necessary dispatch with the microgrid. Considerable efforts have been devoted to optimal scheduling and management of a microgrid [7]. In a past effort Oak Ridge National Laboratory (ORNL) developed 10 microgrid operation and control use cases, which have been widely accepted by the industry [8]. The use cases for control and operations of a microgrid are

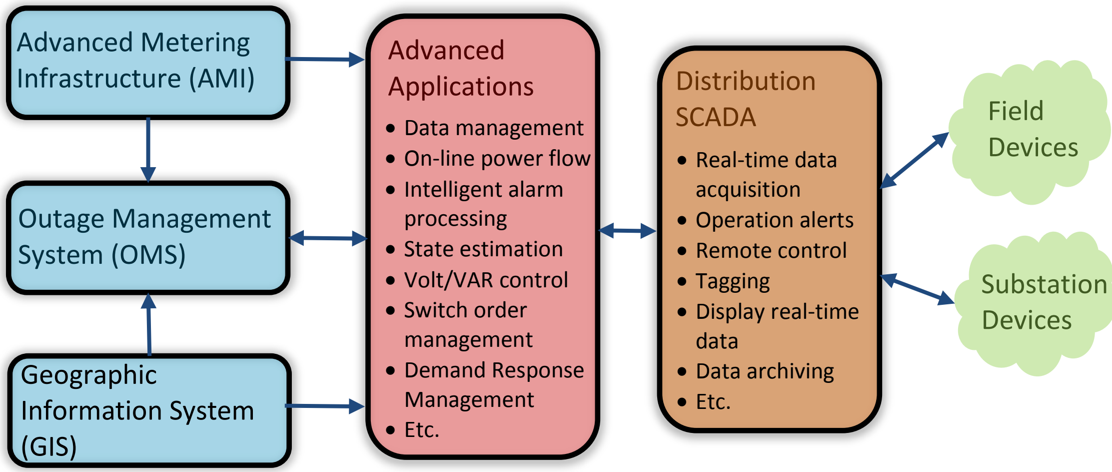
- frequency control,
- voltage control (grid-connected and islanded),
- grid-connected to islanding transition – intentional,
- grid-connected to islanding transition – unintentional,
- islanding to grid-connected transition,
- energy management (grid-connected and islanding),
- protection,
- ancillary services (grid-connected),
- black start, and
- user interface and data management.

While these 10 use cases capture the key requirements of a microgrid controller, a microgrid design has no set constraints on generation resources, demand, and network topology or system configuration. This characteristic of a microgrid results in unique control and operational functions per microgrid and microgrid controller, which has inherently created confusion over the microgrid control options and functions available today. For this reason a complete list of microgrid functions supported by vendor controllers has been developed and is presented in Sect. 2 of this report.

1.3 ADVANCED DISTRIBUTION MANAGEMENT SYSTEM

A distribution management system (DMS) is a decision support system used by distribution operators and field operating personnel for monitoring and control of the electric distribution system in a coordinated and efficient manner. The DMS includes a distribution supervisory control and data acquisition (SCADA) system and various advanced applications such as an advanced metering infrastructure, an outage management system (OMS), and a geographic information system. A typical DMS is illustrated in Fig. 1 [9].

An advanced distribution management system (ADMS) has been constructed from a DMS concept but with additional features. The ADMS integrates energy efficiency, demand response, and distributed resources technologies to enable grid operators to make intelligent decisions in operating the distribution system more efficiently, reliably, and at a lower cost. This system provides electric distribution utilities the ability to incorporate distributed energy resources, demand response, energy storage systems, and electric vehicles, not unlike a microgrid. A microgrid is typically much smaller in size (on the megawatt scale) as compared to a full distribution system and comprises various DGs, energy storage systems, and responsive loads that can be operated in both a grid-connected and islanded mode. As a result many of the ADMS/DMS vendors are attempting to expand the development of ADMS/DMS products to include microgrid management functions. Thus, the vendor specifications on these systems were also included in the survey.



SCADA = supervisory control and data acquisition
VAR = volt-ampere reactive

Fig. 1. A typical DMS.

1.4 SCOPE AND PURPOSE

At this time the absence of a recognized standard for a microgrid controller has resulted in numerous vendor-supported microgrid controllers with various functionalities that are unique in many respects. In most cases these controllers were developed and demonstrated for individual customers at specific microgrid sites. As a result the current state of the microgrid controller industry has been difficult to assess.

This report discusses the results of a recent microgrid controller survey and evaluates the survey results. The microgrid controllers within the survey included vendor- and national-laboratory-developed microgrid controllers. For simplification of the survey, a complete list of microgrid controller functions was developed and delivered to survey participants. The participants then simply indicated with a “yes” or “no” if a function was available in the vendor product (e.g., microgrid controller or DMS/ADMS). All the survey results were collected and compiled to provide a clear indication of the state of microgrid controllers. This information is important and valuable for identifying the necessary research in this area. In addition, the results clearly demonstrate that DOE-funded research in microgrid controls and microgrid controllers is unique and not competing with that of industry.

1.5 CHALLENGES

It should be noted that the survey’s objective was to identify the overall state of microgrid controllers. However, a number of challenges had to be considered when evaluating the results.

- The survey could not capture all of the unique differences of the vendor products. For example, vendor controller communication might only be with vendor-developed assets. Any more detailed assessment would require a much more comprehensive survey, and the information might not be available without a nondisclosure agreement.

- A full comprehensive survey of all microgrid controllers would be difficult because many vendors consider the functionality of the microgrid controller to be business sensitive. As a means of obtaining the survey information and protecting the confidentiality of the data, an anonymized process was promised to remove vendor-specific details. Still, only 52 percent of the respondents replied to the request.

- Due to the inherent nature of the research involved in microgrid controllers and grid modernization, vendors are rapidly changing the development and functionality of these controllers. Therefore, improvements in these functions were probably already present or on the horizon.

2. MICROGRID CONTROLLER SURVEY

2.1 APPROACH

As an initial start to the survey, a complete list of functions that could be present in a microgrid was generated for comparing the capabilities of microgrid controllers. The initial function list was constructed based on the 10 ORNL microgrid operation and control use cases and 18 DMS functions developed by the Institute of Electrical and Electronics Engineers (IEEE) DMS Task Force of the Smart Distribution Working Group for the DMS-OMS State of the Industry Survey. These functions were categorized into five groups—energy management, protection and control, resiliency, ancillary services, and data management—as shown in Fig. 2. Each group has a particular focus or objective.

1. The functions in energy management have the primary target of supporting power balancing in steady state.

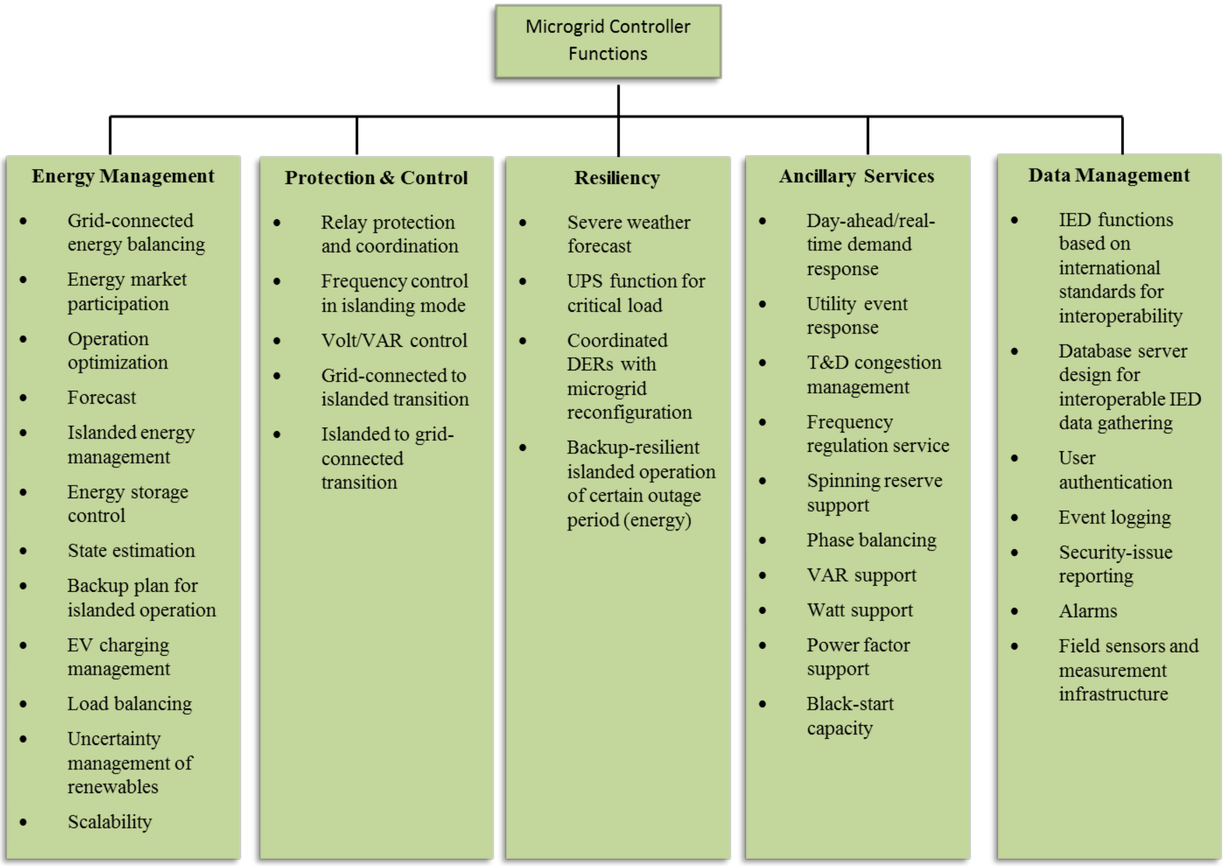
2. The functions in protection and control support voltage and frequency control.

3. The functions in resiliency aim to increase survivability of a microgrid under disturbances or severe weather conditions.

4. The functions in ancillary services strive to support the interaction with the local utility or distribution system operator.

5. The functions in data management address interoperability and data management.

Each of these functions may include several subfunctions or services. Various methods or models can be used to achieve these functions. The survey included questions on these details in an attempt to capture the state of the art of the microgrid controllers. All the functions listed in the survey can be found in Tables 1 through 5, and the specific definitions of these functions can be found in Appendix A.



DER = distributed energy resource
EV = electric vehicle
IED = intelligent electronic device
T&D = transmission and distribution
VAR = volt-ampere reactive

Fig. 2. Microgrid functions.

Table 1. Functions in energy management group

1 Energy Management	1.1.	Grid-Connected Energy Balancing	Unit Commitment (UC) (Stochastic/Robust/Deterministic?)
			Economic Dispatch (ED) (Stochastic/Robust/Deterministic?)
			Optimal Power Flow (OPF) (Stochastic/Robust/Deterministic?)
	1.2.	Energy Market Participation	Transactive Energy/Bidding Function
	1.3.	Operation Optimization	Peak Shaving/Valley Filling
			Loss Minimization
			Conservation Voltage Reduction
	1.4.	Forecast	Load Forecast
			Wind Power Forecast
			Photovoltaic Power Forecast
	1.5.	Islanding Energy Management	UC (Stochastic/Robust/Deterministic?)
			ED (Stochastic/Robust/Deterministic?)
			OPF (Stochastic/Robust/Deterministic?)
			Spinning Reserve/Regulation Management
	1.6.	Energy Storage Control	
	1.7.	State Estimation (SE)	SE for Billing
			SE for Optimization and Control
	1.8.	Backup Plan for Islanding Operation	Contingency Analysis (Power Perspective)
	1.9.	Two-Way Communication	Between Microgrid Energy Management System (EMS) and Controllable Sources/Inverters
			Between Microgrid EMS and Controllable Loads
	1.10.	EV Charging/Discharging Management	Vehicle to Grid?
	1.11.	Load Balancing	
	1.12.	Additional Uncertainty Management of Renewables	
	1.13.	Scalability	Multiple Microgrids or Microgrid Network

Table 2. Functions in protection and control group

2 Protection and Control	2.1.	Relay Protection Coordination	Short-Circuit Protection
			Ground Protection
			Fault Location, Isolation, and Service Restoration
			Disturbance Logging, Time-Tagging, and Analysis
	2.2.	Frequency Control in Islanding Mode	Steady-State Device Level Control (Droop/V-f/PQ Control)
			Coordinated Control of Multiple Device (Within Seconds Level or Subseconds)
			Transient Device Level Control
			Frequency Smoothing
			Low-Frequency Ride-Through
			Emergency Load Shedding
	2.3.	Volt/ VAR and Reactive Power Control	Steady-State Device Level Control (Droop/V-f/PQ Control)
			Optimal Coordinated Load Tap Changers (LTCs), Distributed Energy Resources (DERs), and Capacitor Banks for Voltage Profile Control (Both Grid-Connected and Islanding State)
			Cooptimization of Real and Reactive Power Considering DER's Real and Reactive Power Capability
			Management of Voltage Fluctuations Due to Intermittent DERs
			Low-Voltage Ride-Through
	2.4.	Grid-Connected to Islanding Transition	Intentional Islanding Transition
			Unintentional Islanding Transition
	2.5.	Islanding to Grid-Connected Transition	Black Start
			Synchronization

Table 3. Functions in resiliency group

3 Resiliency	3.1.	Severe Weather Forecast	Storm/Hurricane/Extreme Temperature?
	3.2.	Uninterrupted Power Supply (UPS) Function for Critical Load (Intelligent Load Shedding)	
	3.3.	Coordinate Distributed Energy Resources with Microgrid Reconfiguration	
	3.4.	Backup Plan	Backup Resilient Islanding Operation Plan for Certain Outage Period (Energy)

Table 4. Functions in ancillary services group

<table>
<tr><td rowspan="11">4 Ancillary Services</td><td>4.1.</td><td>Day-Ahead Demand Response</td><td>Price-Driven Day-Ahead Demand Response</td></tr>
<tr><td>4.2.</td><td>Real-Time Demand Response</td><td>Price-Driven Real-Time Demand Response</td></tr>
<tr><td>4.3.</td><td>Utility Event Response</td><td>Active Power/Reserve?</td></tr>
<tr><td>4.4.</td><td>Transmission and Distribution Congestion Management (Network Restoration, Dynamic Line Rating)</td><td></td></tr>
<tr><td>4.5.</td><td>Regulation Service</td><td>Frequency</td></tr>
<tr><td>4.6.</td><td>Spinning Reserve Support</td><td></td></tr>
<tr><td>4.7.</td><td>Phase Balancing</td><td></td></tr>
<tr><td rowspan="4">4.8.</td><td rowspan="4">Provision of Requested Supports</td><td>VAR Support</td></tr>
<tr><td>Watt Support</td></tr>
<tr><td>Power-Factor Support</td></tr>
<tr><td>Black-Start Capacity</td></tr>
</table>

Table 5. Functions in data management group

<table>
<tr><td rowspan="7">5 Data Management</td><td>5.1.</td><td>Intelligent Electronic Device (IED) Functions Based on International Standards for Interoperability</td><td>IEC 61850 or else</td></tr>
<tr><td>5.2.</td><td>Database Server Design for Interoperable IED Data Gathering</td><td></td></tr>
<tr><td>5.3.</td><td>User Authentication</td><td></td></tr>
<tr><td>5.4.</td><td>Event Logging</td><td></td></tr>
<tr><td>5.5.</td><td>Security Issue Reporting</td><td></td></tr>
<tr><td>5.6.</td><td>Alarms</td><td></td></tr>
<tr><td>5.7.</td><td>Field Sensors & Measurements Infrastructure</td><td></td></tr>
</table>

All of these functions were inserted into a Microsoft Excel form and sent to participants. The participant list consists of active members of the IEEE P2030.7 Distribution Resources Integration Working Group/Microgrid Controllers Task Force. The task force members primarily consist of microgrid controller or ADMS/DMS vendors and consultants actively involved in microgrid controller research and development (R&D). The survey did not include utility operators or representatives of colleges or universities. The survey participants are listed in Table 6.

Table 6. Survey participants

Company Name	Company Name	Company Name
ABB	ETAP	Power Analytics
Advanced Control Systems	General Electric	Schneider
Alstom Grid	Green Energy Corp	Siemens
Blue Pillar	Intelligent Power & Energy Research Corporation	Spirae
Eaton	Lawrence Berkeley National Laboratory (Distributed Energy Resources Customer Adoption Model)	Sustainable Power Systems
Encorp	Opus One Solutions	Toshiba
Enphase Energy	Oak Ridge National Laboratory (Complete System-Level Efficient and Interoperable Solution for Microgrid Integrated Controls)	Viridity Energy

As a means of increasing the number of respondents and avoiding burdening participants with too many questions and significant work, participants were asked to put “Y” or “N” to indicate whether each specific function was included in a listed product. The names of the known vendor products were specified, but the vendors were allowed to add columns for other products and provide further specifications on the responses. A sample screenshot from the survey is shown in Fig. 3.

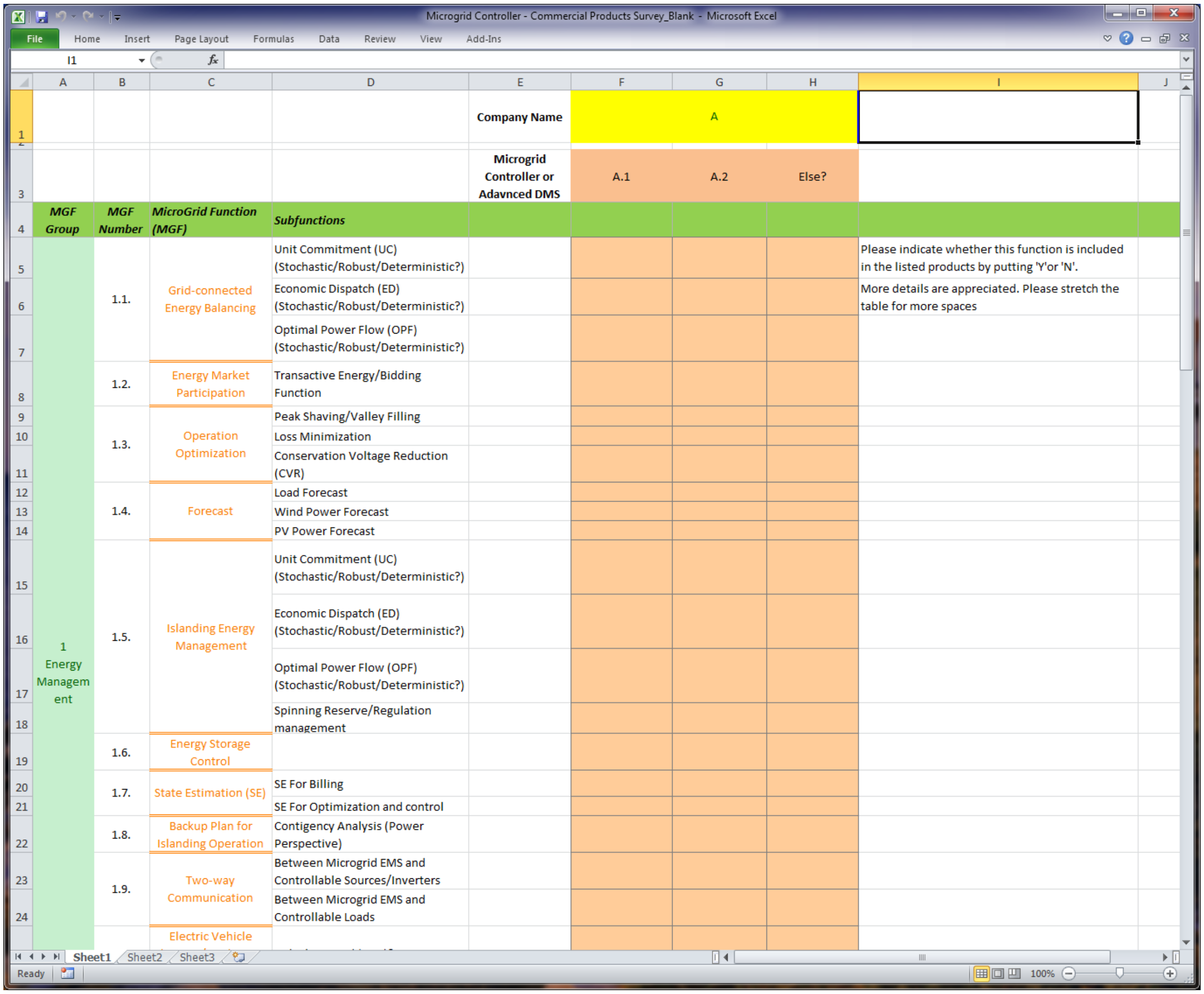


Fig. 3. Sample screenshot from survey.

The main objective of this survey was to evaluate the overall status of the microgrid controller as a guide for R&D in this area. Therefore, after feedback was received, the names of the vendors and products were removed to provide anonymity to all participants.

2.2 SURVEY RESULTS

The survey was first distributed in November 2014. Because the number of members of IEEE P 2030.7 had grown, the survey was redistributed in March 2015. The latest feedback was collected in June 2015. The survey Excel form was emailed to all 21 organizations and vendors listed in Table 6. Currently, 11 of these organizations have participated in the survey. The original survey results from these 11 vendors were anonymized and compiled into a single table for easy comparison. The results are shown in Appendices B through F.

According to the survey results, the functions that have been included in most of the microgrid controllers include

- economic dispatch for grid-connected and islanded modes (9),
- peaking shaving (10),

- loss minimization (8),
- reserve management (9),
- two-way communication (8),
- emergency load shedding (10),
- islanding (9),
- resynchronization (8),
- uninterruptible power supply (UPS) function for critical load (9), and
- provision of requested support (9).

Generally, as basic functions of a microgrid controller, islanding and resynchronization functions are included within most vendor microgrid controller products. These two basic functions are highly interwoven with other functions and have also been developed in commercial products. For example, emergency load shedding is an easy way to quickly regain the balance between load and generation during islanding transition. Economic dispatch and reserve management are necessary functions for operating efficiently and reliably off-grid. Peak shaving, loss minimization, and UPS functions for critical load use the flexibility of local resources and support the end-use customers in grid-connected mode. All of these functions rely on an efficient two-way communication system.

Functions that have not been included in most of the microgrid controllers include

- conservation voltage reduction (3),
- state estimation (5),
- contingency analysis (6),
- electrical vehicle management (4),
- transient device level control (4),
- low-frequency ride-through (3),
- low-voltage ride-through (3),
- severe weather forecast (3), and
- transmission and distribution congestion management (3).

Only a small number of vendors have considered these functions in their products. These functions are more advanced and require complicated control and optimization algorithms. In addition, the realization of the basic functions (islanding and resynchronization) does not rely on these advanced functions.

The survey results would suggest that many of the microgrid controllers are similar and that all of the functions have been derived. While vendors have laid claims to supporting these functions, a true comparison of the ability of a microgrid controller to perform these actions can only be demonstrated at real microgrids or microgrid testbeds [10], which is beyond the scope of this report.

ORNL has been actively developing an open-source microgrid controller to demonstrate the microgrid functions and provide a base case for comparison with other microgrid controllers. This microgrid controller, the Complete System-Level Efficient and Interoperable Solution for Microgrid Integrated Controls (CSEISMIC), currently consists of an energy management system (EMS) and a SCADA system. This architecture was developed in 2015 and allowed comparison to vendor microgrid controllers. Although inheriting some functions and terminologies from SCADA and EMS, CSEISMIC has significant differences from commercial microgrid controllers due to special characteristics and operation strategies.

- The CSEISMIC SCADA not only communicates with individual devices and collects data (like EMS or DMS) but also has real-time control functions such as voltage and frequency regulation in islanded mode, low-voltage/-frequency ride-through, energy storage management as well as DER, and demand response coordination [11].

- The CSEISMIC EMS performs 5 min. look-ahead optimal power flow, which optimizes P and Q simultaneously, whereas most of commercial products optimize P and Q separately [12]. The CSEISMIC approach is especially important in a microgrid because the resources in a microgrid are limited, and a lot of them are resources of both real and reactive power.

- The CSEISMIC EMS uses state-of-the-art optimization algorithms to take uncertainties of renewable sources and loads into account [13]. Proper management of these algorithms that takes into accounts their correlations and demand response will contribute a major value stream to microgrid controllers and encourage the deployment of microgrid technology.

- The CSEISMIC microgrid controller uses a three-phase unbalanced system model for control and optimization of microgrids, while most commercial microgrid controllers use a single-line balanced model. The three-phase unbalanced system model has introduced more interesting characteristics and challenges [14, 15].

The current architecture of CSEISMIC is rapidly being replaced with a new one that supports distributed communications and controls. Unlike traditional bidirectional communication between devices in which one device issues a query and a secondary device responds, the new architecture is built on the Data Distribution Service (DDS), which is a publish/subscribe protocol that enables multiple devices to write and read from the same topic. This subscription-based architecture reduces communication bandwidth requirements and simplifies the addition of devices to the overall microgrid topology. Furthermore, the auto-discovery feature provided by DDS eliminates the need to establish connections to predetermined devices, thereby effectively adapting to the field implementation of the microgrid without requiring time-consuming edits to the code base, device whitelists, or configuration files.

On another note, the current development stages of the ORNL microgrid controller are focusing on more distributed control architecture. A service-oriented architecture for microgrid control and operation is currently under development to allow plug-and-play solutions. Advanced optimization techniques will be developed to encompass larger systems and utilize emerging technologies such as the internet of things, machine learning, real-time hardware in the loop, etc. The next version of CSEISMIC will create an open microgrid reference platform to accelerate research in control, optimization, standards development, and cyber-physical security.

CONCLUSION

This report discussed the results of a recent microgrid controller survey and evaluated the survey results. First, a complete list of functions that could be present in a microgrid was generated for comparing the capabilities of microgrid controllers. A survey form in Microsoft Excel was sent to vendors and national laboratories with microgrid controller products. All feedback was aggregated and analyzed in this report. The results showed the current status of microgrid controllers in the market. The R&D needs in this area have been discussed based on the results. In addition, this work clearly demonstrated that CSEISMIC and DOE–funded research in microgrid controllers is significantly different from that related to commercial microgrid controllers. Thus, DOE–funded microgrid controller research is unique and not competing with that of industry.

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APPENDIX A. MICROGRID FUNCTION DEFINITIONS

Microgrid Function	Description
Grid-connected Energy Balancing	This is a group of functions including unit commitment, economic dispatch, and optimal power flow
Unit Commitment	Schedule the start-up and shunt-down sequence of generators
Stochastic/Robust/Deterministic	The optimization model considers stochastic optimization, robust optimization or deterministic optimization.
Optimal Power Flow	Determines the real and reactive power output for interconnected generators within the system.
Transactive Energy	Microgrid controller is able to bid into the energy market or transact with another entity.
Loss Minimization	Minimizes the power loss within the distribution network.
Conservation Voltage Reduction	Reduces the voltage to the lower half of allowed voltage range to decrease the load consumption
Reserves	Quantifies the amount of needed spinning reserve and regulation capacity and dispatches the generators or responsive loads when islanded accordingly
Energy Storage Control	Controlling and optimizing the charging and discharging of energy storage systems.
State Estimation	Estimates the condition of system and validates with redundant measurements
Backup Plan for Islanding Operation	Preparation of islanding operation and ensuring that enough power capacity is available.
Contingency Analysis (Power Perspective):	Performing the system failure analysis for n-1 or n-2 failures
Load Balancing	Balancing the load between different feeders
Uncertainty Management of Renewables	Any special program for handling the uncertainty of renewables and load.
Scalability	Application for multiple microgrids and different sizes of microgrids
Coordinated Control of Multiple Device	Real power coordination of devices for voltage regulation
Optimal Co-ordinated LTCs, DERs, and Capacitor Banks for Voltage Profile Control (Both Grid-connected and Islanding State)	Coordination of controllable devices in distribution network, such as LTCs, DERs and capacitor banks
Coordinate DERs with Microgrid Reconfiguration	Restoration considering DERs.
Backup Resilient Islanding Operation Plan for Certain Outage Period (Energy):	Preparation of islanding operation, have enough energy for critical loads surviving for certain time period.

APPENDIX B. MICROGRID FUNCTIONS COMPARISON ENERGY MANAGEMENT

	Company Name	**ORNL**	A		B	C			D	E	F		G		H			I		J
Microgrid Controller or ADMS			A.1	A.2	B.1	C.1	C.2	C.3	D.1	E.1	F.1	F.2	G.1	G.2	H.1	H.2	H.3	I.1	I.2	J.1
MGF	***Subfunctions***																			
Grid-connected Energy Balancing	Unit Commitment	Y[1]			Y[3]		Y[1]		Y	Y					Y	Y			Y[1]	Y
	Economic Dispatch	Y[1]			Y[3]		Y[1]		Y						Y	Y			Y[1]	Y
	Optimal Power Flow	Y[1]		Y	Y[4]									Y[5]	Y		Y			Y
Energy Market	Transactive Energy	Y					Y								Y	Y			Y[6]	
Operation Optimization	Peak Shaving	Y	Y	Y	Y[7]		Y		Y	Y				Y	Y[8]		Y		Y	Y
	Loss Minimization	Y	Y	Y	Y[9]		Y			Y		Y		Y			Y			
	CVR			Y	Y[10]									Y						
Forecast	Load Forecast	Y		Y	Y[11]				Y					Y	Y	Y	Y		Y	
	Wind Power Forecast				Y[12]											Y			Y	
	PV Power Forecast	Y			Y[12]				Y		Y			Y	Y	Y			Y	
Islanding Energy Management	Unit Commitment	Y[1]	Y		Y[13]		Y[1]		Y					Y	Y	Y			Y[1]	Y
	Economic Dispatch	Y[1]	Y		Y[13]		Y[1]		Y				Y[1]	Y[14]	Y	Y		Y[1]	Y[1]	Y
	Optimal Power Flow	Y[1]	Y[2]	Y										Y[15]	Y		Y			Y
	Reserves	Y	Y		Y[16]		Y			Y			Y		Y	Y		Y	Y	Y

[1] Deterministic.
[2] Basic.
[3] Using heuristic rules for microgrid controllers; and DRMS for DMS
[4] Using DRMS for DMS
[5] Robust
[6] Manual
[7] As distributed control system function for microgrid controllers; and through automated capacitor and regulator control to reduce peak demand as DMS function
[8] peak shaving only
[9] Voltage and Var Optimization or Feeder Reconfiguration DMS applications
[11] Using DMS load profiles where the forecast is provided by an external system
[12] DMS function using generation profiles with the forecast provided by an external system
[13] heuristic rule for microgrid controllers
[14] partial, deterministic
[15] Robust, back upstream
[16] distributed control system microgrid controllers function

	Company Name	ORNL	A		B	C			D	E	F		G		H			I		J
Microgrid Controller or ADMS			A.1	A.2	B.1	C.1	C.2	C.3	D.1	E.1	F.1	F.2	G.1	G.2	H.1	H.2	H.3	I.1	I.2	J.1
MGF	***Subfunctions***																			
ES Control		Y	Y		Y[16]	Y			Y				Y[17]	Y[5]	Y	Y	Y	Y[17]	Y	Y
State Estimation (SE)	Billing																Y			Y
	Optimization/Control		Y	Y	Y[18]							Y		Y[19]			Y			Y
Backup Plan for Islanding Operation	***Contingency Analysis***	Y			Y[20]					Y					Y		Y			Y
Two-way Communication	***EMS/Sources***	Y	Y	Y	Y[21]	Y				Y	Y		Y	Y	Y	Y		Y	Y	Y
	EMS/ Loads	Y	Y	Y	Y[21]	Y				Y			Y[22]	Y	Y	Y		Y[22]	Y[22]	Y
Electric Vehicle	***Vehicle to Grid (V2G)***				Y[23]		Y		Y								Y			
Load Balancing		Y	Y	Y	Y[24]		Y			Y			Y	Y	Y	Y	Y	Y	Y	Y
Uncertainty Management Renewables		Y	Y		Y[25]				Y					Y[26]		Y				Y
Scalability	***Multiple Microgrids or Microgrid Network***		Y	Y				Y	Y	Y			Y[27]	Y[28]			Y	Y[27]	Y[27]	

[17] limited capabilities
[18] DMS function using Load Allocation or State Estimator
[19] converging with SCADA and AMI data
[20] as a DMS function
[21] Modbus RTU for microgrid controllers
[22] depends upon load controller
[23] Using DRMS but no support for V2G
[24] microgrid controller function
[25] Using forecast profiles and power flow modeling of DER in DMS
[26] online connection impact assessments
[27] to some extent
[28] substation, feeder, community, customer, or sub-customer microgrids

APPENDIX C. MICROGRID FUNCTIONS PROTECTION AND CONTROL

	Company Name	ORNL	A		B	C			D	E	F		G		H			I		J
Microgrid Controller or ADMS			A.1	A.2	B.1	C.1	C.2	C.3	D.1	E.1	F.1	F.2	G.1	G.2	H.1	H.2	H.3	I.1	I.2	J.1
MGF	*Subfunctions*																			
Relay Protection Coordination	Short-Circuit Protection	Y	Y	Y	Y[1]							Y			Y		Y			Y
	Ground Protection		Y		Y[1]							Y			Y		Y			Y
	Fault Location, Isolation & Service Restoration (FLISR)		Y	Y	Y[2]							Y					Y		Y	Y
	Disturbance Logging, Time-Tagging and Analysis	Y		Y	Y[3]								Y		Y		Y	Y	Y	Y
Frequency Control in Islanding Mode	Steady state Device Level Control (Droop/V-f/PQ control)	Y	Y	Y	Y[4]					Y			Y	Y[5]				Y	Y[6]	Y
	Coordinated Control of Multiple Device (Within Seconds level or Subseconds)	Y	Y		Y[7]		Y			Y			Y	Y	Y	Y		Y	Y	Y
	Transient Device Level Control	Y	Y		Y[7]															Y
	Frequency Smoothing				Y[4]					Y			Y[8]	Y[9]	Y	Y		Y[8]		Y
	Low Frequency Ride-Through (LFRT)		Y							Y				Y[10]						
	Emergency Load shedding	Y	Y	Y	Y[11]		Y		Y	Y			Y	Y	Y	Y		Y		Y

[1] using manual short-circuit analysis in DMS
[2] as a DMS function
[3] Logging and time-tagging all power signals from all devices in microgrid control system; Using SCADA historian logging of SCADA monitored events in DMS
[4] microgrid controller function
[5] with power conversion system, PCS
[6] MGMS supports it, but doesn't control itself
[7] through microgrid controller distributed system architecture
[8] as a Load Shedding function
[9] load shedding and DER dispatch
[10] with PCS
[11] using feeder overload shedding function of microgrid control system; and SCADA load shedding application for DMS

	Company Name	ORNL	A		B	C			D	E	F		G		H			I		J
Microgrid Controller or ADMS			A.1	A.2	B.1	C.1	C.2	C.3	D.1	E.1	F.1	F.2	G.1	G.2	H.1	H.2	H.3	I.1	I.2	J.1
MGF	*Subfunctions*																			
Volt/Var Control	Steady state Device Level Control (Droop/V-f/PQ control)	Y	Y[18]	Y	Y[4]					Y			Y	Y				Y	Y	Y
Volt/Var Control	Optimal Co-ordinated LTCs, DERs, and Capacitor Banks for Voltage Profile Control(Both Grid-connected and Islanding State)	Y		Y	Y[12]						Y			Y			Y			Y
Volt/Var Control	Co-optimization of Real and Reactive Power Considering DRE's Real and Reactive Power Capability	Y		Y	Y[12]					Y		Y		Y			Y			Y
Volt/Var Control	Management of Voltage Fluctuations due to Intermittent DERs	Y		Y	Y[13]									Y[14]			Y			Y
Volt/Var Control	Low Voltage Ride-Through (LVRT)			Y										Y[10]						Y
Grid-connected to Islanding Transition	Intentional Islanding Transition	Y		Y	Y[15]		Y			Y			Y	Y[10]	Y	Y		Y	Y	Y
Grid-connected to Islanding Transition	Unintentional islanding transition	Y		Y	Y[15]					Y			Y[17]	Y[10]	Y	Y		Y[17]		Y
Islanding to Grid-connected Transition	Black Start	Y		Y	Y[4]					Y			Y	Y[10]	Y	Y	Y	Y		Y
Islanding to Grid-connected Transition	Synchronization	Y		Y	Y[16]					Y			Y	Y[10]	Y	Y		Y	Y	Y

[12] Using VVO application in DMS, DER is modeled with capacitor and regulator controls
[13] Using VVO voltage violation enforcement
[14] using ESS
[15] microgrid controllers function; and using temporary source energization in DMS
[16] microgrid controllers via f/V setpoints, and via protection relay with sync check
[17] through fast load shed
[18] Basic

APPENDIX D. MICROGRID FUNCTIONS RESILENCY

	Company Name	ORNL	A		B	C			D	E	F		G		H			I		J
	Microgrid Controller or ADMS		A.1	A.2	B.1	C.1	C.2	C.3	D.1	E.1	F.1	F.2	G.1	G.2	H.1	H.2	H.3	I.1	I.2	J.1
MGF	Subfunctions																			
Severe Weather Forecast	Storm/Hurricane/Extreme Temperature?						Y	Y								Y	Y			N
UPS Function for Critical Load (Intelligent Load Shedding)		Y	Y	Y	Y[1]	Y			Y	Y				Y	Y	Y	Y			Y
Coordinate DERs with Microgrid Reconfiguration			Y	Y	Y[2]	Y			Y				Y[3]	Y[3]	Y	Y	Y	Y[3]		Y
Backup Plan	Backup Resilient Islanding Operation Plan for Certain Outage Period(Energy)					Y			Y	Y				Y	Y	Y				Y

[1]Using DMS SCADA Load Shedding application
[2]Using power flow analysis and temporary source energization in DMS
[3]limited

APPENDIX E. MICROGRID FUNCTIONS ANCILLARY SERVICES

	Company Name	ORNL	A		B	C			D	E	F		G		H			I		J
Microgrid Controller or ADMS			A.1	A.2	B.1	C.1	C.2	C.3	D.1	E.1	F.1	F.2	G.1	G.2	H.1	H.2	H.3	I.1	I.2	J.1
MGF	Subfunctions																			
Day-ahead Demand Response	Price Driven Day-ahead Demand Response	Y			Y[1]	Y			Y						Y	Y	Y			N
Real-Time Demand Response	Price Driven Real-Time Demand Response	N			Y[2]	Y			Y						Y	Y	Y			Y
Utility Event Response	Active power/reserve?	Y		Y	Y[3]				Y	Y			Y	Y			Y	Y	Y	Y
T&D Congestion Management (Network restoration, dynamic line rating)		N			Y[4]									Y[5]			Y			
Regulation Service	(Frequency)	N			Y[6]		Y		Y				Y			Y		Y	Y	Y
Spinning Reserve Support		Y			Y[7]								Y			Y		Y	Y	
Phase Balancing		N			Y[8]									Y[9]			Y			
Provide Requested Supports	Var Support	Y		Y	Y[10]					Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	Watt Support	Y		Y	Y[11]				Y	Y			Y	Y	Y	Y	Y	Y	Y	Y
	Power Factor Support	Y		Y	Y[12]				Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	
	Black-Start Capacity	Y			Y				Y	Y			Y	Y[13]	Y	Y	Y	Y		Y

[1] Using DMS in conjunction with DRMS
[2] AMI integration in DMS and demand response, with DRMS
[3] P/Q lopping in grid-connected mode, f/V support for utility fluctuations for microgrid controllers; and using VVO Demand Reduction or Load Transfer application in DMS
[4] Using capability in Restoration Switching Analysis, Line Unloading , and dynamic transformer ratings functions of DMS
[5] alternate transfer capacity
[6] microgrid controller function
[7] distributed control system microgrid controllers function
[8] Using phase balancing capability in Feeder Reconfiguration application in DMS
[9] if single-phase resources available
[10] by microgrid controllers via Q setpoints, and using VVO voltage and capacitor setpoints in DMS
[11] by microgrid controllers via P setpoints
[12] by microgrid controller p.f. correction
[13] with PCS

APPENDIX F. MICROGRID FUNCTIONS GRAPHICAL USER INTERFACE AND DATA MANAGEMENT

	Company Name	ORNL	A		B	C			D	E	F		G		H			I		J
Microgrid Controller or ADMS			A.1	A.2	B.1	C.1	C.2	C.3	D.1	E.1	F.1	F.2	G.1	G.2	H.1	H.2	H.3	I.1	I.2	J.1
MGF	Subfunctions																			
IED Functions Based on International Standards for Interoperability	IEC 61850 or else	Y[1]	Y	Y	Y[2]					Y			Y[3]	Y[3]		Y	Y	Y[3]	Y[5]	Y
Database Server Design for Interoperable IED Data Gathering		N	Y	Y	Y[4]	Y	Y	Y						Y		Y	Y		Y[6]	
User Authentication		Y	Y	Y	Y[7]	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y	Y	Y	Y
Event Logging		Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
Security Issue Reporting		Y		Y	Y	Y	Y	Y	Y				Y	Y	Y	Y	Y	Y		
Alarms		Y	Y	Y	Y[8]	Y	Y	Y	Y	X			Y	Y	Y	Y	Y	Y	Y	Y
Field Sensors & Measurements Infrastructure		Y	Y	Y	Y[9]	Y			Y			Y		Y	Y	Y	Y			Y

[1]Modbus
[2]Modbus for microgrid controllers; DNP3, IEC 60870-5-104, CIM for DMS
[3] 68150 and DNP
[4] trending/historian data storage for microgrid controllers, using SCADA DNP 3.0 for DMS
[5] DNP
[6] PI interface
[7] VPN/SSH/Password HMI
[8] SCADA/HMI
[9] meter/analog inputs for microgrid controller; DNP3 field sensors for DMS