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Comparison of Hierarchical Control and Distributed Control for Microgrid

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CONTENTS

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Abstract—Microgrid concept has been widely adopted by power and energy community to boost the resilience and enhance the economics of the energy system. Stability control and economic control are two main factors to enable the reliable and efficient operation of microgrids. This paper presents two different control approaches for microgrids. The first control method adopts hierarchical structure. Each controllable resource is complied with a local controller and the microgrid is managed and optimized by a central supervisor controller. The second control method adopts the distributed structure. Distributed controller of each energy resource can communicate with each other to achieve global goals. This paper discusses the main features of these two methods and provides recommendations on how to choose appropriate control for different types of microgrids. A case study illustrates the performance difference of the two methods from economic point of view.

1. INTRODUCTION

The US Department of Energy defines microgrid 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 grid-connected or island mode [1]. From utility perspective, a microgrid is treated as a single controllable entity in the distribution system. Microgrid has the potential to facilitate renewable penetration in the distribution system, improve energy efficiency, enhance power quality and reliability, and reduce environmental impact of the power system. During the past decade, microgrids have been gradually deployed for different applications in US and worldwide, such as institutional campuses [2], military bases [3], communities [4], and remote off-grid microgrids [5].

Some previous research work [6] suggested that three different types of control approaches are used to manage microgrid operation including centralized or hierarchical control [7], decentralized control, and distributed control [8]. Both hierarchical control and distributed control require communication to achieve coordination between different energy resources. These two control approaches are most widely used control methods in industry to ensure stable and economical operation of microgrids [8–10]. This paper mainly focuses on the comparison of these two control approaches to help microgrid owners to choose appropriate control approach for different types of microgrids.

Hierarchical control for the microgrid operation can be classified into primary, secondary, and tertiary control. The primary controller has the smallest decision time step to regulate the voltage and the frequency based on local measurements. On the other hand, tertiary controller collects state information of the energy system through the communication infrastructure and makes decisions to improve the overall performances of microgrids, which has a longer decision time step.

Hierarchical control manages the overall system operation using a dedicated central computer to achieve objectives such as minimizing operation cost, minimizing the CO_2 emission, and maximizing the system reliability on the tertiary level. The central energy management system (EMS) in the hierarchical structure could easily integrate objectives as well as operational constraints in a central optimization problem [9, 10]. The central EMS system can easily integrate various types of distributed energy resources (DERs), real-time electricity price signals, thermal system (combined heat and power and district heating system), etc. The load and renewable forecasts can be used to further improve the system economics. The central EMS system usually requires a dedicated powerful computer to solve the optimization problem in real time. Communication and control system redundancy is required to maintain a high reliability of the Information and Communication Technology (ICT) system.

In the hierarchical control structure, the secondary control is mainly responsible for the system-level stability of microgrids. The secondary control includes automatic generation control (AGC), secondary load-frequency control [11, 12], secondary voltage control [13–15], real-time load management, etc. In this level, the secondary controller is used to dynamically determine set-points for local controllers to achieve the overall objectives of microgrids. For example, one objective of AGC is to maintain the system frequency at the nominal value. The AGC can adjust set-points of dispatchable generators to regulate the power outputs of these generators when the system frequency deviates from the nominal value. The power set-point signals are sent from the central controller to local controllers of dispatchable generators through the local area network in the microgrid. For the secondary voltage control problem, the prespecified voltage signals are sent to the dispatchable generation units to maintain bus voltages at desired values [13]. The control interval of the secondary control is usually from tens of milliseconds to half a second.

On the other hand, distributed control can make decision based on local measurements and the communication with its peers. It is very flexible, making it easy to add additional DERs in the system without impacting the normal operation of the rest of the system. Distributed control integrates tertiary and secondary control functions and makes control decision on the order of 100 msec. Any single point failure in the control system would not cause a cascading failure in the microgrid. The plug-and-play feature and the robustness of distributed control make this control mechanism suitable for small and remote microgrids such as remote mining facilities, small islands, and remote villages. Due to the limited calculation capability, distributed controller usually does not conduct predictive control locally, so the limited forecast capabilities may limit the performance of the control system. In addition, the control decision is usually made based on heuristic laws which may be designed based on the most conservative assumptions. Thus, distributed control usually provides a suboptimal solution. It should be noted, however, that as technology advances make low-cost, low-power, high-speed computational capability more available, this situation could well evolve.

In distributed control area, the consensus and cooperative control [16, 17] has attracted more attention in microgrid control community [18–20]. The multi-agent cooperative control method is inspired by biological phenomena [21, 22], which aim to achieve system objectives cooperatively that are difficult to reach by a single agent or centralized controller. In the microgrid control, one of the stability control objectives is to achieve voltage or frequency consensus across the power network, which is a good application area for consensus control. On the tertiary control level, one objective is to achieve incremental cost consensus for generation units across the network [18].

To better understand these two control approaches, this paper presents a comparison study from various perspectives including economics, reliability, design complexity, scalability, and computational complexity. The outline of this paper is given as follows. In the next section, hierarchical control and distributed control are described and compared. In Section 3, the controls in AC and DC microgrids are discussed. Section 4 presents the fault management for AC and DC microgrids. In Section 5, a case study is presented to compare the economic performance of the two control approaches. Finally, the conclusion is discussed in Section 6.

2. MICROGRID CONTROL

Hierarchical control and distributed control are two main control structures used in microgrids. Stability control is used to maintain the stable operation in island mode and mode transitions. Economic control is used to reduce fuel costs and emissions. Both controls are critical to enable the reliable and efficient operation for microgrids.

2.1. Hierarchical Control

As discussed, in a hierarchical control structure, the operation of microgrids can be classified as primary control, secondary control, and tertiary control [7, 13, 23]. A diagram of the operation of microgrids is shown in Figure 1 [7]. The system state information flows from primary level to tertiary level, and the decision signals flow from tertiary level to primary level to achieve overall operation objectives. The primary controller has the smallest decision time step to regulate the voltage and frequency to desired values. On the other hand, tertiary controller collects system state information using the communication infrastructure and makes decisions to improve the overall performances of microgrids and has a longer decision time step. This hierarchical control structure follows the control structure of legacy grid which has been successfully used for a few decades.

The diagram of a microgrid with hierarchical control structure is shown in Figure 2. The central controller implements tertiary control functions such as EMS, state estimation, and voltage-var control. The central controller can communicate with local controllers of energy resources in the microgrid to send dispatch signals and obtain status and measurement of local units. The stability control function is implemented in local controllers to achieve real-time power balancing and power sharing.

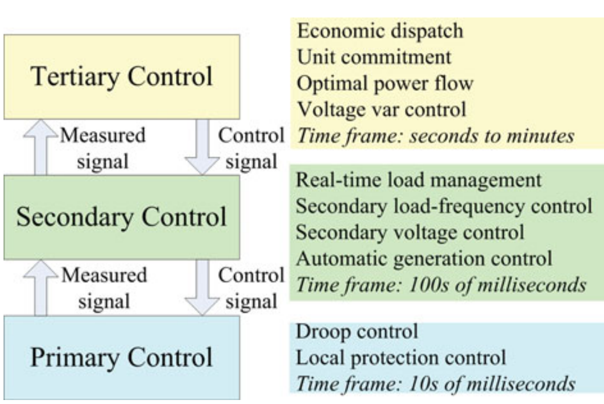

FIGURE 1. Diagram of microgrid control operations based on the concept proposed in J. M. Guerreo et al., *IEEE Trans. Ind Electron*, pp. 158-172, 2011.

The economic control or EMS system is on the level of tertiary control. This type of control decision is usually updated on the order of seconds to minutes. The main objective of microgrid EMS is to dispatch controllable resources including distributed generators, energy storage systems, and controllable loads to minimize operation costs and emissions while satisfying power balance constraint, security constraint, and operational constraints (voltage, current, or frequency constraint). In addition, microgrid EMS may include the capability to isolate the microgrid from the main grid for planned events. In the hierarchical control structure, the microgrid EMS could be implemented on a central computer which behaves as a central controller of a microgrid. The central controller oversees the overall system operation and optimally dispatches controllable units in the system. The energy optimization problem is usually formulated as a mixed integer linear programming (MILP) problem. The model predictive control approach is usually adopted to optimize the microgrid energy utilization over a predefined time horizon [9, 10]. Other applications including voltage-var control, state estimation, and thermal system management can also be implemented in the microgrid central controller.

The stability control is on the level of secondary control. The decision interval of stability control is approximately 100 msec to achieve dynamic balancing of generation and load especially when the microgrid is operating in island mode [24]. For AC microgrids, the stability control is used to balance the active power and reactive power to maintain the frequency and voltage in normal ranges. For the DC microgrids, the stability control is used to maintain the system voltage profile in the normal range through the fast dynamic control. The stability control function is implemented on local controllers of distributed generators, energy storage systems (ESSs), controllable loads, and point of common coupling (PCC) breakers. This type of control is based on local measurements and makes control decisions on the order of 100 msec. This control decision interval is critical when the microgrid is operating in island mode or the system is experiencing large disturbances such as short-circuit faults and generation unit tripping, leading to an unplanned outage. In the steady-state operation, the local controller also regulates the energy resources to follow the set-points communicated by the central controller to achieve the power sharing.

In the hierarchical control structure, the AGC signal for generators is updated every half second to a few seconds to maintain the system frequency and voltage at nominal values [25]. The load and renewable fluctuations could be compensated by AGC. ESSs or fast controllable resources may be required to dynamically balance the generation and the load in operational real time. The economic dispatch signal is sent

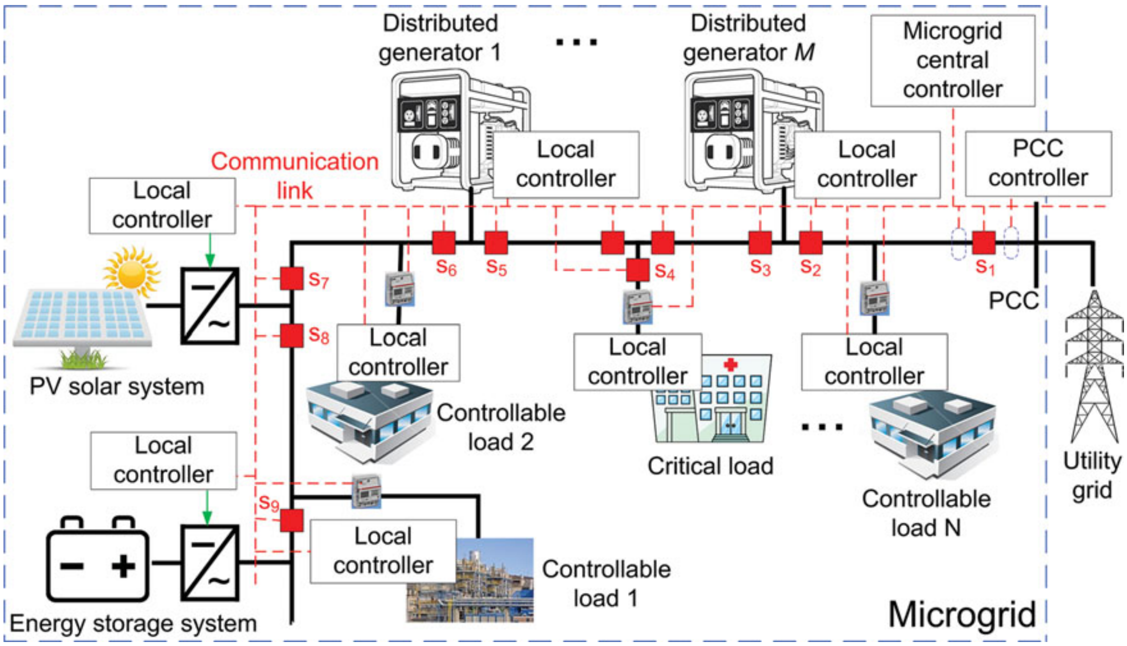

FIGURE 2. Diagram of a microgrid with hierarchical control structure.

to each controllable unit on the order of minute. Hierarchical control only requires vertical communication and does not require any peer-to-peer communication which reduces the requirements on the communication system.

2.2. Distributed Control

Distributed control is another control structure for microgrids. Due to the distributed feature of microgrids and the simple DER configurations in small microgrids, the distributed control structure is an attractive solution, particularly for small and remote microgrids. Figure 3 illustrates the main feature and structure of a distributed control system. The system does not have a central controller, but the system has a central monitoring computer to oversee the operation of the whole system. The central computer can perform off-line analysis or download configuration settings to distributed controllers during system commissioning and maintenance stages. All

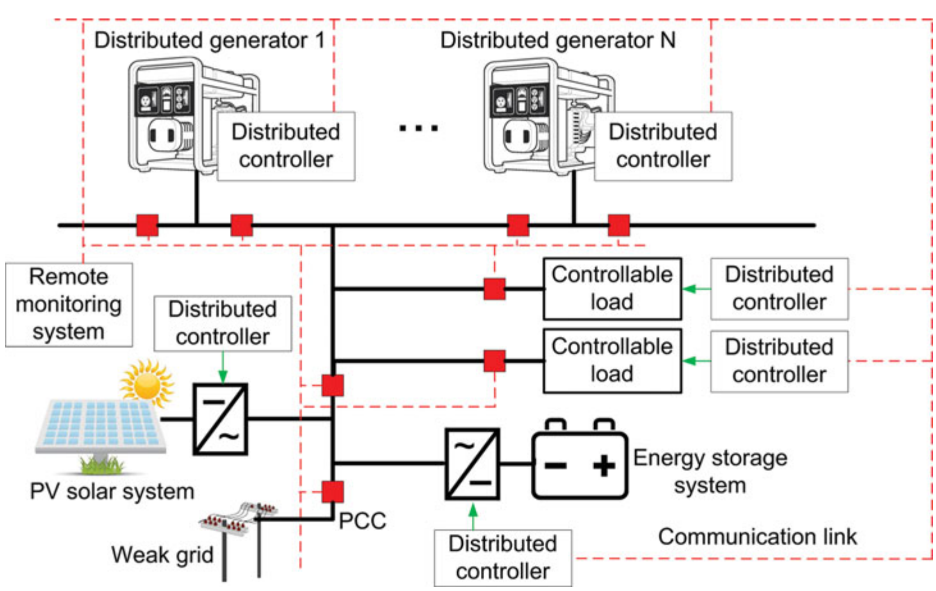

FIGURE 3. Diagram of a microgrid with distributed control structure.

control functions are implemented on distributed controllers. In addition to the vertical communication for monitoring, diagnostic, and visualization, the peer-to-peer (horizontal) communication plays a dominant role in the coordination of various distributed resources to achieve a global operation goal.

Each distributed controller broadcasts the on/off status and loading condition of its associated distributed unit on the order of 100 msec. Other units receive the message and make local decisions correspondingly. The stability and economic control functions are both implemented on the distributed controller. The droop control and power sharing strategy are implemented in the distributed controller to enable each unit to dynamically achieve power sharing and power balancing. In addition, heuristic laws are implemented in the distributed controller to achieve certain system-level objectives such as maximizing the use of renewable energy and minimizing the fossil fuel consumption. Look-ahead control strategy may be difficult to be implemented in the distributed controller. Since the heuristic control usually only makes suboptimal decision, the economic performance of the distributed control system is generally not as good as a system with central EMS control. On the other hand, distributed control is very flexible, permitting the integration of additional energy resources in the existing microgrid without negative impact on the system. This feature enables the plug-and-play function which is very attractive for portable and remote microgrids.

2.3. Comparison

The two control approaches are compared from various perspectives including economics, reliability, design complexity, scalability, and computational complexity.

Hierarchical control can integrate a comprehensive centralized EMS to minimize energy cost and maximize the reliability and security of microgrids. The central EMS could be formulated as a look-ahead optimization problem to obtain a global optimal solution. The central controller plans and optimizes the microgrid operation for as long as the supply and demand could be reasonably predicted, typically the next 12–24 hr, and updates the control solution on a shorter time scale, such as every 15 min, in response to the most recent near-term load and renewable energy availability forecasts. The look-ahead EMS is usually formulated as a MILP problem. To complete the optimization task in operational real time, a dedicated high performance computer is usually needed to perform the calculation. This may add cost and complexity of the control system. Once the optimization in the current decision time interval is completed, the control commands are transmitted to local controllers to regulate the set-points of controllable resources in microgrids. Only vertical communication is needed to accomplish the control function. Another advantage of hierarchical control is that the microgrid network model can be integrated into the central controller to improve the performance of the central control. The central controller usually uses the network model in the EMS to optimally regulate the power flow in the network while satisfying current and voltage constraints in operational real time.

Distributed control usually uses heuristic method to improve the economic operation of microgrids. The main heuristic laws may include maximizing the use of renewable energy, minimizing the fuel consumption, limiting the load and generation change rates to maintain stability, charging the energy storage when extra renewable energy or other low-cost energy is available, discharging the energy storage when the demand exceeds generation capacity, limiting the state of charge (SOC) of energy storage, etc. The heuristic method has two main disadvantages. The first disadvantage is that heuristic method may only achieve suboptimal control for economic operation due to the limited capabilities for forecasting and global coordination. To achieve certain level of reliability for microgrid, the heuristic laws are usually designed based on the most conservative assumptions which may have suboptimal effects on the microgrid economic performance. The second disadvantage is that it is usually very difficult for heuristic method to anticipate all possible operating scenarios in the design stage especially for large microgrids with multiple DERs and complex distribution network. When unexpected events happen, the heuristic control may result in significant load interruption or even blackout. Distributed control may require fast peer-to-peer communication (approximately 100 msec interval) to achieve system-level coordination. This strategy could improve the stability performance of the system, but, at the same time, it sets stringent requirements on communication system. Even though distributed control is more challenging in large microgrids with multiple types of DERs, its flexibility and interoperability make this method very applicable for small microgrids especially diesel-solar-storage or diesel-wind-storage microgrids [26].

Communication system is equally important for both hierarchical control and distributed control. In the hierarchical control structure, communication infrastructure is used to transmit economic control and AGC signals from the central controller to local controllers. The system state measurements are transmitted back to the central controller for monitoring and visualization. The vertical communication dominates the bandwidth of the communication network. If the communication system fails, local controllers will lose the economic control signals. The AGC signals are also blocked. The microgrid will lose the ability for economic operation and system-level frequency/voltage regulation. The system frequency and voltage would be locally maintained by primary droop controls. The system may operate with steady-state frequency and voltage deviations from nominal values [24]. In the distributed control structure, a distributed controller exchanges information with its peers to maintain the system stability and certain level of reliability and economics. In case of communication failure, the coordination between ESSs and renewable energy resources would be lost and the distributed controllers would not be able to respond system disturbances as desired without peer-to-peer communication. Only droop controls actively maintain the basic system stability and power sharing.

Even though the communication network is critical for both control approaches, the distributed structure does have a unique feature that makes it robust subject to communication link failure or cyber/physical attacks. Any single point failure in the communication or control system in the distributed structure would not have significant impact on the rest of the system's normal operation, but that is not the case for the hierarchical system. If the communication link connecting the central controller is failed or the central controller is attacked, the whole system would immediately lose the system-level coordination and the economic operation capability. To achieve the same level reliability, redundancy needs to be added to existing control and communication infrastructure which may increase the microgrid installation cost.

The comparison of hierarchical control and distributed control is summarized in Table 1. Hierarchical control is usually more suitable for large microgrids with multiple types of DERs and a time-varying utility electric price signal. In addition, the communication requirement is usually lower than distributed control. On the other hand, the distributed control system has a more reliable control system, simple control algorithm, and less expensive control hardware.

Features	Hierarchical control	Distributed control
Economics	Optimal	Suboptimal
Control system reliability	Central controller failure results in microgrid losing coordination and optimal operation	Reliable
Design complexity	Complex	Simple
Scalability	Can integrate any type of DERs and any type of utility electricity price profile	It is difficult to scale up to more than three types of DERs
Computational complexity	High	Low
Hardware Platform	Powerful computer	Embedded controller
Communication bandwidth	Low	High

TABLE 1. Comparison of hierarchical control and distributed control for microgrids

3. CONTROLS IN DC AND AC MICROGRIDS

In AC microgrids, stability controller is usually responsible for frequency and voltage regulations with approximately 100 msec decision interval to maintain generation and load balancing. In case of a high-penetration renewable island microgrid, the intermittent renewable energy sources may generate significant power fluctuations across the system which may cause negative impacts on the power quality. In this case, additional ESSs, such as flywheel energy storage and lithium-ion battery [27], may be required to actively smooth out the fluctuations created by renewable resources. The ESSs could also compensate the slow responses of fossil fuel generation units as well as improving the stability margin of the island microgrid. The ESSs are responsible for smoothing out the power fluctuations as well as compensating the low ramp rate and long startup time of conventional AC generators. Once the sustained power sources are on-line or regulated to the desired states, the ESSs will be regulated back to the desired SOC for later use. This type of stability control strategy has been successfully used to control remote island microgrids with fossil fuel generators, renewable energy resources, and ESSs [27].

In DC microgrids, the stability controller is usually responsible for voltage regulation and power sharing with a smaller decision time interval compared with AC systems. In DC microgrids, all the rotating machines are decoupled from the DC grids by converters, so DC grids have faster transient dynamics than the AC grids which are directly coupled with rotating machines that provide mechanical energy storage (inertia). The decoupled generation units could be used as fast energy storages to deliver transient energy to stabilize DC buses which could potentially reduce the size of the dedicated energy storages in DC microgrids.

The economic control strategy is also similar for both AC and DC microgrids. In AC microgrids, AC generation units need to be synchronized with the main grid. The prime movers need to be operated at constant speeds to maintain synchronization with the main grid. The only control variable of the AC generator is the active power set-point. In DC microgrids, the rotational velocity of a generator can be regulated independently to make the machine operate in its maximal efficiency region [28] which could significantly reduce the fuel consumption. This concept has been successfully

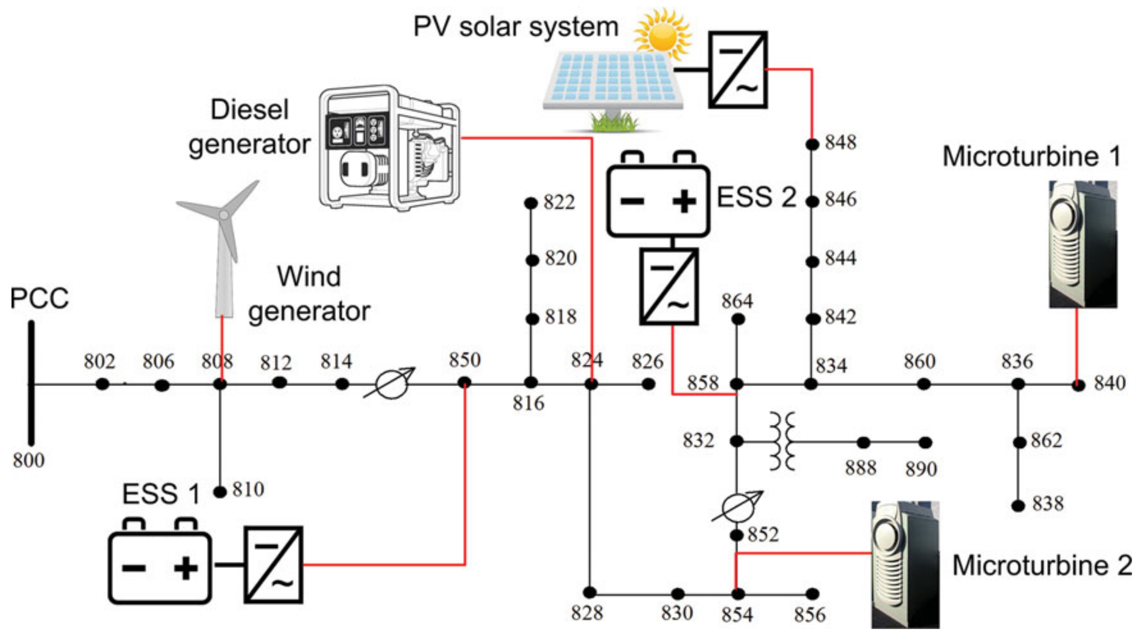

FIGURE 4. One-line diagram of the modified IEEE 34-node system.

demonstrated on a low voltage DC ship system for efficiency improvement up to 20% [29–31]. This is one major advantage of DC microgrids.

4. FAULT MANAGEMENT IN DC AND AC MICROGRIDS

Microgrid protection is different from conventional AC distribution system protection. Microgrids may accommodate high-penetration intermittent energy resources with power electronics interfaces. The high-penetration DERs may cause reverse power flow; power converters may reduce the fault current level; the intermittent energy resources may cause more frequent topology changes in the microgrid. In AC microgrids, existing protection method needs to be revised to accommodate large penetrations of DER which may cause reverse power flow and low fault current levels [32]. Adaptive or model-based protection strategy [33–36] may be needed to compensate the power fluctuation and the frequent system topology change caused by intermittent renewable energy resources.

In DC microgrids, new fault detection, location, and isolation approaches need to be developed. It is a challenge to use existing AC protection solution to isolate DC faults in a reasonable amount of time. Extensive research studies have been focused on how to quickly and reliably detect, locate, and isolate faults in DC microgrids [37–41]. DC microgrids include various types of energy sources, such as converter-based AC sources, ESSs, capacitors, and active loads. When a fault happens, the behavior of fault currents from different energy sources could be significantly different. Previous research work [40, 42, 43] provides a good overview of typical fault current contributions from these energy sources. International Electrotechnical Commission (IEC) standard 61660 [42] and the work in [43] present a general method to estimate the fault currents using main DC circuit parameters without detailed time-domain simulation.

Main DC protection methods for microgrids include over-current protection [44], differential protection [45], impedance protection [46–48], transient energy-based protection [49], current derivative protection [50], and converter fault current limiting method [51–53]. A combination of multiple protection methods is usually required to achieve the most reliable fault detection, location, and isolation for a DC distribution system.

The protection control in microgrids could also be classified as central/hierarchical control or distributed control. The fault detection algorithm is usually implemented locally on the control unit of each protective device. The protection coordination mechanism could be implemented on a central supervisory controller. The supervisory controller could communicate with each protective device to update the relay settings. The coordination algorithm could also be implemented locally on each distributed controller. The coordination is achieved through the peer-to-peer communication.

5. CASE STUDIES

To compare the performance of hierarchical control and distributed control for microgrid economic operation, this section presents a simple case study to illustrate the differences of these two control approaches. Assume that the microgrid includes one medium voltage distribution feeder with DERs. The PCC is at the feeder head of a substation. The one-line diagram of a modified IEEE 34-node system is shown in Figure 4. Three fossil fuel distributed generators, two ESSs, one wind generator, and one PV/solar unit are added in the original IEEE 34-node system [54]. Some of DERs are placed close to feeder or lateral end to provide voltage support if required. Other DERs are placed on the main feeder to provide power for upstream or downstream loads. The length of all the long lines in the original IEEE 34-node system is reduced to 6000 ft. All the other parameters were kept the same as the original system. The line-to-line AC voltage is 24.9 kV. The total generation capacity of rotating machines in the microgrid is 1080 kW. The maximum load demand of the system is 1800 kW, which is higher than the generation capacity of rotating machines. In the island mode, some non-critical loads may need to be interrupted to ensure that the generation can always cover the load demand. The energy storage and renewable energy resources are also used to provide extra power to minimize load interruption.

The parameters of distributed generators (DGs) are shown in Table 2. The DG parameters are chosen based on the data in the literature [55–57]. The price of fuel for the microturbine (MT) was less than that of fuel for the diesel generator. The minimum active power output limit of each generator was chosen as 20% of its power capacity. The parameters for ESSs are shown in Table 3. The charging and discharging efficiency of ESS are also considered. The minimum energy capacity of each ESS is chosen to be 40% of its maximum energy capacity. The maximum charging rate of each ESS is 20% of its discharging rate. The parameters for renewable resources are shown in Table 4. The renewable resources can be continuously or discretely controlled. In the continuous control mode, the power set-point is given to control the power output of the renewable resource continuously. In discrete control mode, the renewable resource can only be on or off.

DG name	DG 1 (diesel)	DG 2 (MT1)	DG3 (MT2)
Bus number	824	840	854
No-load cost ($/hr)	4	3	5
Fuel cost ($/kWh)	0.22	0.085	0.085
Startup cost ($)	10	10	10
Shut-down cost ($)	10	10	10
Pmax (kW)	360	270	450
Pmin (kW)	72	54	90
Qmax (kvar)	174	130	217
Qmin (kvar)	0	0	0
Ramp rate (%/min)	40	30	30

TABLE 2. DG parameters for the modified IEEE 34 node system

ESS name	ESS1	ESS2
Bus number	850	858
Max charging rate	−20 kW	−40 kW
Max discharging rate	100 kW	200 kW
Max energy capacity	200 kWh	600 kWh
Minimum energy capacity	80 kWh	210 kWh
Charging efficiency	80%	85%
Discharging efficiency	85%	90%

TABLE 3. ESS parameters for the modified IEEE 34-node system

The central microgrid energy optimization formulation has been presented in [9]. The problem is formulated as a MILP problem. The model predictive control (MPC) approach is adopted to optimize the microgrid economic operation over a prespecified time horizon. The up-to-date load and renewable forecasts are used in each operational planning period which executes every half an hour. The on/off status of each distributed generator and charging/discharging status of each energy storage device from the planning results would be used in real-time economic dispatch which executes once every few minutes.

The decision time interval of the look-ahead energy optimization is chosen as 30 min. The planning horizon is chosen as 24 hr. The decision variables include on/off status of each distributed generator, charging/discharging status of each energy storage device, and on/off status of controllable loads. The planning optimization is executed and applied once each hour. Once the planning result is available, the real-time economic dispatch is used to decide the actual power set-point of each DER. The decision time step of economic dispatch is chosen as 5 min. A microgrid planned outage function is also implemented in the central EMS system. The load shedding decision during the outage period is made right before the outage happens using the most recent forecast information. In the planned outage control algorithm, load shedding

Name	Wind	Solar PV
Bus number	808	848
Capacity (kW)	400	200
Control type	Continuous or discrete	Continuous or discrete

TABLE 4. Renewable resource parameters for the modified IEEE 34 node system

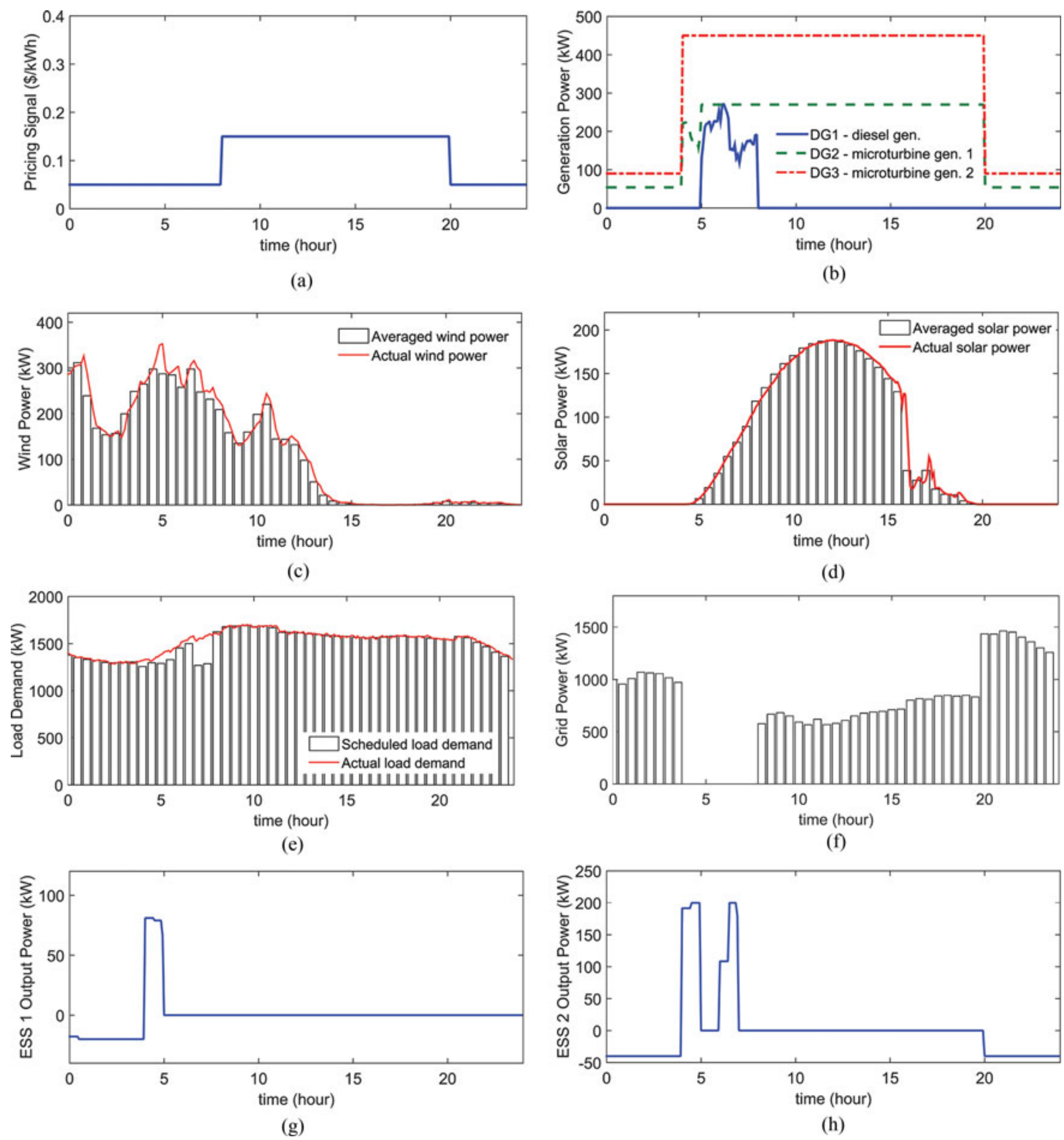

FIGURE 5. The energy optimization results using central look-ahead optimization method. (a) Utility electricity price rate, (b) power output of each generator, (c) power output of wind generator, (d) power output of PV/solar unit, (e) load demand curve, (f) power input from utility grid, (g) power output of ESS 1, and (h) power output of ESS 2.

list is generated for each hour during the outage period. When the load demand is high, more loads would be interrupted to keep generation and load balanced. If load demand is low, no load would be interrupted.

It was assumed that the microgrid was operating in grid-connected mode at the beginning of the simulation. It was also assumed that a planned utility grid outage happened from 4 to 8 hr. The microgrid was returned to grid-connected mode at hour 8. The test results over a 24-hr window are shown in Figure 5. ESSs were charged from 0 to 4 hr to prepare for the grid outage. During this period, the utility electricity rate is lower than fossil fuel generators, so only two micro-turbine generators were on-line with minimum power to maintain enough spinning reserve for unplanned emergency. At hour 4, the microgrid was switched from grid-connected mode to island mode. The two micro-turbine generators were controlled to full power and the ESSs were discharged to minimize the load interruption. The diesel generator was brought up to full power to supply the load demand. Since the generation capacity is less than the peak load demand, load shedding was initiated during the utility outage to maintain the power balance. As shown in Figure 5(e), the load demand (bars) is lower than the original demand (curve) without load interruption. At hour 8, the microgrid was switched back to grid-connected mode and the utility electricity rate increased from 5 to 15 cents/kWh. The two micro-turbine generators were maintained at full power since their generation cost was lower than utility. The diesel generator was brought off-line to save the operation cost because of the higher cost of diesel fuel. When the utility electricity rate was returned to 5 cents/kWh at hour 20, the micro-turbine generators were regulated to minimum power levels for economic operation while maintaining enough spinning reserve for unexpected events. The charge cycle for the ESSs was initiated so they would be ready for later use.

ESSs and renewable resources are fully utilized to avoid using expensive energy resources. During very low load demand period, renewable resources are fully utilized to charge energy storages for later discharging. When a multiple-step utility pricing signal is used, ESSs are fully charged during low utility price period and discharged during high utility price period to reduce the operational cost. Planned outage function in the central controller optimally provides optimal load shedding solutions as well as maintaining enough spinning reserve for the microgrid when needed. The central economic control fully utilizes the most recent load and renewable forecasts to improve the performance.

Distributed control is implemented to compare the performance with the central EMS system. The decision time interval of the economic control in distributed controller is chosen as 5 min since the data resolution is 5 min. This decision interval can be much smaller in the real applications depending on load and generation variation rate. The main heuristic laws include maximizing the utilization of renewable energy from wind and solar, minimizing the fuel cost, limiting the load and generation change rates for stability, charging the energy storage when extra renewable energy or when other low-cost energy is available, discharging the energy storage when the demand exceeds the generation capacity or when the utility electricity cost is high, and limiting the SOC of the ESSs. The same load and renewable generation profiles are used in this case study.

The simulation results are summarized in Figure 6. When the outage happens at hour 4, all three DGs are ramped to the maximum power immediately to avoid load shedding. With the increase of the load demand, the ESSs are discharged to provide the power to the increased load until the SOC hits the minimum limit. The load shedding is initiated after the ESSs run out of power. Non-critical loads are disconnected to ensure that the total load demand is always less than the generation. In this way, the generation and load are balanced to avoid instabilities.

By using the central EMS, the total operation cost during the 24-hr period is \$3232. If distributed control is used, the total operation cost is \$3363. The energy cost using distributed control is little higher than the central EMS system. In distributed control, the diesel was started right after the outage happens. The diesel generator was started earlier than the start time in the central EMS. The diesel fuel is more expensive than fuel for the microturbine generator. In addition, the

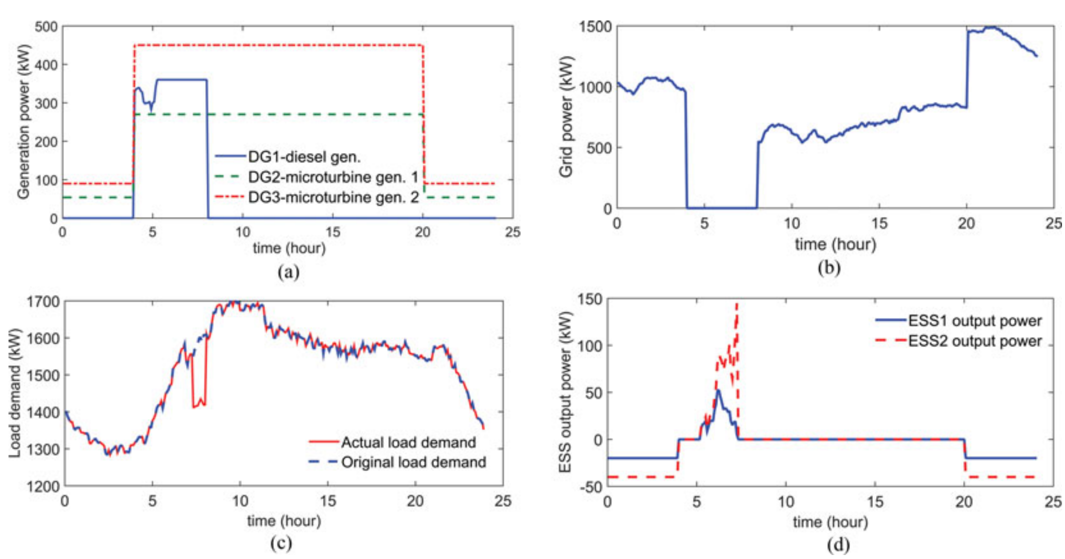

FIGURE 6. The energy optimization results using distributed control method with 5-min time resolution. (a) Power output of each generator, (b) power input from utility grid, (c) load demand curve, and (d) Power output of energy storage.

no-load cost of the diesel generator will also increase the total operation cost. In the central EMS result, the discharge of ESSs at hours 4–5 allows the system to avoid using high cost DG which could help reduce the total operation cost. Actually, this is an easy case for distributed control. If the utility has a more complicated rate profile (multiple steps or real-time pricing), distributed control will have difficulties deciding when to charge or discharge ESSs to minimize operation cost. In the islanded operation, distributed control also has difficulties to coordinate various types of DGs and ESSs to reduce the operation cost.

To assess the computational complexity of the EMS algorithm, a test case was used to perform the calculation on different platforms including a regular PC and an embedded controller. Since the hourly look-ahead optimization consumes most of the calculation resource, the calculation time of each look-ahead optimization for the modified IEEE 34 node system (as shown in Figure 5) is used to evaluate the performance of the algorithm. Assume that the planning horizon was 24 hr. The decision time step in each planning was 30 min. Each look-ahead optimization problem includes 1296 decision variables and 2692 constraints. The calculation times of look-ahead optimization for both grid-connected and island operations are summarized in Table 5. The results presented in Table 5 are the averaged values from 1000 runs. A standard windows machine with Intel(R) Core(TM) i5-4300 M CPU@2.60 GHz and 8 GB RAM is used to perform the calculation. To compare the performance on different control platforms, an embedded control system with AM335 × 1 GHz ARM® Cortex-A8 and 512 MB DDR3 RAM is used to perform the same calculation task.

The standard PC can finish each look-ahead optimization in a minute, but the embedded controller requires more than 10 times longer compared with regular PC. Since the look-ahead optimization results would be used in the real-time economic dispatch with 5 min decision interval, each optimization needs to be finished in 5 min. Thus, the embedded controller is not a good choice for a central optimization platform. The real-time economic dispatch is formulated as a quadratic programming (QP) problem to determine the power set-point of each DER for the current decision time interval.

Control platform	Windows machine (sec)	Embedded control system (sec)
Grid-connected mode	9.8	194
Island mode	8	554

TABLE 5. Calculation time of look-ahead optimization for the modified IEEE 34 node system

The computational complexity of the real-time economic dispatch is relatively low. For the modified IEEE 34 node system, each economic dispatch can be finished in half a second using the PC.

6. CONCLUSION

This paper presented a comparison study between hierarchical control and distributed control for microgrids. Hierarchical control is more suitable for large microgrids with multiple types of DERs and a time-varying utility electric price signal. In addition, the communication requirement is lower than it is for distributed control. On the other hand, the distributed control system has a more reliable control system, simple control algorithm, and less expensive control hardware.

A case study illustrates the performance difference of the two methods from economic point of view. The central EMS in the hierarchical control system can get better optimization results compared with heuristic method in distributed control. The main reason is that the central EMS could optimally plan the overall microgrid operation over a predefined time horizon using the most recent forecasts. On the other hand, distributed control is a flexible and low-cost solution for small microgrids. The computational complexity of the central EMS algorithm is also explored. The results indicated that a dedicated powerful computer is required to perform a look-ahead energy optimization for a microgrid with over seven DERs in reasonable amount of time. Embedded control system is difficult to achieve the computational performance target for the central EMS. The computational complexity of heuristic control is relatively low. This type of control could be implemented on an embedded controller or other industrial control platforms such as programmable logic controllers.

REFERENCES

[1] Ton, D., *DOE Microgrids Program Overview, Power Systems Engineering Research and Development*, DOE Office of Electricity Delivery & Energy Reliability, June 3, 2015.

[2] Zeglinski, D., "Real Time Energy Monitoring and Management – UCSD Campus Microgrid," *25th Annual IDEA Campus Energy Conference*, Arlington, VA, February 2012.

[3] Broekhoven, S. V., Judson, N., Galvin, J., and Marqusee, J., "Leading the charge: microgrids for domestic military installations," *IEEE Power Energy Mag.*, Vol. 11, No. 4, pp. 40–45, July/August 2013.

[4] Che, L., Shahidehpour, M., Alabdulwahab, A., and Al-Turki, Y., "Hierarchical coordination of a community microgrid with AC and DC microgrids," *IEEE Trans. Smart Grid*, Vol. 6, No. 6, pp. 3042–3051, March 2015.

[5] Yuan, C., Haj-ahmed, M. A., and Illindala, M. S., "Protection strategies for medium-voltage direct-current microgrid at

a remote area mine site," *IEEE Trans. Ind. Appl.*, Vol. 51, No. 4, pp. 2846–2853, January 2015.

[6] Dragicevic, T., Lu, X., Vasquez, J. C., and Guerrero, J. M., "Dc microgrids-part I: a review of control strategies and stabilization techniques," *IEEE Trans. Power Electron.*, Vol. 31, No. 7, pp. 4876–4891, July 2016.

[7] Guerrero, J. M., Vasquez, J. C., Matas, J., de Vicuna, L. G., and Castilla, M., "Hierarchical control of droop-controlled AC and DC microgrids – a general approach toward standardization," *IEEE Trans. Ind. Electron.*, Vol. 58, No. 1, pp. 158–172, January 2011.

[8] Mahieux, C., and Oudalov, A., "Balancing act: microgrid optimization control stabilizes production in solar and hybrid microgrids," *ABB Rev.*, pp. 20–25, February 2015.

[9] Yang, F., Feng, X., Oudalov, A., Li, Z., and Wang, Z., "Microgrid energy management system and method for controlling operation of a microgrid," patent application number US 13/955,575, July 31, 2013.

[10] Zadeh, M. R. D., Hajimiragha, A., and Krok, M. J., "Power generation optimization in microgrid including renewable power source," patent application number US 13/358,487, January 25, 2012.

[11] Lopes, J. A. P., Moreira, C. L., and Madureira, A. G., "Defining control strategies for MicroGrids islanded operation," *IEEE Trans. Power Syst.*, Vol. 21, No. 2, pp. 916–924, May 2006.

[12] Madureira, A., Moreira, C., and Lopes, J. A. P., "Secondary load-frequency control for microgrids in islanded operation," *Proc. Internationa Conference on Renewable Energy and Power Quality*, Zaragoza, Spain, 2005, pp. 1–4.

[13] Mehrizi-Sani, A., and Iravani, R., "Potential-function based control of a microgrid in islanded and grid-connected modes," *IEEE Trans. Power Syst.*, Vol. 25, No. 4, pp. 1883–1891, November 2010.

[14] Arcidiacono, V., Menis, R., and Sulligoi, G., "Improving power quality in all electric ships using a voltage and VAR integrated regulator," *Proc. IEEE Electric Ship Technologies Symposium*, Arlington, VA 2007, pp. 322–327.

[15] Arcidiacono, V., Castellan, S., Menis, R., and Sulligoi, G., "Integrated voltage and reactive power control for all electric ship power systems," *Proc. International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Taormina, Italy, May 2006, pp. 878–882.

[16] Olfati-Saber, R., Fax, J. A., and Murray, R. M., "Consensus and cooperation in networked multi-agent systems," *Proc. IEEE*, Vol. 95, No. 1, pp. 215–233, January 2007.

[17] Olfati-Saber, R., and Murray, R. M., "Consensus problems in networks of agents with switching topology and time-delays," *IEEE Trans. Automat. Contr.*, Vol. 49, No. 9, pp. 1520–1533, September 2004.

[18] Zhang, Z., and Chow, M.-Y., "Convergence analysis of the incremental cost consensus algorithm under different communication network topologies in a smart grid," *IEEE Trans. Power Syst.*, Vol. 27, No. 4, pp. 1761–1768, November 2012.

[19] Feng, X., Butler-Purry, K. L., and Zourntos, T., "Multi-agent system-based real-time load management for all-electric ship power systems in DC zone level," *IEEE Trans. Power Syst.*, Vol. 27, No. 4, pp. 1719–1728, November/December 2012.

[20] Feng, X., Butler-Purry, K. L., and Zourntos, T., "A multi-agent system framework for real-time electric load management in MVAC all-electric ship power systems," *IEEE Trans. Power Syst.*, Vol. 3, No. 3, pp. 1327–1336, May 2015.

[21] Viscidoa, S. V., Parrish, J. K., and Grünbaum, D., "The effect of population size and number of influential neighbors on the emergent properties of fish schools," *Ecol. Model.*, Vol. 183, No. 2–3, pp. 347–363, April 2005.

[22] Potts, W. K., "The chorus-line hypothesis of manoeuvre coordination in avian flocks," *Nature*, Vol. 309, pp. 344–345, May 1984.

[23] Feng, X., *A Bio-Inspired Multi-agent System Framework for Real-time Load Management in All-electric Ship Power Systems*, Ph.D. Dissertation, Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, US, 2012.

[24] Feng, X., "Dynamic balancing for low inertia power systems," *Proc. of IEEE PES General Meeting*, Vancouver, Canada, July 2013, pp. 1889–1893.

[25] Wood, A. J., Wollenberg, B. F., and Sheblé, G. B., *Power Generation, Operation, and Control*, 3rd ed., Wiley-Interscience, November 2013.

[26] *Rocky Mountain Institute and Carbon War Room, Renewable Microgrids: Profiles from Islands and Remote Communities across the Globe*, November 2015. www.rmi.org/islands_renewable_microgrids.

[27] Oudalov, A., and Mahieux, C., "Microgrids – the mainstreaming of microgrids using ABB technologies," *ABB Rev.*, pp. 54–60, April 2014.

[28] Li, D., *Efficient Generation of Power in Medium Voltage Direct Current System: Variable Speed Operation and Rectifier Considerations*, Ph.D. Dissertation, Department of Electrical Engineering, University of South Carolina, Columbia, SC, US, 2013.

[29] Hansen, J. F., Lindtjorn, J. O., and Vanska, K., "Onboard dc grid for enhanced DP operation in ships," *Proc. of Marine Technology Society Dynamic Positioning Conference*, Houston, TX, 2011.

[30] Hansen, J. F., Lindtjorn, J. O., Myklebust, T. A., and Vanska, K., "Onboard dc grid – the newest design for marine power and propulsion systems," *ABB.*, https://library.e.abb.com/public/b4f3f099e9d21360c1257a8a003beac2/ABB%20Generations_20%20Onboard%20DC%20grid.pdf.

[31] "Onboard DC grid – the step forward in power generation and propulsion," *ABB.*, http://www04.abb.com/global/seitp/seitp202.nsf/0/292d42e87306453dc12579ad0050a457/$file/12_10_OnboardDCGrid_Technical-Information.pdf.

[32] Che, L., Khodayar, M. E., and Shahidehpour, M., "Adaptive protection system for microgrids," *IEEE Electr. Mag.*, Vol. 2, No. 1, pp. 66–80, March 2014.

[33] Laaksonen, H., Ishchenko, D., and Oudalov, A., "Adaptive protection and microgrid control design for Hailuoto island," *IEEE Trans. Smart Grid*, Vol. 5, No. 3, pp. 1486–1493, May 2014.

[34] Venkata, S. S., Wilson, D., Ren, J., and Miller, M., "Advanced and adaptive protection for active distribution," *Proc. 22nd International Conference on Electric Distribution*, Stockholm, June 2013, pp. 1–4.
[35] Gnana Swathika, O. V., and Hemamalini, S., "Prims-aided Dijkstra algorithm for adaptive protection in microgrids," *IEEE J. Emerg. Select. Top. Power Electron.*, Vol. 4, No. 4, pp. 1279–1286, December 2016.
[36] Haj-ahmed, M. A., and Illindala, M. S., "Investigation of protection schemes for flexible distribution of energy and storage resources in an industrial microgrid," *IEEE Trans. Ind. Appl.*, Vol. 51, No. 3, pp. 2071–2080, May/June 2015.
[37] Cuzer, R., and Venkataramanan, G., "The status of DC micro-grid protection," *Proc. 2008 IEEE IAS Annual Meeting*, Edmonton, Canada, 2008, pp. 1–8.
[38] Ritchie, D., Booth, C., and Devlin, J., "Protection of future marine electrical systems," *Proc. 46th IUPEC*, Soest, Germany, 2011, pp. 1–6.
[39] Brozek, J. P., "DC overcurrent protection – where we stand," *IEEE Trans. Ind. Appl.*, Vol. 29, No. 5, pp. 1029–1032, September/October 1993.
[40] Fletcher, S. D. A., Norman, P. J., Galloway, S. J., and Burt, G. M., "Optimizing the roles of unit and no-unit protection methods within DC microgrids," *IEEE Trans. Smart Grid*, Vol. 3, No. 4, pp. 2079–2087, December 2012.
[41] Salomonsson, D., Soder, L., and Sannino, A., "Protection of low-voltage DC microgrids," *IEEE Trans. Power Deliv.*, Vol. 24, No. 3, pp. 1045–1053, July 2009.
[42] Short-Circuit Currents in d.c. *Auxiliary Installations in Power Plants and Substations, Part 1: Calculation of Short-Circuit Currents*, IEC 61660–1, 1997.
[43] Feng, X., Qi, L., and Wang, Z., "Estimation of Short Circuit Currents in Mesh DC Networks," *Proc. of 2014 IEEE PES General Meeting*, July 2014, pp. 1–5.
[44] Reis, M., "Optimization of DC feeder rate of rise overcurrent protection settings using delta I cumulative distribution," *Proc. 2004 IEEE Industrial and Commercial Power Systems Technical Conference*, Clearwater Beach, Florida, 2004, pp. 63–66.
[45] Fletcher, S. D. A., Norman, P. J., Fong, K., Galloway, S. J., and Burt, G. M., "High speed differential protection for smart dc distribution systems," *IEEE Trans. Smart Grid*, Vol. 5, No. 5, pp. 2610–2617, September 2014.
[46] Feng, X., Qi, L., and Pan, J., "Fault inductance based protection for DC distribution systems," *Proc. of IET Conference on Development of Power System Protection*, March 2016, pp. 1–6.
[47] Feng, X., Qi, L., and Pan, J., "A novel fault location method for DC distribution protection," *IEEE Trans. Ind. Appl.*, Vol. 53, No. 3, pp. 1834–1840, May–June, 2017.
[48] Hill, J. E., Fletcher, S. D., Norman, P. J., and Galloway, S. J., "Protection system for an electrical power network," U.S. Patent Application US 20120200966 A1, 2012.
[49] Li, Q., and Pan, J., "Method and apparatus for the protection of dc distribution systems," U.S. Patent Application 14255674, 2014.
[50] Kong, W., Qin, L., and Yang, Q., "Integrated protection and control, network management – solution for DC traction power supply system," *Proc. of IET Conference on Development of Power System Protection*, 2004, pp. 123–127.
[51] Marquardt, R., "Modular multilevel converter topologies with dc-short circuit current limitation," *Proc. of 8th International Conference on Power Electronics – ECCE Asia*, Shilla Jeju, Korea, May 2011, pp. 1425–1431.
[52] Sun, K., Soto, D., Steurer, M., and Faruque, M. O., "Experimental verification of limiting fault currents in MVDC systems by using modular multilevel converters," *Proc. of 2015 IEEE Electric Ship Technologies Symposium*, Alexandria, VA, June 2015, pp. 27–33.
[53] Staudt, V., Jager, M. K., Rothstein, A., Steimel, A., Meyer, D., Bartelt, R., and Heising, C., "Short-circuit protection in dc ship grids based on MMC with full-bridge modules," *Proc. of International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles*, Aachen, March 2015, pp. 1–5.
[54] IEEE 34 Node Test Feeder, *Distribution System Analysis Subcommittee, Power System Analysis*, Computing and Economics Committee, IEEE.
[55] Goldstein, L., Hedman, B., Knowles, D., Freedman, S. I., Woods, R., and Schweizer, T., "Gas-fired distributed energy resource technology characterizations," Technical Report, NREL/TP-620-34783, National Renewable Energy Laboratory, November 2003.
[56] Pipattanasomporn, M., Willingham, M., and Rahman, S., "Implications of on-site distributed generation for commercial/industrial facilities," *IEEE Trans. Power Syst.*, Vol. 20, No. 1, pp. 206–212, February 2005.
[57] Vuorinen, Asko, *Planning of Optimal Power Systems*, 2009 Edition, Published by Ekoenergo Oy, 2009.

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