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Microgrid Controller Survey Report: 2024 Update

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Electrification and Energy Infrastructures Division

MICROGRID CONTROLLER SURVEY REPORT: 2024 UPDATE

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ABBREVIATIONS

ADMS	Advanced Distribution Management System
CSEISMIC	Complete System-level Efficient and Interoperable Solution for Microgrid Integrated Controls
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DMS	Distribution Management System
DOE	US Department of Energy
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
LTC	Load Tap Changer
ORNL	Oak Ridge National Laboratory
PV	Photovoltaic
T&D	Transmission and Distribution
UPS	Uninterruptible Power Supply
VAR	Volt-Amps Reactive

ABSTRACT

In the past decade, the number of microgrids deployed by electric utilities, end-use customers, and third parties has been increasing significantly both in the US and worldwide. The increase is driven by various reasons, such as carbon emission reduction, energy efficiency improvement, reliability and resilience enhancement, energy infrastructure modernization, and more. Microgrid controllers, as the most important components in these deployed microgrids, optimally coordinate the operation and control of the microgrid assets (e.g., distributed energy resources [DERs], energy storage systems, demand response, and even electric vehicles) and ensure that the microgrid is being operated in an efficient, clean, and resilient manner. To that end, the market for microgrid controllers has been growing rapidly in recent years. Various microgrid controllers have been released and continuously updated by vendors to satisfy the different needs of microgrid customers. However, the functionalities demonstrated by microgrid controllers released by different vendors show a huge difference because of a lack of widely known and accepted industrial standards, and various microgrid customers have specific requirements for different applications and scenarios. To obtain a clear view of the current state of the commercial microgrid controllers' functionalities and identify potential research gaps, a survey of the functionalities of commercial microgrid controllers developed by vendors and national laboratories was conducted in 2023. The results of the survey are presented in this report with the current status of commercial microgrid controllers analyzed, potential research gaps identified, and future research trends revealed.

1. INTRODUCTION

1.1 MICROGRIDS

A microgrid is defined by the Microgrid Exchange Group as "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 has been widely adopted by government agencies (e.g., US Department of Energy [DOE]) as well as academia and the electrical industry [2]. By this definition, a microgrid can be regarded as a controllable entity connected to a distribution network. In grid-connected mode, a microgrid could not only produce clean, low-cost, and sustainable energy to customers but also participate in voltage and frequency regulation and even provide inertia response [3–5]. Through seamlessly transforming into islanded operation, microgrids could survive with a high probability during widespread power outages caused by extreme weather events and thus effectively improve the resilience of distribution grids [6, 7]. In summary, microgrids enable an option for achieving efficient and resilient electricity supply for the nation in a clean, affordable, and sustainable way [8]. As a result, microgrids have been increasingly deployed in the US, as shown in Figure 1 [9].

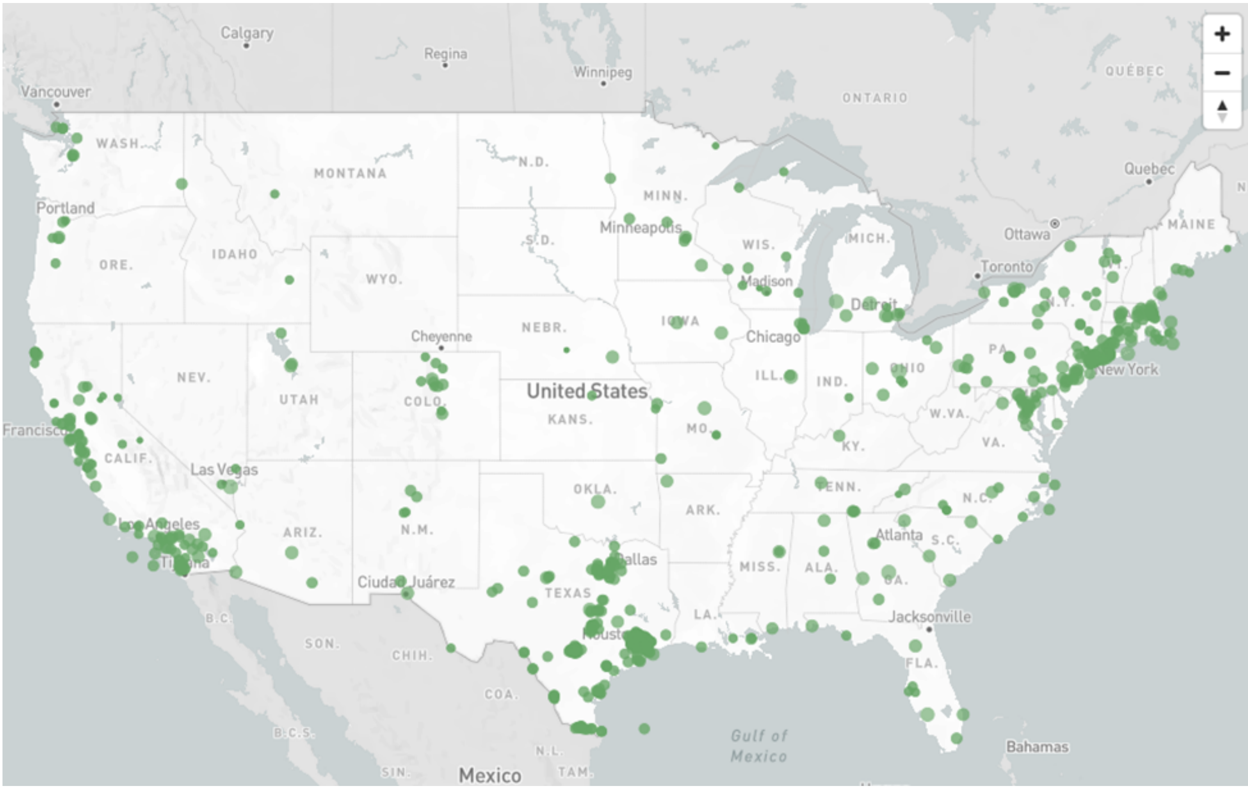


Figure 1. Microgrids deployed in the continental US.

Microgrids have long been viewed as an effective mechanism for integrating various DERs and providing a resilient power supply for critical loads during widespread outages. As modern utility grids transition from the traditional centralized structure into a distributed structure with ever-denser microgrids and DERs, networked microgrids, which are formulated by connecting adjacent microgrids and properly coordinating their controls, could achieve additional benefits. These benefits include increased loading capacity and DER hosting capacity, better efficiency, and more resilience as well as extended longevity of service, reduced operating costs, and the potential to coordinate and control aggregated assets to assist the distribution system restoration after extreme events [10]. Nevertheless, the utilities are now facing the significant challenge of complex coordination and integration of these DERs, microgrids, and networked microgrids.

Although microgrids share common characteristics, such as locality, independency, and intelligence, the specific implementation of the microgrid can vary extensively from one deployment to another. These variations can include whether the microgrid is isolated or able to connect to other power systems, the type of generating resources and energy storage systems that are connected, the type of control systems that operate the system, the reason for which the microgrid was deployed, who owns and operates the microgrid, and the regulatory structure under which the microgrid operates. Because of these variations, different microgrid implementations might be controlled and operated by microgrid controllers with very different functionalities. Example microgrids for commercial, rural, and island implementations are illustrated in Figure 2.

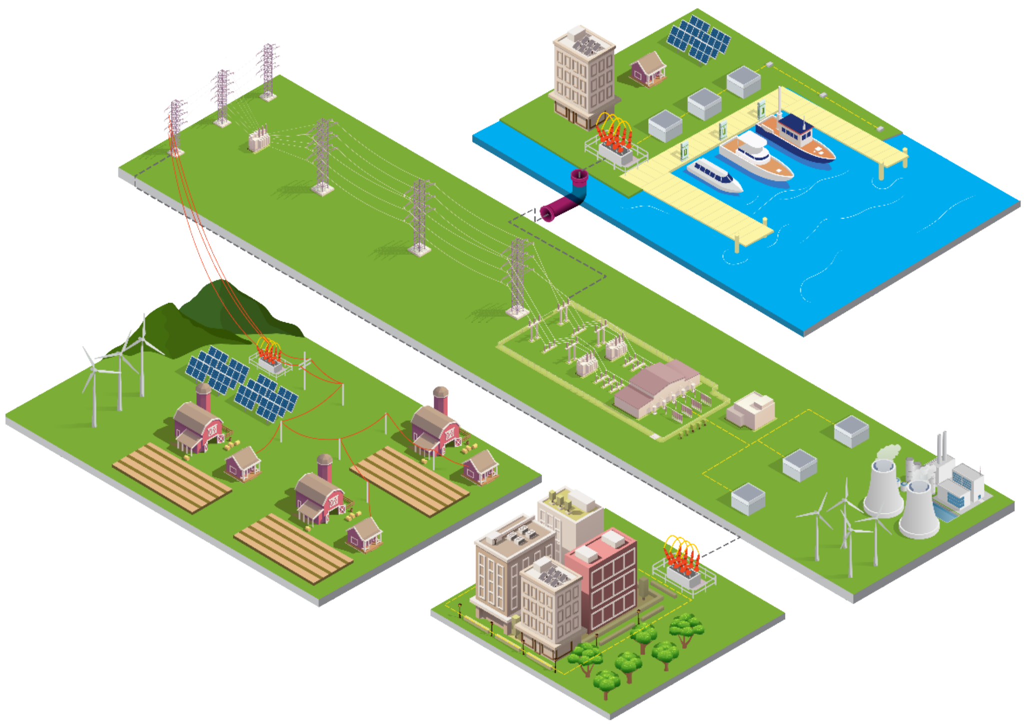


Figure 2. Example microgrids: (bottom) commercial, (lower left) rural, and (upper right) island implementations.

1.2 MICROGRID CONTROLLER

Achieving resilient, clean, and sustainable electricity supply from a microgrid requires a coordinated and coherent operation of the microgrid assets, including DERs, energy storage systems, demand response, and even electric vehicles. To that end, the market for microgrid controllers has been growing rapidly in recent years. According to a recent report by Research and Markets, the microgrid controller market is expected to reach USD 18.7 billion by 2029, which is up from USD 6.8 billion in 2024, at a compound annual growth rate of 22.6% during the 2024–2029 period. The US is expected to have the largest market share of microgrid controllers in the North American market during the forecast period [11].

Generally, a microgrid considers forecasted output of renewable distributed generation 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 dispatching for achieving targeted economic, emission, or resilience goals. As some of the pioneers on microgrid controllers, researchers at Oak Ridge National Laboratory (ORNL) developed 10 microgrid operation and control use cases in 2014 [12]. The use cases for control and operations of a microgrid include the following:

- Frequency control
- Voltage control (grid-connected and islanding)
- 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
- User interface and data management

These 10 use cases have been widely adopted by the industry in the past for development of their prototype microgrid controllers. Also, the Institute of Electrical and Electronics Engineering (IEEE) P2030.7 *Standard for the Specification of Microgrid Controllers* simplified these 10 use cases into two core functions: the dispatch function, which dispatches individual devices in given operating modes and with specified set points, and the transition function, which supervises the transitions between connected and disconnected states and ensures the dispatch is appropriate for the given state [13]. In specific, the transition function includes unplanned islanding, planned islanding, reconnect, and black start. It should be noted that the standard only provides the minimum functional technical requirements that are universally needed to assure a technically sound operation of the microgrid.

The Complete System-Level Efficient and Interoperable Solution for Microgrid Integrated Controls (CSEISMIC) microgrid controller developed by ORNL is shown in Figure 3 as an example of a microgrid controller [14]. Generally, CSEISMIC is a central controller consisting of two parts: MicroSCADA (supervisory control and data acquisition) and MicroEMS (energy management system). MicroSCADA collects real-time microgrid data, sets the operation modes of the generation and loads to maintain system stability, and communicates with all the components in the microgrid, including the microgrid switch, energy resources, loads, and protection relays. MicroSCADA also communicates with MicroEMS to send microgrid measurement data and receive optimization dispatch. MicroEMS performs optimized power dispatch to meet operation objectives and receive commands from the upper stream distribution system operator to provide ancillary services. Therefore, the CSEISMIC is the interface or agent between the distribution system operator and the microgrid, and CSEISMIC also acts as the control and management center of the microgrid and its components. It enables the integration of different technologies and subsystems (inverter-based and machine-based energy resource control, energy management, communication, and protection) used to fulfill the microgrid function requirements.

Various microgrid controllers have been released and are continuously updated by vendors to satisfy the different needs of microgrid customers. However, the functionalities demonstrated by microgrid controllers released by different vendors show a huge difference because they lack widely known and accepted industrial standards, and various microgrid customers have specific requirements for different applications and scenarios. This issue has created confusion over the microgrid control options and functions that are available today. For this reason, a complete list of microgrid functions has been developed and is presented in Section 2.1 of this report.

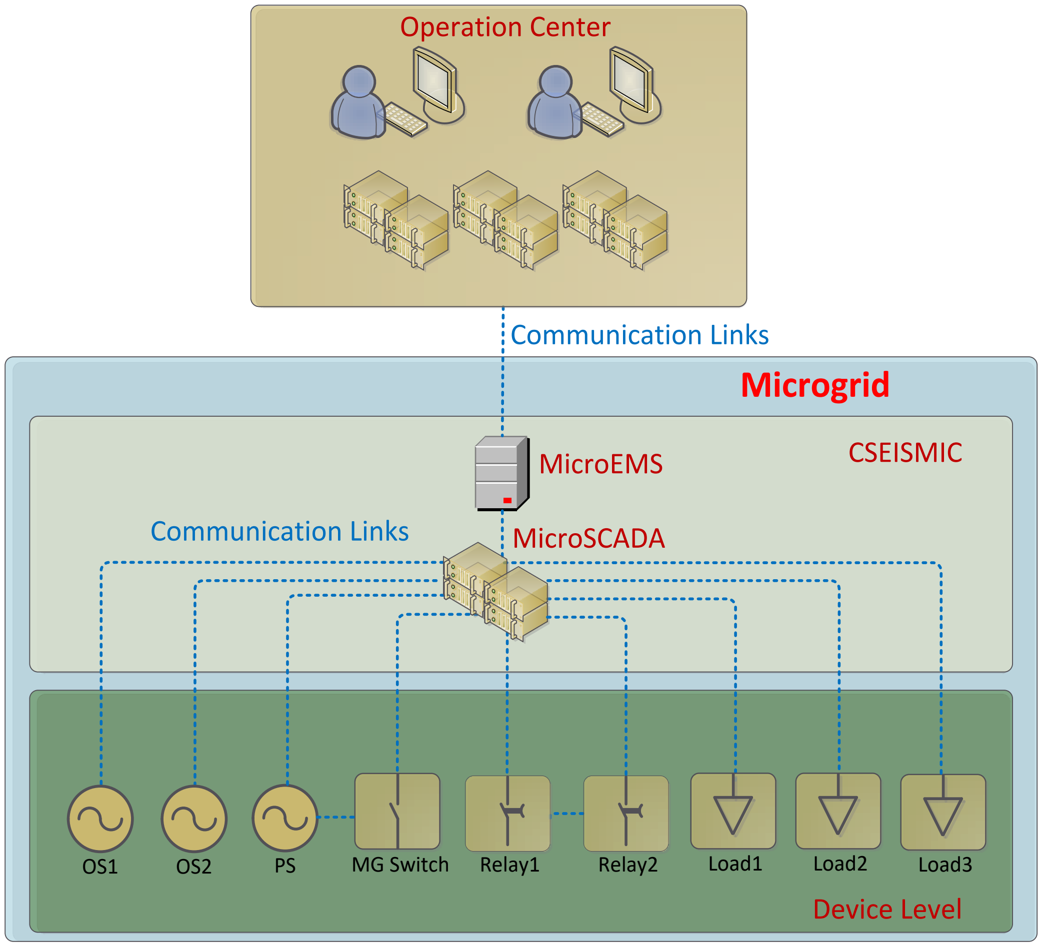


Figure 3. Example microgrid controller: CSEISMIC developed by ORNL.

1.3 DISTRIBUTION MANAGEMENT SYSTEM, ADVANCED DISTRIBUTION MANAGEMENT SYSTEM, AND DISTRIBUTED ENERGY RESOURCE MANAGEMENT SYSTEM

A distribution management system (DMS) is a visualization and decision support system used by utility operators and field operation and maintenance crews for monitoring and controlling the electric distribution system in a coordinated and efficient manner. The DMS is a powerful set of tools that allows utility operators to view and manage their distribution networks from topology and power flow to automation and switch order management. The DMS usually includes functions such as distribution power flow; voltage/VAR control; fault location, isolation, and service restoration; feeder reconfiguration; and more. An example of a DMS implemented at EPB of Chattanooga and developed by Open Systems International Inc. is shown in Figure 4 [15].

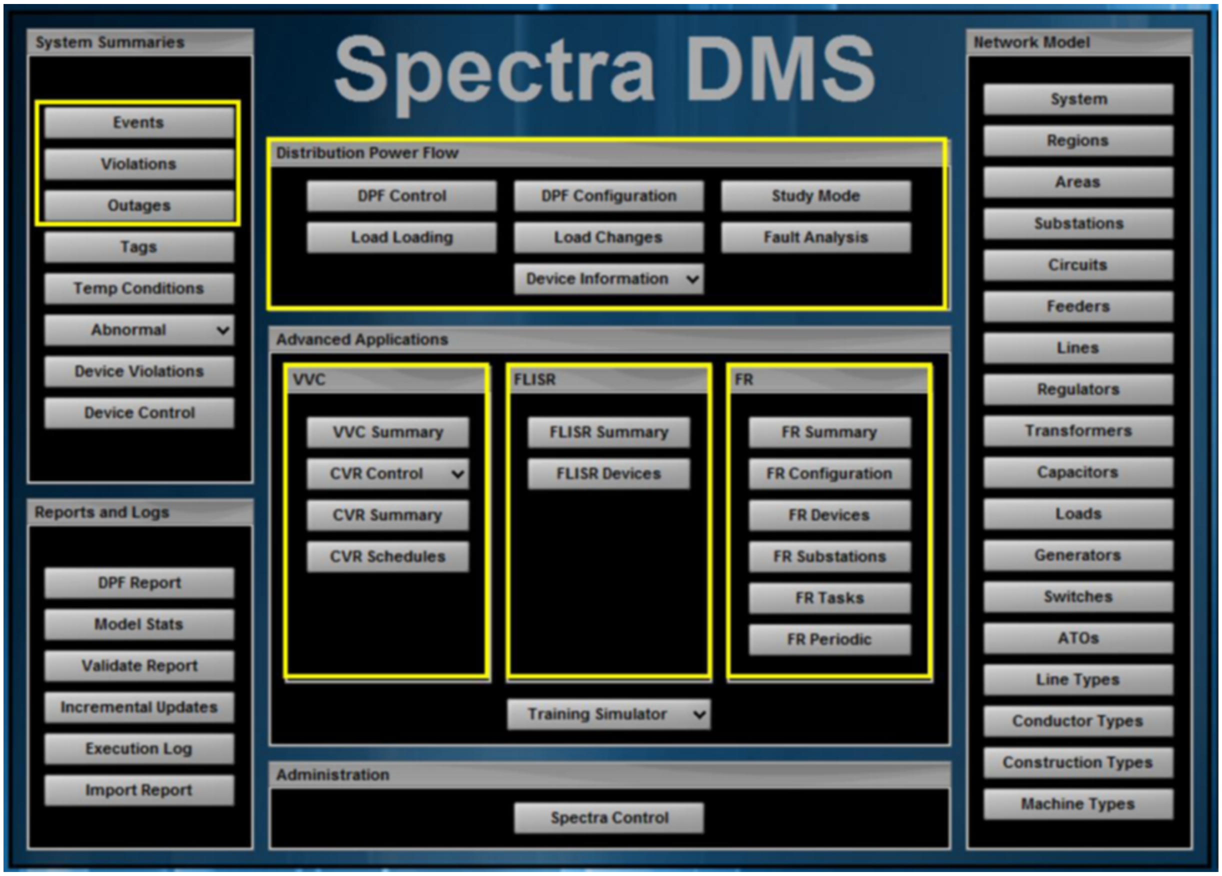


Figure 4. Spectra DMS suite developed by Open Systems International Inc.

The advanced distribution management system (ADMS) was constructed from the DMS concept but with additional features. The ADMS integrates energy efficiency technologies, demand response, DERs/DERs aggregators, and energy storage technologies to enable grid operators to make intelligent decisions when operating the distribution system more efficiently, reliably, and at a lower cost. Similar to microgrids, the DERs, energy storage systems, and responsive loads could be operated in both grid-connected and islanded modes. As a result, many ADMS/DMS vendors are attempting to expand the development of ADMS/DMS products to include certain microgrid management functions, e.g., DER dispatch. However, the major functions of ADMS/DMS are very different from microgrid controllers. In addition, ADMS/DMS and microgrid controllers have distinctly different markets, target customers and applications Thus, the ADMS/DMS products were not included in the survey.

Besides DMS/ADMS, DER aggregators and some utilities have been utilizing a software platform called distributed energy resource management system (DERMS), which is a control system that enables optimized control of the grid and DERs. DERMS solves the problem of how to integrate DERs into grid operations and supports many functionalities, such as, DER forecasts, DER situational awareness, DER energy management and arbitrage, DER fleet management, congestion relief using DERs, Volt/VAR control and dynamic network topology, etc. Although, DERMS has some functions overlapped with microgrid controllers, they are very different in the majority of functions, markets and customers. For this reason, the DERMS products were not included in the survey, either.

1.4 SCOPE AND PURPOSE

Because of the lack of widely recognized industrial standards for microgrid controllers and different applications of microgrids, the functionalities of existing commercial microgrid controllers might be significantly different from each other. In some cases, a microgrid has only been developed and demonstrated for individual customers at specific sites. As a result, the current state of the microgrid controller industry is difficult to assess.

To assess the current state of commercial microgrid controllers and identify the potential research and development gaps, ORNL conducted a survey of the functionalities of commercial microgrid controllers developed by vendors and national laboratories in 2015–2016, and the corresponding results were compiled and analyzed in a report in 2016 [16]. For simplification of the survey, a complete list of microgrid controller functions was developed and delivered to the survey participants. The participants simply needed to indicate whether a function was available in their microgrid controller products by putting a “yes” or “no” behind the function. Then, the survey results were collected and compiled to provide a clear indication of the state of commercial microgrid controllers.

It has been 7 years since the last survey of the functionalities of commercial microgrid controllers was published. Considering the increasing deployment of microgrids and the rapid changes and upgrades to venders’ microgrid controllers for new applications or requirements from customers, this survey may now be out of date for the following reasons:

- Vendors are rapidly changing the design and functionality of their microgrid controllers to satisfy the requirement of both existing and new customers—especially customers with new application scenarios for microgrids.
- New players have joined the market with their new products as the market of microgrids has been increasingly expanded in the last several years.
- The whole electrical industry has new focuses, such as resiliency, decarbonization, compatibility issues, and more, which drive the vendors to make adaptions by adjusting the functions of their microgrid controllers.

To obtain a clear view of the current state of the commercial microgrid controllers’ functionalities and identify potential research gaps, a new survey of the functionalities of commercial microgrid controllers developed by vendors and national laboratories was conducted in 2023. The results of the new survey are compiled and compared with those of the previous survey in this report. This updated report is presented with the current status of commercial microgrid controllers analyzed, potential research gaps identified, and future research trends revealed.

1.5 CHALLENGES

Notably, the objective of this survey was to assess the overall state of existing commercial microgrid controllers and identify potential research and development gaps. A horizontal comparison of different microgrid controllers was out of the scope of this survey. Also, a number of challenges existed when evaluating the results, including the following:

- The survey cannot capture very detailed features of vendors’ products. For example, both vendors’ microgrid controllers have communication links with an on-site device, but one controller might be compatible only with the same vendor’s developed assets because the communication protocol used was specifically designed by that vendor. However, another controller may be compatible with other vendor's developed assets because it may be compatible with all standard communication protocols, such as International Electrotechnical Commission's IEC 61850, DNP3, Modbus, and others. Capturing these details would require a much more comprehensive survey, and the information might be business confidential or simply unavailable without a nondisclosure agreement.

- A full, comprehensive survey of all existing commercial microgrid controllers is difficult because many vendors consider the functionality of their microgrid controllers to be business sensitive. To protect the confidentiality of the data and obtain more survey responses, an anonymized process promised to remove vendor-specific details. However, only approximately 50% of the respondents replied to the request.

- Because of the inherent nature of the research involved in microgrid controllers, vendors are frequently updating the functionality of their microgrid controllers upon requests from various microgrid clients. Therefore, the survey results presented here might not be able to catch the most recent changes and updates for some microgrid controllers.

2. MICROGRID CONTROLLER SURVEY

2.1 APPROACH

In the previous survey in 2016, a complete list of functions that could be included in a microgrid controller was generated based on the 10 ORNL microgrid operation and control use cases and 18 DMS functions developed by the IEEE DMS task force of the Smart Distribution Working Group for the DMS–Outage Management System State of the Industry Survey [8, 17]. These functions were categorized into five groups: energy management, protection and control, resiliency, ancillary services, and data management, as shown in Figure 5. Each group has a particular focus or objective:

(1) The functions in energy management have the primary target of supporting power balancing in a steady state for both grid-connected and islanded modes.

(2) The functions in protection and control support voltage and frequency control in a transient state for both grid-connected and islanded modes.

(3) The functions in resiliency aim to increase survivability and recovery of a microgrid under severe disturbances or extreme weather conditions.

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

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

In this survey, the five function groups and most of the functions in each group were preserved, although new functions were added by reviewing literature and recent microgrid projects to capture any new functions, requirements, and focuses. In the energy management function group, new functions, such as price taker/bidder/active market player, centralized/distributed communication, and multi-microgrids coordination, were added. In protection and control function group, grid forming/following control was added to reflect the state-of-the-art research and development in this area. In the resiliency function group, severe weather/temperature forecast and component damage estimation were added. In the ancillary service function group, phase balancing was added. Finally, event replay and alarm processing were added into the data management function group.

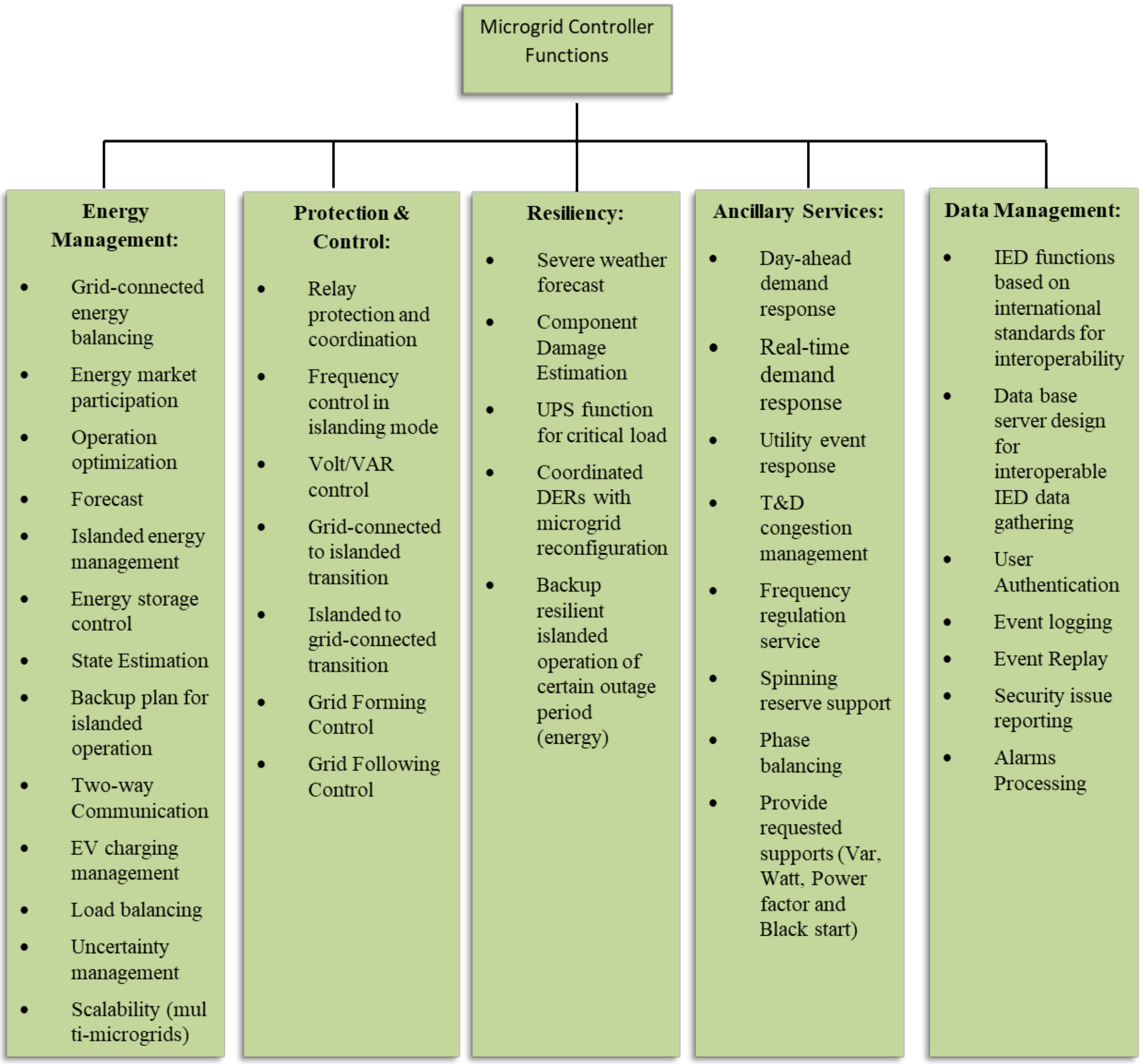


Figure 5. Microgrid controller functions. Each function may include two or more subfunctions, and a subfunction might be realized using different methods. To capture the state of the art of the microgrid controllers and identify potential research and development gaps, this study tried to include more details on whether the function was developed, how the function was realized, and to what extent it was realized in the survey. All functions listed in the survey can be found in Table 1–Table 5. The specific definitions of these functions can be found in Appendix A.

Table 1. Functions in energy management group

1 Energy Management	1.1.	Grid-Connected Energy Balancing	Unit Commitment (Stochastic/Robust/Deterministic?)
			Economic Dispatch (Stochastic/Robust/Deterministic?)
			Optimal Power Flow (Stochastic/Robust/Deterministic?)
	1.2.	Energy Market Participation	Price Taker
			Bidder/Active Market Player
	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	Unit Commitment (Stochastic/Robust/Deterministic?)
			Economic Dispatch (Stochastic/Robust/Deterministic?)
			Optimal Power Flow (Stochastic/Robust/Deterministic?)
			Spinning Reserve/Regulation Management
	1.6.	Energy Storage Control	Primary
			Secondary
			Tertiary
	1.7.	State Estimation	State Estimation for Billing
			State Estimation for Optimization and Control
	1.8.	Backup Plan for Islanding Operation	Contingency Analysis (Power Perspective)
	1.9.	Two-Way Communication	Centralized Communication
			Distributed Communication
	1.10.	Electric Vehicle Charging/Discharging Management	Vehicle to Grid?
	1.11.	Load Balancing	Balancing Loads Between Feeders
	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 or Subseconds)
			Transient Device-Level Control
			Frequency Smoothing
			Low-Frequency Ride-Through
			Emergency Load Shedding
	2.3.	Volt/Var Control	Steady-State Device-Level Control (Droop/V-f/PQ control)
			Optimal Coordinated Load Tap Changers, Distributed Energy Resources, and Capacitor Banks for Voltage Profile Control (Both Grid-Connected and Islanding State)
			Cooptimization of Real and Reactive Power Considering Distributed Energy Resources' Real and Reactive Power Capability
			Management of Voltage Fluctuations Owing to Intermittent Distributed Energy Resources
			Low-Voltage Ride-Through
			High-Voltage Ride-Through
			Phase Angle Jump Compensation (Cold Load Pick-Up)
	2.4.	Grid-Connected to Islanding Transition	Intentional Islanding Transition
			Unintentional Islanding Transition
	2.5.	Islanding to Grid-Connected Transition	Black Start
			Synchronization
	2.6.	Grid Forming Control	Voltage Support
			Frequency Support
	2.7.	Grid Following Control	Active Power Regulation
			Reactive Power Regulation

Table 3. Functions in resiliency group

3 Resiliency	3.1.	Severe Weather Forecast	Storm/Hurricane
			Extreme Temperature
			Other
	3.2.	Component Damage Estimation	Damage Modeling
	3.3.	Uninterruptible Power Supply Function for Critical Load (Intelligent Load Shedding)	—
	3.4.	Coordinate DERs with Microgrid Reconfiguration	Fixed Boundary
			Dynamic Boundary
	3.5.	Backup Plan	Backup Resilient Islanding Operation Plan for Certain Outage Period (Hours/Days/Weeks)

Table 4. Functions in ancillary services group

4 Ancillary Services	4.1.	Day-Ahead Demand Response	Price-Driven Day-Ahead Demand Response
	4.2.	Real-Time Demand Response	Price-Driven Real-Time Demand Response
	4.3.	Utility Event Response	Active Power/Reserve?
	4.4.	Transmission and Distribution Congestion Management (Network Restoration, Dynamic Line Rating)	—
	4.5.	Frequency Regulation Service	(Frequency)
	4.6.	Spinning Reserve Support	—
	4.7.	Phase Balancing	Balancing Loads Between Phases
	4.8.	Provide Requested Supports	Var Support
			Watt Support
			Power Factor Support
			Black-Start Capacity

Table 5. Functions in GUI and data management group

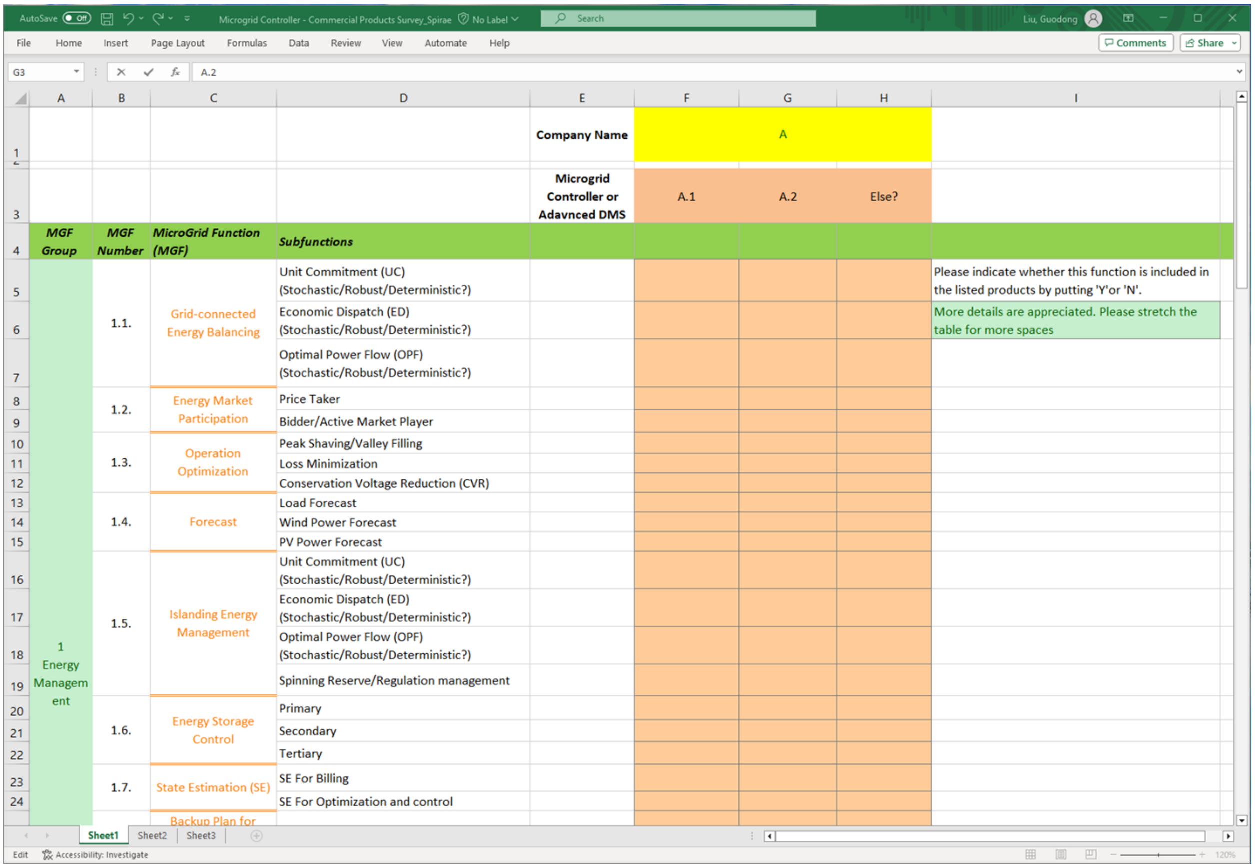
5 GUI and Data Manageme nt	5.1.	Intelligent Electronic Device Functions Based on International Standards for Interoperability	IEC 61850 or Other
	5.2.	Database Server Design for Interoperable Intelligent Electronic Device Data Gathering	—
	5.3.	User Authentication	—
	5.4.	Event Logging	—
	5.5.	Event Replay	—
	5.6.	Security Issue Reporting	—
	5.7.	Alarm Processing	—

All these functions were put into a Microsoft Excel form and sent to the survey participants. The participant list was based on the participants of the previous survey in 2016, which mainly included all active members of the IEEE P2030.7 Distribution Resources Integration Working Group/Microgrid Controllers Task Force. These task force members primarily consist of microgrid controller vendors and consultants actively involved in microgrid controller research and development. Some companies in the previous participant list have gone out of business or have shifted their business out of the microgrid area, and new players have joined the market with their new products as the market of microgrids has been increasingly expanded in the last several years. The updated survey participants are listed in Table 6.

Table 6. Participants of the survey

Company Name		
ABB	Spirae	Tesla Energy
GE	Caterpillar	Pareto Energy
Siemens	S&C Electric	ELM
Schneider	Power Analytics	Powerflex
SEL	Cummings	EdgeTunePower
Eaton	Sustainable Power Systems	New Sun Road
Honeywell	Hitachi	ORNL (CODAS+MO)

To make the survey easy to take and to avoid burdening participants with too many questions and significant work, participants were asked to put a simple "Y" or "N" to indicate whether the specified function has been included in a listed product. The names of the known vendor products were specified. Nevertheless, the vendors were allowed to add columns for other products and provide further specifications on the responses. A snapshot of the survey form is shown in Figure 6.



	MGF Group	MGF Number	MicroGrid Function (MGF)	Subfunctions	Company Name / Microgrid Controller or Adavnced DMS	A.1	A.2	Else?	
1					Company Name	A			
3					Microgrid Controller or Adavnced DMS	A.1	A.2	Else?	
5	1 Energy Management	1.1.	Grid-connected Energy Balancing	Unit Commitment (UC) (Stochastic/Robust/Deterministic?)					Please indicate whether this function is included in the listed products by putting 'Y'or 'N'.
6				Economic Dispatch (ED) (Stochastic/Robust/Deterministic?)					More details are appreciated. Please stretch the table for more spaces
7				Optimal Power Flow (OPF) (Stochastic/Robust/Deterministic?)					
8		1.2.	Energy Market Participation	Price Taker					
9				Bidder/Active Market Player					
10		1.3.	Operation Optimization	Peak Shaving/Valley Filling					
11				Loss Minimization					
12				Conservation Voltage Reduction (CVR)					
13		1.4.	Forecast	Load Forecast					
14				Wind Power Forecast					
15				PV Power Forecast					
16		1.5.	Islanding Energy Management	Unit Commitment (UC) (Stochastic/Robust/Deterministic?)					
17				Economic Dispatch (ED) (Stochastic/Robust/Deterministic?)					
18				Optimal Power Flow (OPF) (Stochastic/Robust/Deterministic?)					
19				Spinning Reserve/Regulation management					
20		1.6.	Energy Storage Control	Primary					
21				Secondary					
22				Tertiary					
23		1.7.	State Estimation (SE)	SE For Billing					
24				SE For Optimization and control					
			Backup Plan for						

Figure 6. An example of the survey form.

Notably, the main objective of this survey was to assess the overall status of commercial microgrid controllers, identify any potential gaps, and guide future research and development in this area. To encourage the participation of vendors, anonymity on the vendors' names and their products was promised to all participants. Thus, the names of the vendors and the products were removed to provide anonymity to all participants after feedback was received.

2.2 SURVEY RESULTS

The survey was first distributed in June 2023, and the latest feedback was collected in March 2024. The survey Excel form was emailed to all 21 vendors and national labs listed in Table 6. Currently, survey results from 10 survey participants have been received on 11 microgrid controller products. The original survey results of these 10 survey participants were anonymized and compiled into a single table for easy comparison. The results are shown in Appendixes B–F.

The survey results of 2024 were compared with those of 2016. The comparison of functions that have been well-developed are shown in Table 7. Overall, the current microgrid controllers have more functions that are well-developed compared with the previous microgrid controllers that were reported in 2016.

Table 7. Survey results: well-developed functions

2016 Results (out of 11 participants)	2024 Results (out of 10 participants)
Economic dispatch for grid-connected and islanded modes (9)	Economic dispatch for grid-connected and islanded modes (9)
Peaking shaving (10)	Peaking shaving (9)
Loss minimization (8)	Loss minimization (6)
Reserve management (9)	Reserve management (7)
Two-way communication (8)	Two-way communication (7)
Emergency load shedding (10)	Emergency load shedding (8)
Islanding (9)	Islanding (10)
Resynchronization (8)	Resynchronization (9)
Uninterruptible power supply function for critical load (9)	Uninterruptible power supply function for critical load (9)
Provide requested support (9)	Provide requested support (10)
	Black start (10)
	Energy storage control (9)
	Steady-state coordinated device level f and V control (9)
	Grid forming P and Q control (9)
	Grid following P and Q control (10)
	Utility event response (9)
	Disturbance logging and replay (9)
	Management of voltage fluctuations owing to intermittent DERs (8)
	User authentication (10)
	Security issue reporting (8)
	Alarm processing (8)

In the 2016 results, most functions that have been well-developed were still basic functions of microgrid controllers, such as dispatch for grid-connected and islanded operating modes, islanding, resynchronization, uninterruptible power supply function for critical load, and others, or other functions closely coupled with basic functions, such as peak shaving, loss minimization, reserve management, and providing requested support, which are all closely related to basic dispatch functions. Also, an efficient two-way communication system is necessary for all these functions. Comparing with the 2016 results, the 2024 results show that more functions have been well-developed other than the basic functions in the 2016 results. First, the current microgrid controllers make microgrids more controllable. For example, functions including energy storage control, steady-state coordinated device level f and V control, grid forming P and Q control, and grid following P and Q control enhance the controllability of microgrids. Second, the current microgrid controllers make the microgrid more responsive. Functions such as black start, management of voltage fluctuations owing to intermittent DERs, and utility event response make microgrids more responsive to both internal and external events. Third, the current microgrid controllers became more human-interactive. Functions such as disturbance logging and replay, security issue reporting, and alarm processing improve the microgrid controller's user operability.

Compared with the survey results of 2016, the functions that remain undeveloped or were not included in most of the microgrid controllers in 2024 are listed in Table 8. Generally, some changes are present, but these changed functions are still not popular or commonly included in current microgrid controllers for three reasons. First, some of these functions are control functions that are usually hosted at the inverter level, such as transient device-level control, low-frequency ride-through, and low-voltage ride-through. The microgrid controllers only simply enable these functions or provide set points. The functions are directly executed by a device-level controller and are thus not included in microgrid controllers. Second, some of these functions are advanced functions that require data and parameters of the whole distribution system and complicated optimization algorithms, such as conservation voltage reduction, state estimation, contingency analysis, and transmission and distribution (T&D) congestion management. These functions are most hosted by the DMS/ADMS and are thus not included in microgrid controllers. Third, some of these functions are usually hosted by professional third-party products, such as severe weather forecast and electric vehicle charging management. In summary, these undeveloped functions in Table 8 do not necessarily mean that R&D gaps exist here but more frequently indicate that these functions could be hosted and executed beyond the microgrid controllers. Thus, the microgrid controller could be more focused and efficient.

Notably, a function might be realized using different methods in different vendors' products. Although vendors have laid claims to supporting these functions, a true comparison of the ability for a microgrid controller to perform these actions can only be demonstrated on real microgrids or microgrid test beds [18], which is beyond the scope of this report.

Table 8. Survey results: undeveloped functions

2016 Results (out of 11 participants)	2024 Results (out of 10 participants)
Conservation voltage reduction (3)	Conservation voltage reduction (1)
State estimation (5)	State estimation (5)
Contingency analysis (6)	Contingency analysis (6)
Electric vehicle management (4)	Electric vehicle management (4)
Transient device-level control (4)	Transient device-level control (6)
Low-frequency ride-through (3)	Low-frequency ride-through (4)
Low-voltage ride-through (3)	Low-voltage ride-through (3)
Severe weather forecast (3)	Severe weather forecast (4)
T&D congestion management (3)	T&D congestion management (3)

2.3 GAP ANALYSIS

Although most of the listed functions have been included in most commercial microgrid controllers, some functions have been undeveloped. These functions might be critical to the economy and resiliency of microgrids. As a result, these R&D gaps have been summarized in Table 9. These R&D gaps are introduced as the following.

- Energy market participation: Although the majority of the survey results indicated that they have included function of energy market participation in their microgrid controllers, most results indicate that they only participate in the energy market as price takers. Only four responses claim that they can actively bid into the energy market [19]. As the Federal Energy Regulatory Commission's FERC Order No. 2222 has opened the door to microgrids and DERs in wholesale markets, allowing DERs and DER aggregators larger than 100 kW to participate and compete in all Independent System Operator (ISO)/ Regional Transmission Organization (RTO) markets, it will become more common for microgrids to be directly bid into energy markets [20].

- Load and photovoltaic (PV) power forecasts: Load forecast and PV power forecast have been developed and included in most microgrid controllers, but wind power forecast is rare. Different from wind farms in bulk power systems, the wind turbines installed in microgrids generally have very small capacity. Its power output is heavily affected by the nearby microclimate and shows significant randomness [21].

- Multiple microgrids or microgrid network: Traditionally, microgrid technology creates individual islands with rigid boundaries. However, as microgrids become more widespread, the importance increases that these microgrids can collaborate to maximize the utilization of renewables and increase resiliency [22].

- Additional uncertainty management of renewables: The dispatch models currently used in microgrid controllers are still a deterministic model without or with simple predefined reserve levels. The uncertainties of renewable generation outputs have been neglected. Additionally, the stability of microgrids has been neglected because of the nonlinearity of the system in transient states. Advanced dispatch algorithms, which could solve the challenges associated with the high penetration of variable renewable generation and guarantee the efficient and secure operation of future microgrids, need to be further investigated [23].

- Phase angle jump compensation: As microgrids usually have high penetration of renewable energy resources integrated through power electronic converters, the significant changes of renewable power generation and loads could cause voltage sags, which might cause tripping or damage of converters and even unexpected load interruptions. For this reason, phase jump compensations, such as dynamic voltage restorers, are necessary for improving the voltage quality from voltage sags [24]. Currently, this function has rarely been included in existing microgrid controllers.

- Severe weather forecast and component damage estimation or modeling under extreme weather conditions: Microgrids are critical for improving the resilience of the power supply, especially during severe weather events such as storms and extreme cold and hot temperatures. Effective forecasting of when and the extent of these extreme weather events could give microgrid operators time to make corresponding preparations for mitigating the loss. Additionally, effective prediction of the damages to each component could make the pre-event preparation more targeted and effective. These areas still need further investigation.

- T&D congestion management: Microgrids could provide various kinds of ancillary services to distribution and transmission system operation, such as congestion relief. However, because of the small capacity of DERs in microgrids, effective T&D congestion relief requires coordination of multiple microgrids, feeder power flow rerouting, and even dynamic line rating.

- Phase balancing: Although most commercial microgrid controllers still use the single-phase balanced model, the three-phase unbalanced system model has shown more interesting characteristics and challenges [25]. Given that the majority of rooftop PV and residential electric vehicle charging units are single-phase generation and demand, the power imbalance between phases might get worse without proper mitigating measures, leading to power quality issues.

Table 9. Summarized R&D gaps

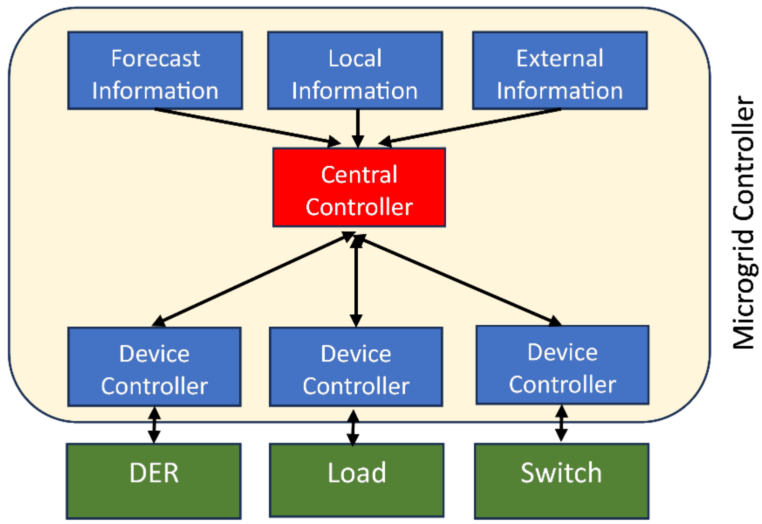
Function Group	Function
Energy Management	Energy market participation: active market bidder (4)
	Wind power forecast (1)
	Multiple microgrids or microgrid network (4)
	Additional uncertainty management of renewables (5)
Protection and Control	Phase angle jump compensation (cold load pick-up) (0)
Resiliency	Severe weather forecast: storm (3)
	Severe weather forecast: extreme temperature (0)
	Component damage estimation and modeling (0)
Ancillary Services	Phase balancing (2)
	T&D congestion management: power flow rerouting (3)
	T&D congestion management: dynamic line rating (1)

2.4 RESEARCH TRENDS

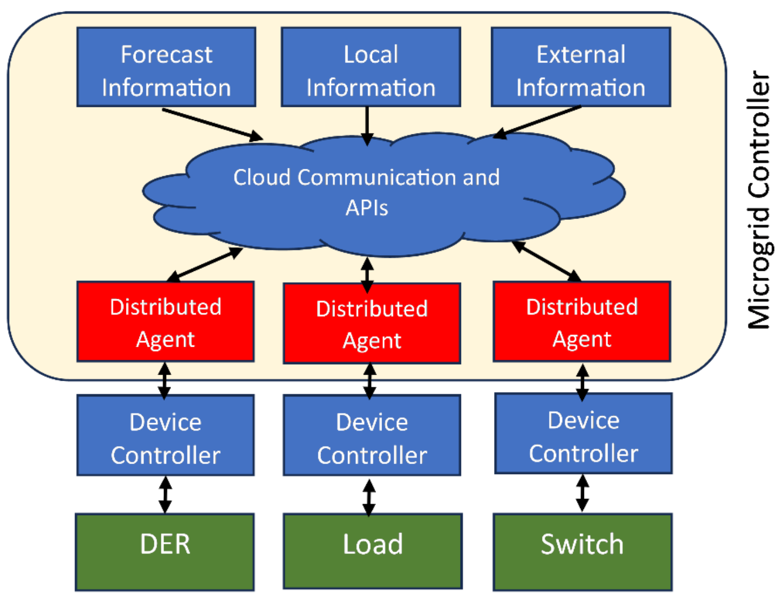
Existing commercial microgrid controllers generally use a hierarchical centralized control, in which a central controller collects all information of the DERs and loads in the microgrid, relies on central intelligence to make dispatch decisions based on collected information, and sends control set points to individual components, as shown in Figure 7a. Although, this structure is straightforward, easy to implement, and has been working well for microgrids owned and operated by a single entity (e.g., utility), this centralized control architecture is subject to scalability and privacy issues because all data and information are sent to the central controller.

As more DERs are being deployed in the distribution system, the hybrid ownership model, in which the utility owns the microgrid and the customer or third-party owns DERs and controllable loads, has grown significantly. For example, the Southern Company Connected Community microgrid was owned by the local utility (i.e., Alabama Power), and the customers owned and controlled the main load (i.e., home appliances, such as water heater, air conditioner, and more). Under this situation, a transactive energy-based distributed control structure has increasingly gained attention, as shown in Figure 7b. The distributed control structure does not need to collect any information about the customers beyond the interface points (i.e., customers' meters) and makes dispatch decisions based on the negotiation of all distributed agents [26]. Transactive energy is a set of economic and control mechanisms that allows a dynamic balance of supply and demand across the entire electrical infrastructure using value (e.g., price) as a key operational parameter [27]. Under this framework, DERs and load are directly controlled by their owners rather than the microgrid controller to ensure the autonomy and privacy of customers. Customers receive nodal price signals and adjust their generation and consumption correspondingly.

As the number of microgrids with different resources increases, ownership models and purposes (i.e., use case strategies) are being integrated into the distribution network, communication, and data sharing between those microgrids and the DMS will be necessary for realizing various benefits of microgrids. Existing works assume some level of observability inside of the microgrids with minimal barriers presumed to communication and data sharing. Because future microgrids may be independently owned and operated with mixed business models, identifying the minimum data exchange and value propositions to accessing and governing these data will become a crucial consideration. The distributed control structure could preserve the autonomy and privacy of microgrids and customers and reduce the amount of data exchange while also enabling plug-and-play for emerging controllable devices at the grid edge.



(a) Centralized control



(b) Distributed control

Figure 7. Microgrid control structures

In the past, the microgrid controllers were focusing on functions of intentional and unintentional islanding and resynchronization, which are most realized through control design of inverters. The advanced secondary and tertiary functions have been neglected. Currently, grid edge device controllers are becoming smarter. Most of primary control (e.g., islanding) and a certain amount of secondary control (e.g., voltage and frequency regulation, resynchronization, and more) could be directly handled by the device controller with little intervention from microgrid controllers. Meanwhile, as the cloud service becomes more and more powerful and popular, the complex secondary and tertiary control functions could be realized in the cloud by using emerging technologies, such as the Internet of Things, machine learning, digital twin, and more. In this way, users could automatically configure their microgrid controller by selecting preferred functions in the cloud based on their site-specific needs.

CONCLUSION

This report discusses the results of a recent microgrid controller survey and evaluates 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. Then, a survey form in Microsoft Excel with these functions listed was sent to vendors and national laboratories with microgrid controller products. All survey results were compiled and compared with those of the previous survey in this report. The results showed the status of microgrid controllers in the market. Potential research gaps were identified, and future research trends were revealed.

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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 shutdown sequence of generators.
Stochastic/Robust/Deterministic	The optimization model considers stochastic optimization, robust optimization, or deterministic optimization.
Optimal Power Flow	Determine the real and reactive power output for interconnected generators with electrical network constraints.
Bidder/Active Market Player	The microgrid controller is able to bid into the energy market or make transactions with another entity.
Price Taker	The microgrid controller directly accepts the price from the local energy market.
Peak Shaving	The microgrid controller reduces the pick load of the microgrid or reduces the demand or increases the generation of the microgrid during the grid's peak demand periods.
Loss Minimization	Minimize the power loss within the distribution network.
Conservation Voltage Reduction	Reduce the voltage to the lower half of the allowed voltage range to decrease the load consumption
Load Forecast	Forecast the load demand in the next day, hour, or 5 minutes.
Wind Power Forecast	Forecast the power generated by wind turbines in the next day, hour, or 5 minutes.
PV forecast	Forecast the power generated by photovoltaic (PV) panels in the next day, hour, or 5 minutes.
Reserve Management	Quantify the amount of needed spinning reserve and regulation capacity and dispatch the generators or responsive loads when islanded accordingly.
Energy Storage Control	Control and optimize the charging and discharging of energy storage systems.
State Estimation	Estimate the condition of the system and validate with redundant measurements.
Centralized Communication	Centralized communication is a central command center for all communication efforts.
Distributed Communication	Distributed communication is the handling, managing, and analyzing of vast amounts of data across multiple computers or servers.
Backup Plan for Islanding Operation	Prepare islanding operation and ensure that enough power capacity is available.
Contingency Analysis (Power Perspective):	Perform the system failure analysis for $n-1$ or $n-2$ failures.
Load Balancing	Balance the load between different feeders.
Uncertainty Management of Renewables	Any special program for handling the uncertainty of renewables and the load is included in this category.
Scalability	The scalability is the application for multiple microgrids and networked microgrids with different sizes, purposes, assets, and more.
Fault Location, Isolation & Service Restoration	Quickly determine fault locations, isolate faults, and automatically restore power during outages.
Steady state Device Level Control	This category includes droop/V-f/PQ control.

Disturbance Logging	Record the current and voltage curves during the faults.
Coordinated Control of Multiple Device	Coordinated control is the real power coordination of devices for voltage regulation.
Transient Device Level Control	Transient coordination for power electronic devices and other equipment.
Frequency Smoothing	Reduce fluctuation of the system frequency caused by penetration of renewable energy resources.
Low-Frequency Ride-Through	This category is the capability of microgrids to stay connected in short periods of lower grid frequency.
Emergency Load Shedding	Reduce power demand by turning power off to some customers to help prevent longer, larger outages.
Optimal Coordinated load tap changers (LTCs), Distributed Energy Resources (DERs), and Capacitor Banks for Voltage Profile Control (Both Grid-Connected and Islanding State)	This category is the coordination of controllable devices in a distribution network, such as LTCs, DERs, and capacitor banks.
Cooptimization of Real and Reactive Power Considering DER's Real and Reactive Power Capability	This category is the coordination of real and reactive output of DERs considering the constraints of DERs' capacity limits.
Low-Voltage Ride-Through	This category is the capability of microgrids to stay connected in short periods of lower nodal voltage.
Phase Angle Jump Compensation	Compensate voltage sags with phase jumps by injecting the required number of volt-amperes into the system.
Severe Weather Forecast	Forecast hurricanes, extreme temperatures, and more.
Component Damage Estimation	Estimate the probability of components damaged under certain scenarios.
Coordinate DERs with Microgrid Reconfiguration-Fixed Boundary	Restore considering DERs and microgrids.
Coordinate DERs with Microgrid Reconfiguration-Dynamic Boundary	Restore considering DERs' and microgrids' expansion of electrical boundaries.
Backup Resilient Islanding Operation Plan for Certain Outage Period (Energy)	When preparing the islanding operation, have enough energy for critical loads to survive for a certain period.
Day-Ahead/Real-Time Demand Response	This category is the price-driven day-ahead/real-time demand response.
Utility Event Response	Respond to real-time requests from system operators and markets.
Transmission and Distribution (T&D) Congestion Management	Adjust power outputs to help relieve T&D congestion.
Phase Balancing	Balance loads between phases.
Event Replay	Replay the events using recorded data.
Alarm Processing	Transform the raw alarm information derived from a power system's control, monitoring, and protection functions into a form that is finally presented to the power system operator.

APPENDIX B. MICROGRID FUNCTIONS COMPARISON ENERGY MANAGMENT

	Company Name	ORNL	A	B	C		D	E	F	G	H	I
Microgrid Controller or Advanced Distribution Management System			A.1	B.1	C.1	C.2	D.1	E.1	F.1	G.1	H.1[8]	I.1
Microgrid Function Group	***Subfunctions***											
Grid-connected Energy Balancing	Unit Commitment	Y[1,2]	Y	Y	Y[1]	Y[1]	Y	—	Y	Y	—	—
	Economic Dispatch	Y[1,2]	Y	Y	Y[1]	Y[1]	Y	—	Y	Y	—	Y
	Optimal Power Flow	Y[1,2]	N	Y	Y[1]	—	Y	—	Y	—	—	—
Energy Market	Price Taker	Y	Y	—	Y	Y[3]	Y	Y	Y	Y	—	—
	Bidder/Active Market Player	Y	—	—	Y	Y[4]	Y	—	Y	—	—	—
Operation Optimization	Peak Shaving	Y	Y	Y	Y	Y[5]	Y[7]	Y	Y	Y	—	Y
	Loss Minimization	Y	Y	Y	—	—	—	—	Y	Y	—	Y
	Conservation Voltage Reduction	Y	—	—	—	—	—	—	—	—	—	—
Forecast	Load Forecast	Y	Y	—	Y	Y[6]	Y	Y	Y	Y	—	Y
	Wind Power Forecast	—	—	—	Y	Y[6]	—	—	—	—	—	—
	PV Power Forecast	Y	Y	—	Y	Y[6]	Y	Y	Y	Y	—	Y
Islanding Energy Management	Unit Commitment	Y[1,2]	Y	Y	Y[1]	—	Y	Y[9]	Y	Y	—	Y
	Economic Dispatch	Y[1,2]	Y	Y	Y[1]	Y	Y	Y	Y	Y	—	Y
	Optimal Power Flow	Y[1,2]	—	Y	Y[1]	—	Y	N	Y	—	—	Y
	Reserves	Y[1,2]	Y	Y	Y	Y	Y	N	Y	—	—	Y

[1] Deterministic
[2] Stochastic
[3] Import of energy market prices
[4] Forward energy requirements to aggregator
[5] Also demand charge reduction.
[6] 48 h
[7] Peak shaves only

[8] Please note that this solution is a high-speed grid management system. It operates in microseconds, is proactive, responds to the grid's real-time information, and can be distributed across the grid to minimize communication latencies. Given its operation speed, the management solution is not within the energy management system category. It is instead a tertiary power management system.
[9] We support a variation that adjusts the settings for the dispatch of backup generators based on State of charge (SOC).

	Company Name	ORNL	A	B	C		D	E	F	G	H	I
Microgrid Controller or Advanced Distribution Management System			A.1	B.1	C.1	C.2	D.1	E.1	F.1	G.1	H.1	I.1
Microgrid Function Group	***Subfunctions***											
Energy Storage Control	Primary	Y	Y	Y	—	—	Y	—	Y	Y	Y[13]	Y
	Secondary	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Tertiary	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
State Estimation	Billing	—	—	Y	—	—	—	—	—	—	—	—
	Optimization/Control	—	—	Y	Y	—	—	Y	Y	—	—	Y
Backup Plan for Islanding Operation	***Contingency Analysis***	Y	Y	Y	—	—	Y	—	Y	Y	—	N
Two-way Communication	***Centralized Communication***	—	Y	Y	Y	Y	Y	Y	Y	Y	—	Y
	Distributed Communication	Y	—	Y	—	—	Y	—	—	—	Y[14]	Y
Electric Vehicle	***Vehicle to Grid***	Y	Y	—	—	Y	N	—	—	—	Y	—
Load Balancing		Y	—	Y	—	—	Y	?[12]	—	—	Y	Y
Uncertainty Management of Renewables		Y	—	Y	—	—	—	—	Y	—	Y	Y
Scalability	***Multiple Microgrids or Microgrid Network***	Y[10]	—	—	Y	Y[11]	—	?[15]	—	—	Y	Y

[10] Distributed energy management for networked microgrids based on Alternating Direction Method of Multipliers (ADMM)

[11] Up to four microgrids

[12] We do not balance load between feeders within a microgrid, but we do make the microgrid net load controllable to utility Distributed Energy Resource Management System (DERMS).

[13] Our solution can operate as primary, secondary, and tertiary control systems for the operation of battery energy storage system (BESS) within the context of microgrids. Please note that at the tertiary layer, the operation speed of our solution is faster than conventional energy management system.

[14] A key feature of our microgrid management system is distribution over the grid in a systematic manner.

[15] Hopefully soon!

APPENDIX C. MICROGRID FUNCTIONS PROTECTION AND CONTROL

	Company Name	ORNL	A	B	C		D	E	F	G	H	I
Microgrid Controller or Advanced Distribution Management System			A.1	B.1	C.1	C.2	D.1	E.1	F.1	G.1	H.1	I.1
Microgrid Function Group	*Subfunctions*											
Relay Protection Coordination	Short-Circuit Protection	Y	Y	Y	–	–	Y	–	Y	Y	Y	Y
	Ground Protection	Y	Y	Y	–	–	Y	–	Y	Y	Y	Y
	Fault Location, Isolation & Service Restoration	Y	Y	Y	–	–	–	–	Y	–	Y	Y
	Disturbance Logging, Time-Tagging and Analysis	Y	Y	Y	Y	–	Y	Y	Y	Y	N	Y
Frequency Control in Islanding Mode	Steady state Device Level Control (Droop/V-f/PQ control)	Y	Y	Y	–	Y	Y	–	Y	Y	Y	Y
	Coordinated Control of Multiple Device (Within Seconds level or Sub seconds)	Y	Y	Y	–	Y [1]	Y	–	Y	–	Y	Y
	Transient Device Level Control	–	Y	Y	–	–	–	–	Y	Y	Y	Y
	Frequency Smoothing	Y	Y	Y	–	Y [2]	Y	–	Y	–	Y	Y
	Low Frequency Ride-Through	–	Y	–	? [4]	–	–	–	Y	–	Y	Y
	Emergency Load shedding	Y	Y	Y	–	Y [3]	Y	–	Y	–	Y	Y

[1] Typically within seconds
[2] As a distribution management system function
[2] By battery storage system
[3] Within 70 ms
[4] NA

	Company Name	ORNL	A	B	C		D	E	F	G	H	I
Microgrid Controller or Advanced Distribution Management System			A.1	B.1	C.1	C.2	D.1	E.1	F.1	G.1	H.1	I.1
Microgrid Function Group	***Subfunctions***											
Volt/Var Control	Steady state Device Level Control (Droop/V-f/PQ control)	Y	Y	Y	—	Y	Y	—	Y	Y	Y	Y
	Optimal Co-ordinated load tap changers (LTCs), distributed energy resources (DERs), and Capacitor Banks l	Y[5]	Y	Y	—	—	—	—	Y	—	Y	—
	Co-optimization of P and Q Considering DER's Capability	Y	Y	Y	—	—	—	—	Y	—	Y	—
	Management of Voltage Fluctuations due to Intermittent DERs	Y	Y	Y	—	Y	—	—	Y	Y	Y	Y
	Low Voltage Ride-Through	—	Y	Y	—	—	—	—	—	—	Y	—
	High Voltage Ride-Through	—	Y	—	—	—	—	—	—	—	Y	—
	Phase Jump Compensation	—	—	—	—	—	—	—	—	—	—	—
Grid-connected to Islanding	Intentional Islanding Transition	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Unintentional islanding transition	Y	Y	Y	Y	Y	Y	Y[6]	Y	Y	Y	Y
Islanding to Grid-connected	Black Start	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Synchronization	Y	Y	Y	Y	Y	Y	—	Y	Y	Y	Y
Grid Forming Control	Voltage Support	Y	Y	Y	Y	Y	Y	—	Y	Y	Y	Y
	Frequency Support	Y	Y	Y	Y	Y	Y	—	Y	Y	Y	Y
Grid Following Control	Active Power Regulation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Reactive Power Regulation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

[5] This function is usually hosted by distribution management system.

[6] This can often be done with a synchronizing relay without a microgrid controller.

APPENDIX D. MICROGRID FUNCTIONS RESILIENCY

	Company Name	ORNL	A	B	C	D		E	F	G	H	I
Microgrid Controller or Advanced Distribution Management System			A.1	B.1	C.1	D.1	D.2	E.1	F.1	G.1	H.1	I.1
Microgrid Function Group	Subfunctions											
Severe Weather Forecast	Storm	Y	Y	–	–	–	Y	–	–	Y	–	–
	Extreme Temperature?	–	–	–	–	–	Y	–	–	–	–	–
	Other	–	–	–	–	–	–	–	–	–	–	–
Component Damage Estimation	Damage Modeling	–	–	–	–	–	–	–	–	–	–	–
Uninterruptible Power Supply Function for Critical Load	Intelligent Load Shedding	Y	Y	Y	–	Y	Y	Y	Y	Y	–	Y
Coordinate Distributed Energy Resources with Microgrid Reconfiguration	Fixed Boundary	Y	–	Y	Y	Y	Y	Y	–	–	Y	Y
	Dynamic Boundary	Y	–	Y	Y	Y	Y	–	–	–	Y	Y
Backup Plan	Backup Resilient Islanding Operation Plan for Certain Outage Period (Energy)	Y [2]	Y	Y	–	Y	–	–	Y	Y	–	–

[1]Up to four zones
[2]Realized through resilience-oriented scheduling with constraint of islanding operation horizon

APPENDIX E. MICROGRID FUNCTIONS ANCILLARY SERVICES

	Company Name	ORNL	A	B	C		D	E	F	G	H	I
Microgrid Controller or Advanced Distribution Management System			A.1	B.1	C.1	C.2	D.1	E.1	F.1	G.1	H.1	I.1
Microgrid Function Group	Subfunctions											
Day-ahead Demand Response	Price Driven Day-ahead Demand Response	Y	Y	–	–	–	Y	Y	Y	–	–	–
Real-Time Demand Response	Price Driven Real-Time Demand Response	Y	Y	Y	–	–	Y	Y	Y	–	–	–
Utility Event Response	Active power/reserve?	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y
Transmission and Distribution (T&D) Congestion Management	Power flow Rerouting	Y	Y	–	–	–	–	–	–	–	Y	–
	Dynamic Line Rating	–	–	–	–	–	–	Y	–	–	–	–
Frequency Regulation Service	Frequency	Y	Y	Y	Y	Y [1]	–	–	Y	–	Y	Y
Spinning Reserve Support	Reserve	Y	Y	–	Y	Y	Y	–	Y	–	–	Y
Phase Balancing	Balancing Loads Between Phases	Y [2]	–	–	–	–	–	–	–	Y	–	–
Provide Requested Supports	Var Support	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y
	Watt Support	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Power Factor Support	Y	Y	–	Y	Y	Y	–	Y	Y	Y	Y
	Black-Start Capacity	Y	–	Y	Y	Y	Y	–	Y	Y	Y	Y

[1] Feeder Reconfiguration Request (FRR), Feeder Condition Monitor (FCR), …
[2] If single-phase resources available

APPENDIX F. MICROGRID FUNCTIONS GRAPHICAL USER INTERFACE AND DATA MANAGEMENT

	Company Name	ORNL	A	B	C		D	E	F	G	H	I
Microgrid Controller or Advanced Distribution Management System			A.1	B.1	C.1	C.2	D.1	E.1	F.1	G.1	H.1	I.1
Microgrid Function Group	Subfunctions											
Intelligent Electronic Device (IED) Functions Based on International Standards for Interoperability	IEC 61850 or else	Y [1]	Y	Y	—	Y [2]	Y [5]	—	Y	Y	Y [6, 7]	Y
Database Server Design for Interoperable IED Data Gathering	Database Server Design	—	—	—	Y	Y	N	Y	Y	Y	—	Y
User Authentication		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Event Logging		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Event Replay		Y	Y	Y	Y	Y [3]	Y	Y	Y		Y	Y
Security Issue Reporting	warning	Y	—	—	Y	Y [4]	Y	Y	Y	Y	Y	Y
Alarm Processing	Ranking/screening	Y	Y	Y	Y	Y	Y	Y	Y	—	—	Y

[1] MQTT, Modbus
[2] 61850, DNP3, IEC 104, Modbus 3, 68150 and DNP
[3] COMTRADE replay via SIGRA.
[4] via syslog to SIEM
[5] Modbus RTU, IP and LonWorks, TCP/IP, BACNet MSTP, HTTP/JSON
[6] IEC-61850-compliance
[7] Solution mainly operates based on Goose Messaging given its high speed.