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Interconnection, Integration, and Interactive Impact Analysis of Microgrids and Distribution Systems

Energy Systems Division

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Interconnection, Integration, and Interactive Impact Analysis of Microgrids and Distribution Systems

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CONTENTS

ACKNOWLEDGEMENT vii

LIST OF ACRONYMS viii

EXECUTIVE SUMMARY ix

INTRODUCTION 1

SECTION I – INTERACTION BETWEEN THE MICROGRID AND THE DMS UNDER NORMAL AND FAULT CONDITIONS 3

1.1 OPERATIONAL MODES OF A MICROGRID 3
- 1.1.1 Grid-Connected Mode 3
- 1.1.2 Grid-Connected to Island Mode Transition 4
- 1.1.3 Island to Grid-Connected Mode Transition 5
- 1.1.4 Island Mode 6

1.2 OPERATION STRATEGIES OF MICROGRIDS 6
- 1.2.1 Single Microgrid 6
- 1.2.2 Multiple Microgrids 7

1.3 INTERACTIONS AND OPERATION IMPACTS IN MICROGRIDS AND DISTRIBUTION SYSTEMS 11
- 1.3.1 Information Exchange During Normal Conditions 11
- 1.3.2 Information Exchange During Emergency Conditions 12
- 1.3.3 Summary of Information Exchange 12
- 1.3.4 Issues with Communicated Data 14

SECTION II – INTERNAL OPERATION OF A MICROGRID THAT IMPACTS DISTRIBUTION SYSTEM OPERATION 17

II-A INTERACTIONS BETWEEN MICROGRIDS AND DISTRIBUTION SYSTEMS UNDER NORMAL AND FAULT CONDITIONS 17

2.1 USE CASES UNDER NORMAL OPERATIONS 17
- 2.1.1 A-1: Frequency Control with Supply and Demand Side Variations in Both Microgrids and Distribution Systems 17
- 2.1.2 A-2: Coordinated Volt-VAR Control and Optimization 19
- 2.1.3 A-3: Short-term Operations Planning for Interchange Schedule 21
- 2.1.4 A-4: On/Off Schedule of DERs 22
- 2.1.5 A-5: Harmonic Monitoring and Compensation with Microgrid Participation 24
- 2.1.6 A-6: Unbalance Compensation with Microgrid Participation 25
- 2.1.7 A-7: Microgrid Mode Transition from Intentional/Unintentional Island Operation to Grid-Connected Operation 27

CONTENTS (CONT.)

2.1.8 A-8: Microgrid Mode Transition from Grid-Connected Operation to Intentional Island Operation 29
2.1.9 A-9: Coordinated Energy Management for Economic Dispatch 31
2.1.10 A-10: Microgrid Model Update and Verification for Different Grid Operation Conditions 32
2.1.11 A-11: Distribution System Reconfiguration with Multiple Microgrids 33
2.2 USE CASES UNDER EMERGENCY OPERATIONS 35
2.2.1 B-1: Coordinated Load Shedding with Load and DER Variations in Both Microgrids and Distribution Systems 35
2.2.2 B-2: Coordinated Microgrid Protection 36
2.2.3 B-3: Power Outage Mitigation Using Multiple Microgrids Integrated with DMS 38
2.2.4 B-4: Virtual Microgrid Implementation and Energy Management Scheme for Emergency Power Support 39
2.2.5 B-5: Fault Isolation for Grid-Side Faults 41
2.2.6 B-6: Post-fault Recovery for Grid-Side Faults 42
2.2.7 B-7: Fault Isolation for Microgrid-Side Faults 44
2.2.8 B-8: Post-fault Recovery for Microgrid-Side Faults 45
2.2.9 B-9: Microgrid Mode Transition from Grid-Connected Operation to Unintentional Island Operation 47
2.2.10 B-10: Fault Ride-Through Capability of Microgrids 48

II-B POWER QUALITY CONSIDERATIONS INTERNAL TO THE MICROGRID 51
2.3 MICROGRIDS OPERATION QUANTITIES FOR ONLINE POWER QUALITY MONITORING 51
2.4 IDENTIFICATION OF ONLINE MONITORING STRATEGIES FOR MICROGRID POWER QUALITY 52
2.4.1 Online Monitoring Strategy for Microgrid Harmonics 52
2.4.2 Online Monitoring Strategy for Microgrid Unbalance 53
2.4.3 Online Monitoring Strategy for Voltage Violations 53
2.5 EVALUATING THE EFFECTIVENESS OF ONLINE POWER QUALITY MONITORING STRATEGIES 54

SECTION III – IMPACT OF MICROGRID OPERATION ON THE DISTRIBUTION SYSTEM AND DMS OPERATION 55

III-A POWER EXCHANGES BETWEEN MICROGRIDS AND DISTRIBUTION SYSTEMS – ELECTRICITY MARKETS 55
3.1 DEFINITION OF MICROGRID POOLS PARTICIPATING IN JOINT POWER DISPATCH 55
3.2 MICROGRID DISPATCH RULES AND OPERATION STRATEGIES 57
3.2.1 General Rules 57
3.2.2 Optimal Scheduling Strategy within the Microgrid 58

CONTENTS (CONT.)

3.2.3 Dispatch Rules from Distribution Grid and Market 59
3.3 POWER DISPATCH INTERACTION BETWEEN MICROGRID POOLS, DISTRIBUTION UTILITY AND MARKETS 59
III-B PROTECTION COORDINATION BETWEEN MICROGRIDS AND THE DISTRIBUTION SYSTEM 61
3.4 PROTECTION SCHEMES OF DMS IN ACTIVE DISTRIBUTION NETWORKS 61
3.5 PROTECTION SCHEMES OF MICRO EMS 63
3.6 REQUIREMENTS FOR DMS AND MICRO EMS PROTECTION FUNCTIONS TO FACILITATE COORDINATION 64
3.6.1 Challenges of Distribution System Protection Due to Integration of Microgrids 64
3.6.2 DMS and Micro EMS Protection Function Requirements to Facilitate Coordination 66
3.7 ANALYSIS OF DMS AND MICRO EMS PROTECTION COORDINATION IN VARIOUS EVENT SCENARIOS 70
3.7.1 DMS and Micro EMS Protection Coordination for Grid-Side Faults 70
3.7.2 DMS and Micro EMS Protection Coordination for Microgrid-Side Faults 72

SECTION IV – TOOLS AND TECHNIQUES FOR THE INTEGRATION OF MICROGRIDS IN THE DMS – POWER FLOW AND FAULT ANALYSIS 75

4.1 MAJOR ADVANCED DMS APPLICATIONS AFFECTED BY INTEGRATION OF MICROGRIDS 75
4.1.1 On-line Power Flow 75
4.1.2 Short-Circuit Analysis 76
4.1.3 Fault Location, Isolation, and Service Restoration 76
4.1.4 Volt-VAR Optimization 77
4.2 ANALYSIS OF THE IMPACT ON INDIVIDUAL ADVANCED APPLICATIONS FROM INTEGRATION OF MICROGRIDS 78
4.2.1 On-line Power Flow 78
4.2.2 Short-Circuit Analysis 79
4.2.3 Fault Location, Isolation, and Service Restoration 79
4.2.4 Volt-VAR Optimization 80
4.3 REQUIREMENTS OF AND EFFECTIVE APPROACHES TO MODIFYING ADVANCED APPLICATIONS TO SUPPORT INTEGRATION OF MICROGRIDS 81
4.3.1 On-line Power Flow 82
4.3.2 Short-Circuit Analysis 83
4.3.3 Fault Location, Isolation, and Service Restoration 83
4.3.4 Volt-VAR Optimization 84

SUMMARY AND CONCLUSION 85

CONTENTS (CONT.)

REFERENCES 87

APPENDIX 89

FIGURES

1 Multiple Microgrid System 8

2 Data Communication and Function Mapping between a Microgrid Controller and a DMS. 13

3 Control Signals Generated by Advanced Applications to Adjust Operation of a Microgrid. 14

4 Schematic of Microgrid Pools. 56

5 Distribution System Basic Protection Coordination Scheme. 62

6 Sample Distribution System Integrated with Microgrids and DERs. 71

TABLES

1 Dispatch Strategy for Multiple Microgrids 58

2 Interaction and Information Exchange in Microgrid Scheduling 60

3 Summary of Distribution System Protection Devices 62

4 Summary of Main Distribution System Protection Issues Due to Microgrid and DER Integration 65

5 Solutions to Main Distribution System Protection Issues Due to Microgrid and DER Integration 69

6 Interconnection System Response to Abnormal Voltages 91

7 Interconnection System Response to Abnormal Frequencies 92

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LIST OF ACRONYMS

AGC	Automatic generation control
AMI	Advanced metering infrastructure
APF	Active power filter
DER	Distributed energy resource
DERMS	Distributed energy resources management system
DG	Distributed generation
DMS	Distribution management system
DSO	Distribution system operator
EMS	Energy management system
EPS	Electric power system
ESS	Energy storage system
FLISR	Fault location, isolation, and service restoration
ICT	Information communications technology
IED	Intelligent electronic device
Micro EMS	Microgrid energy management system
OLPF	Online power flow
POI	Point of interconnection
PQ	Power quality
PV	Photovoltaic
RAS	Remedial action scheme
RES	Renewable energy sources
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
SOM	Switch order management
UBLF	Unbalanced load flow
VVO	Volt-VAR optimization

EXECUTIVE SUMMARY

Distribution management systems (DMSs) are increasingly used by distribution system operators (DSOs) to manage the distribution grid and to monitor the status of both power imported from the transmission grid and power generated locally by a distributed energy resource (DER), to ensure that power flows and voltages along the feeders are maintained within designed limits and that appropriate measures are taken to guarantee service continuity and energy security. When microgrids are deployed and interconnected to the distribution grids, they will have an impact on the operation of the distribution grid. The challenge is to design this interconnection in such a way that it enhances the reliability and security of the distribution grid and the loads embedded in the microgrid, while providing economic benefits to all stakeholders, including the microgrid owner and operator and the distribution system operator.

The interconnection and integration of microgrids into distribution systems can be facilitated, and the presence of microgrids better benefit all stakeholders, if appropriate tools are developed to represent and control microgrids from within the DMS. Such microgrid models and control tools will allow a detailed analysis of the impacts of microgrids on the feeders to which they are connected and the distribution system in its entirety. The tools will also enable interaction with the microgrid that benefits all stakeholders. The models will represent, among other features, the aggregation of DERs and loads within the microgrid and the control functions implemented by the microgrid controller.

This report deals with some of the technical issues related to integrating microgrids into a distribution system and its DMS. It first describes elements of the operation of microgrids within distribution systems, including possible modes of operation and interactions in normal and faulted operating conditions (Section I). It provides background information, in the form of use cases, on some of the internal modes of operation of microgrids that may impact the distribution system, including normal and faulted operation (Section II). It then addresses operating modes in which the microgrid interacts with the distribution system, including power exchanges under normal operation and fault conditions as well as protection coordination (Section III). Finally, it discusses power system analysis tools, such as power flow and fault analysis tools that can be used to analyze the impact of the integration of microgrids in distribution systems (Section IV).

INTRODUCTION

This report lays the foundation for the studies and tools needed for the analysis of the interconnection, integration and impact analysis of microgrids connected to distribution systems in steady state, transient and fault conditions. It identifies the new issues that the connection of microgrids poses for the operation of existing distribution systems. It indicates the tools available for the studies, and details the modifications and additions needed to existing tools to manage the specificity of microgrids as systems of systems.

This report is useful as the basis for detailed and quantified studies of the impact of microgrids on distribution systems under different non-ideal operating conditions. It identifies the specific considerations that the DMS should take into account in operating a system with embedded microgrids under normal operation, including power exchanges, and under faulted conditions, including detailed specification of the required protection schemes. It also establishes the operational requirements of microgrids to enable them to meet distribution system operational requirements and to facilitate coordination between the DMS and microgrids. In addition, it identifies the considerations needed to develop detailed models of microgrids for different studies related to their integration into the operation of the DMS.

The report is organized in four sections:

- *Section I, Interaction Between the Microgrid and the DMS Under Normal and Fault Conditions*, deals with one of the more sensitive issues that arises when connecting any new equipment or system to a distribution grid, the risk of a negative impact on the grid and of jeopardizing its reliability, security, and power quality. We describe microgrid modes of operation, including grid-connected and island modes, and the transition between modes. Operating strategies of the microgrid under normal and abnormal or fault conditions are discussed. Interactions between single and multiple microgrids and the distribution system are presented, including the required information exchange.

- *Section II, Internal Operation of the Microgrid That Impacts Distribution System Operation*, addresses the same concerns as Section I, but from the perspective of the microgrid's internal operation under normal and fault conditions, taking into account embedded distributed energy resources and load management (demand response). The impact of the control of these resources and loads, including curtailment, on voltage and frequency are discussed. We address power quality issues, including harmonics, voltage unbalance, and voltage violations resulting from the presence of DERs on microgrids and the distribution grid. Related issues, such as coordinated energy management for operating cost minimization, feeder reconfiguration, power outage mitigation, emergency power support, fault isolation and post-fault recovery, and islanding are discussed. The second part of this section deals with power quality issues within the microgrid, including harmonics and unbalance, and with monitoring approaches.

- *Section III, Impact of Microgrid Operation on the Distribution System and DMS Operation*, deals with operating issues of the microgrid that directly impact the distribution system, namely (a) the participation of the microgrid in electricity markets and the microgrid resources that need to be internally dispatched to allow this participation and the optimal scheduling of these resources, and (b) coordination between the protection devices of the microgrids and the protection devices of the distribution system and the associated DMS, and the requirements for facilitating the protection coordination. Both issues — market participation and protection coordination — involve the operation, control and protection of distributed energy resources. We consider operating modes and scenarios, including fault scenarios on the distribution feeder, and propose solutions to mitigate the impact of abnormal operation (faults). Grid-connected and island modes are considered. Various protection coordination schemes are discussed, including schemes with and without communication.

- *Section IV, Tools and Techniques for the Integration of Microgrids into the DMS – Power Flow and Fault Analysis*, presents existing tools and discusses the changes and adaptations required to accommodate the presence of microgrids. These tools incorporated into the DMS calculate power flow and faults in the network. Power flow calculations are used to determine loading on the distribution lines and the voltage at load nodes, and are also used to identify abnormal operating conditions and determine remedial action. Short-circuit calculations verify that equipment can interrupt the fault currents and withstand short circuit currents. A function implemented in the DMS and associated with faults is fault location, isolation and service restoration. This function increases the reliability of the distribution system by allowing distribution feeder reconfiguration. A function associated with load flow and node voltage regulation is volt-VAR optimization, which activates equipment along the distribution feeders to regulate the voltage. These DMS tools need to be adapted when interconnecting and integrating microgrids. Some of the issues include (a) both the stochastic nature of the generation present within a microgrid and the reverse power flow resulting from the contribution of the generation within the microgrid in the case of power flow control, and (b) the fault contributions of the microgrid for fault analysis. We propose approaches to tackle these new issues. Similarly, the presence of microgrids will impact the two functions described above: fault location, isolation and service restoration, and volt-VAR optimization. For these two functions, the issues are described, new requirements identified and solutions, in the form of new algorithms, proposed.

SECTION I – INTERACTION BETWEEN THE MICROGRID AND THE DMS UNDER NORMAL AND FAULT CONDITIONS

According to the Department of Energy's (DOE's) Microgrid Exchange Group, "*A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode*." While a microgrid can operate in either a grid-connected mode or in an island mode, the safe and reliable operation of microgrids in both modes requires proper planning, coordination, control and operation strategies. For example, in the grid-connected mode, a microgrid has to be synchronized with the main distribution grid, and in the disconnected (island) mode, a microgrid has to be able to maintain quality voltage and frequency with effective load-following characteristics. It also has to be prepared for reconnecting to the distribution grid through the synchronization process.

In this chapter, we will cover a) identification of the operation modes of microgrids for connection to and disconnection from the distribution system, b) identification of the operation strategies of microgrids for connection to and disconnection from the distribution system in normal operation, emergency and faulted conditions, c) analysis of the interactions and operation impacts in microgrids and the distribution system for connected and disconnected operation modes, and d) identification of the communication requirements between the DMS and the integrated microgrid energy management system (micro EMS).

1.1 OPERATIONAL MODES OF A MICROGRID

A microgrid can operate in three modes:

1. Grid-connected mode
2. Transition mode (transition from grid-connected mode to island mode and vice versa)
3. Island mode

1.1.1 Grid-Connected Mode

In grid-connected mode, a microgrid is connected with the main distribution grid and can supply power to the main grid or receive power from the main grid, depending on the local generation and energy storage capacities and local load demands of the microgrid, as well as the committed power exchange schedules between the microgrid and the main grid. When local generation capacity exceeds local demands, the microgrid can supply power to the main grid. When local demand exceeds local generation, the microgrid can import power from the main grid. System stability and energy balance, given the high fluctuations of DER output, are particularly important for a microgrid in grid-connected mode. Operation in grid-connected mode may also reduce the need for additional storage.

1.1.2 Grid-Connected to Island Mode Transition

A microgrid may need to disconnect from the main grid, either intentionally or unintentionally. The microgrid controller will be responsible for managing its resources to ensure a smooth transition from grid-connected to island operation mode, which may be intentional or unintentional.

a) ***Intentional Islanding***

An intentional islanding process may be initiated for many reasons, such as a scheduled outage or maintenance on one or more sections of the main distribution system, a part of the main grid experiencing a widespread disturbance, or a new dispatch request from the system operator during normal operation. After the transition, every isolated microgrid will operate in island mode and maintain its own energy balance and quality voltage and frequency, even during time periods with disturbances.

According to IEEE Standard 1547, an intentional island is the result of “intentional events for which the time and duration of the planned islanding are agreed upon by all parties involved.” Intentional disconnection occurs when the microgrid responds to a command or request from the distribution grid to operate in island mode. The disconnection should not induce large voltage and frequency fluctuations in the microgrid and the distribution grid, and the microgrid should maintain its power balance after disconnection. It is a common practice in the transition process to ramp-down power exchanges at the point of interconnection (POI) to near zero to ensure minimum impact on both sides during the transition. Additional control and/or hardware devices can be deployed to alleviate voltage and current surges during the transition. Intentional disconnection can be either planned or unplanned.

Planned intentional islanding involves ramping down the power flow at the POI to near zero and then disconnecting the microgrid from the main grid. The process is carried out in a planned manner, with the main grid operating in a normal operation mode. The transition process is executed with a reasonable warning period, and can either be one of the following:

- *Command planned islanding*: The utility or operating entity requests that the microgrid transition to island mode at a specific time in the future with sufficient time for planning.

- *Scheduled planned islanding*: A scheduled tariff transition or operating agreement dictates that the microgrid transition to island mode at a specific time.

An unplanned/unscheduled intentional islanding will also need effective support from the microgrid controller and will involve one of the following two scenarios:

- *Outage driven:* A confirmed grid outage is detected by the recloser or switch at the POI, which opens and starts the unplanned/unscheduled islanding transition.

- *Command driven*: A triggering event is detected by the monitoring platform, which directs the islanding recloser or switch at the POI to open and start the unscheduled islanding transition. Alternatively, the utility operation center receives the triggering event(s) and uses DMS/SCADA to open the recloser. When the recloser at the POI is opened, the battery inverter in the microgrid receives the recloser open status and switches from the current-source mode to the voltage-source mode. At the same time, the microgrid controller and the DMS/SCADA receive the recloser open status to update their models. The microgrid controller may shed loads and use storage if generation is inadequate, or curtail DER output if generation is excessive, thus instantly balancing the power when the POI breaker is opened. As additional generation resources are brought on-line later on, the shed loads can be restored.

b) ***Unintentional Islanding***

In this mode transition, a section of the utility distribution grid may be disconnected following a fault on the main grid.

According to IEEE Standard 1547, unintentional islanding can occur following inadvertent events that are typically initiated by the loss of an area electrical power system (EPS) or an equipment failure. The associated microgrids in the islanded part of the system may be automatically disconnected from the main grid by anti-islanding protective schemes. When the unintentional islanding process is triggered by such an event, the DMS and the corresponding microgrids should be notified of the operation mode transition. Both the micro EMS and the DMS should ensure the power balance in their own grids after the mode transition. Transient frequency and voltage requirements should be satisfied for both the microgrids and the distribution grid during the transition. Active devices in both the microgrids and the distribution grid can be used to alleviate transient voltage/current spikes during operation mode transition.

The transient process of unintentional islanding should be accomplished within two seconds, according to IEEE Standard 1547.

1.1.3 Island to Grid-Connected Mode Transition

Prior to the reconnection of the microgrid to the distribution grid, the synchronization monitoring/control mechanism should ensure that the islanded microgrid and the distribution system are ready for synchronization with the voltage, frequency, and phase angle difference across the POI switch being within the limits defined by IEEE Standard 1547:
$|\Delta V| < 3$, $|\Delta f| < 0.1$ Hz and $|\Delta\delta| < 10^0$.

After a severe disturbance in the distribution grid that results in microgrid islanding, the reconnection process shall not be initiated until the distribution grid voltage recovers back to Range B of the American National Standards Institute/National Electrical Manufacturers Association (ANSI/NEMA) Standard C84.1-2006. [1]

The synchronization control mechanism may further delay the reconnection for up to five minutes after the distribution system voltage and frequency are recovered to the ranges identified above. If the disconnection was triggered by an unknown event, the reconnection should not be initiated until it is confirmed that the distribution system will be stable.

1.1.4 Island Mode

In the island mode of operation, the microgrid is fully independent of the main distribution grid operation, and its local controller fully manages its energy resources and loads in order to ensure the secure and stable operation of the microgrid. When in island operation, the microgrid controller may periodically communicate with the DMS or the corresponding upstream devices of the distribution network to be aware of the appropriate condition for reconnection.

1.2 OPERATION STRATEGIES OF MICROGRIDS

In either grid-connected or island operation mode, a microgrid should meet specific operation requirements under normal and abnormal operating conditions. The requirements include maintaining an acceptable voltage profile, grid frequency, synchronization, and load following. The operation strategy should consider not only the case of a microgrid connected with the distribution grid, but also the case of multiple microgrids interacting together. The following subsection describes the operation strategy of microgrids.

1.2.1 Single Microgrid

The requirements for a single microgrid under normal and abnormal conditions, based on IEEE Standard 1547, are summarized below. Details are given in the Appendix and are also available in References.[2], [3], [4]

a) ***Normal Conditions***

- A microgrid must have a proper grounding scheme that should be well coordinated with the distribution grid to avoid the occurrence of any possible overvoltage or safety issues in the microgrid or the distribution grid.

- In grid-connected mode, a microgrid operates in parallel with the distribution grid through a single active POI or multiple POIs. Voltage fluctuations should be within ±5 percent of the prevailing voltage level. The requirements for limiting voltage flicker should also bemet.

- The microgrid must cease to energize the distribution grid at any POI when the grid is de-energized.

- If the aggregated capacity at each POI is more than 250 kVA, its connection status may be monitored, including the monitoring of real power output, reactive power output, and voltage at the POI.

- When required by the distribution grid, isolation devices may be equipped with a circuit breaker at each POI of the microgrid.

- The interconnection system must meet applicable surge and EMI standards.

b) ***Abnormal Conditions***

- In the event of distribution grid faults, the microgrid should cease to energize the grid at any POI.

- When a microgrid operates in island mode, it may be energizing a portion of the isolated distribution grid through a POI.

- The microgrid should cease to energize the isolated portions of the distribution grid at any POI before reconnecting to the distribution grid for grid-connected mode operation.

- Power balance inside the microgrid should be achieved before it is reconnected to the distribution grid, and zero power exchange should be maintained after reconnection until it is ready to start transaction schedules.

- The voltage at the POI of the microgrid should be continuously monitored. If the voltage at the POI is within a range shown Table 6 of the Appendix, the microgrid should cease to energize the distribution grid at the POI.

- When the system frequency falls within a range listed in Table 7 of the Appendix, the microgrid should cease to energize the distribution grid at the POI.

- Reconnection of the microgrid can take place when the voltage is within the range of 88% to 110% of the base voltage, and the frequency is within the range of 59.3 Hz to 60.5 Hz. The reconnection at the POI should include an adjustable or a fixed delay (e.g., five minutes).

1.2.2 Multiple Microgrids

We discussed a single microgrid operation strategy in connection and disconnection with the main distribution grid in the previous section. The concept of multiple microgrids is relatively new, and there is no clear definition for planning the operation and control of multiple microgrids. In this section, we consider an architecture where multiple microgrids, configured in the distribution grid, are directly connected with the main grid with no interconnection between the microgrids (see Figure 1). Any exchange of power between two microgrids happens through the distribution grid in coordination with the DMS. It is also assumed that each microgrid is capable of operating in standalone mode. We refer to this system as a multiple microgrid system. In this architecture, each microgrid controller can communicate with the DMS. Connections, disconnections and power exchanges are coordinated through the DMS.

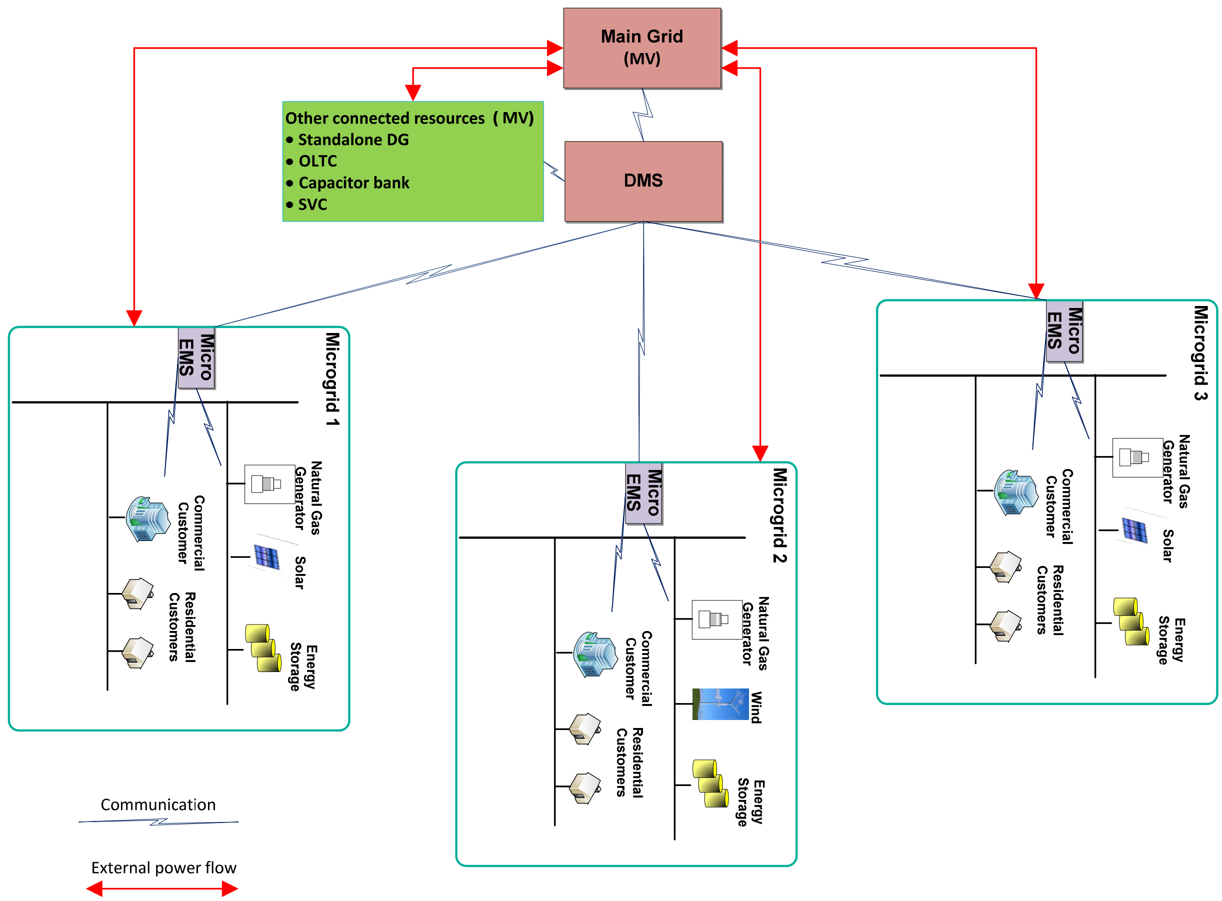

Figure 1 Multiple Microgrid System

Based on the architecture shown in Figure 1, we will highlight some of the operation strategies of a multiple microgrid system. Since a distribution grid is managed by a distribution system operator (DSO), it is important to understand the interaction between multiple microgrids and the DMS. One of the main challenges in operation strategies with multiple microgrids is the presence of multiple microgrid controllers, which may need to coordinate with the DMS for the secure and stable operation of the entire distribution grid under normal and emergency conditions.

a) ***Coordination of Tie-line Power***

Each microgrid should maintain its scheduled tie-line power with the main distribution grid under normal operation and support power exchange via tie-lines during abnormal operation. Power exchange between multiple microgrid systems as a single entity and the distribution grid should be coordinated among the individual microgrid controllers and the DMS.

b) ***Synchronization***

Under normal operating conditions, all microgrids are synchronized with the main grid at the POIs. During the process of interconnection, the requirements for voltage, frequency and phase angle should be met. A microgrid operating in island mode should have enough lead time for synchronization with the main grid. This means that an islanded microgrid should be able to operate in standalone mode for that amount of time and should be able to balance its energy locally. Each microgrid controller should coordinate with the DMS for the purpose of synchronization.

c) ***Voltage/VAR Support***

One of the main concerns with multiple microgrids is the voltage rise effect caused by the presence of multiple DERs in microgrids. Each microgrid in the multiple microgrid system should locally manage its voltage as well as coordinate with the DMS and other microgrids for reactive power support. Thus a two-level coordinated voltage control action between the DMS and individual microgrids is required, functioning through the management of available resources such as microgrids, distributed generation (DG) units directly connected at the medium voltage (MV) level, voltage regulators (VRs) and on load tap changer (OLTC) transformers, and other reactive power support devices, such as capacitor banks or static VAR compensators (SVCs).

d) ***Load Shedding***

Load shedding is required to maintain system frequency and voltage within limits when there is less generation than demand. Each microgrid should determine what loads need to be disconnected at a given time following the variations in load and DER output. Similarly, the DMS in coordination with other microgrids should determine if load shedding should be triggered based on the monitoring data and the predicted data for both sources and loads.

e) ***Black Start***

"Black start" is the restoration process after a blackout — a set of rules to be followed for system restoration. In a multiple microgrid architecture, local self-healing techniques can be exploited, since a substantial number of microgrids and other DG units connected to the network can provide service restoration in their areas of influence. Multiple microgrid black start capabilities can be used to reduce the customer service interruption, so the multiple microgrid restoration procedure should aim to supply consumers as soon as possible while satisfying system operation conditions. The following sequence of actions should be carried out in order to restore the low voltage distribution grid after a general blackout: [5]

- Disconnect all loads, sectionalize the corresponding medium-voltage/low-voltage (MV/LV) transformers, and switch off the reactive power sources in order to avoid large frequency and voltage deviations.

- Sectionalize the multiple microgrid around each microgrid and around each DG unit with black start capability to create small islands within the multiple microgrid system.

- Energize a part of the MV network using black-start-capable energy resources, such as diesel generators.

- Synchronize the islands within the multiple microgrid system with the MV network according to synchronization criteria in order to avoid large voltage and frequency deviations.

- Connect a certain amount of controllable load in the MV network, depending on the available capacity of storage and total generation.

- Synchronize the islanded microgrid with the main grid.

- Energize the remaining MV branches and the MV/LV transformers upstream of the microgrid. At this stage, the islands containing isolated DG units are already synchronized and the multiple microgrid is strong enough to energize the remaining branches of the MV network.

- Restore loads. At this stage, the MV network is fully energized, and some loads can be connected depending on the generation capacity.

- Connect the non-controllable energy sources (i.e., photovoltaic [PV] and wind) without battery storage capability.

- Increase load. In order to feed as much load as possible, other loads can be connected.

- Activate the automatic frequency control to ensure that the multiple microgrid system frequency is near its nominal value while in island mode.

- Reconnect multiple microgrids to the upstream high voltage (HV) network when it becomes available. The synchronization conditions should be verified again.

f) ***Power Outage Mitigation***

If a power outage takes place in a segment of the network following a fault condition, the multiple microgrids in coordination with the DMS can help in mitigating it. When the outage is detected, the DMS should be able to determine an alternate path for rerouting the supply through other microgrids in the system. The microgrid controllers in each microgrid should work with the DMS to isolate the fault area and restore the service. During the process, the desired frequency and voltage throughout the system should be ensured, and the availability of DERs for emergency power support should be identified. The necessary data exchange between the micro EMS and the DMS during power outage mitigation should be identified and the power balance inside each microgrid must be ensured.

g) ***Coordinated Microgrid Protection***

The protection of a microgrid should consider the fault current contribution from the individual microgrid side and from the distribution system side, which requires coordination between the microgrid controllers and the DMS. For the protection of the circuits and devices inside the microgrid, different operation modes should be considered, and the relay settings should be adjusted accordingly. In particular, for grid-connected operation mode the relay settings should be larger, since the fault current is contributed by DERs, other microgrids in the system, and the upstream distribution system. On the other hand, in the island operation mode the fault current is solely contributed by the DERs, so the fault current level is much lower than in the grid-connected mode. The relay settings should be lower. Also, in this mode of operation, other microgrids in the system should not contribute to the fault currents of islanded microgrid.

Each microgrid controller should be capable of detecting any internal fault occurring anywhere. When an internal fault is detected, the microgrid should disconnect itself from the rest of the system to ensure that the fault will not cause an operation problem to the distribution grid. Power balancing within the microgrid should be done after isolating the faulted section or disconnecting from the distribution grid.

h) ***Distribution System Reconfiguration***

Reconfiguration with multiple microgrids is particularly useful for grid resiliency in the event of a natural disaster or fault condition that isolates multiple segments of the network. Multiple microgrids provide an alternate power rerouting scheme that maximizes distributed generation output power, reduces network power losses, or restores loads not supplied in a fault scenario. Rerouting can be performed through multiple switching operations. The DMS, in coordination with other microgrid controllers, can determine the optimal network reconfiguration based on available power from both feeders and microgrids. Short-term DER and load forecasting data can be used to support the network reconfiguration. The available power should be supplied by each of the feeders and by the microgrids with high available power. The power balance after the network reconfiguration should be ensured, and no new loops should be reformed after the reconfiguration.

1.3 INTERACTIONS AND OPERATION IMPACTS IN MICROGRIDS AND DISTRIBUTION SYSTEMS

As discussed above, a microgrid can operate in either a grid-connected or a grid-disconnected (island) mode. The integration of DMS and micro EMS needs to ensure that both the distribution grid and the microgrids can maintain reliable operation under normal operation and contingency conditions, as well as make a seamless transition from one mode to the other.

When connected to the distribution grid, a microgrid should have the necessary data communication with the DMS for operation coordination under normal operation and emergency conditions.

1.3.1 Information Exchange During Normal Conditions

- The DMS needs to receive information on the energy interchange and voltage/VAR support schedules between the microgrid and the distribution grid at the POI.

- The DMS needs to receive real-time data including phase voltages, currents, kWs, and kVARs at the active POIs.

- Each microgrid should also provide a simplified internal operation topology to the DMS to indicate whether it forms wheeling paths to the distribution grid if more than one POI is active. Wheeling paths and their impact are described in "Guidelines for Implementing Advanced Distribution Management Systems: Requirements for DMS Integration with DERMS and Microgrids."[3]

1.3.2 Information Exchange During Emergency Conditions

- In emergency conditions, whether initiated from a microgrid or from the distribution grid in the grid-connected mode, emergency energy interchange and voltage/VAR support may be needed from the other party (or other microgrids in the case of multiple microgrid system).

- The request for emergency support should be forwarded to the other party and confirmed quickly to effectively relieve the emergency.

- In the event of severe fault conditions in either the distribution grid or the microgrid, POIs should be disconnected by the relay protections. This type of disconnection is classified as unintentional disconnection. The DMS should inform other impacted microgrids in the network about the fault condition and instruct them to disconnect from the affected segment of the network. The interaction between various actors and information exchange for unintentional disconnection is shown in the table in subsection 2.2.9.

- For intentional disconnection, the DMS should instruct the microgrids to prepare for the disconnection, including reducing the energy interchange to near zero at the POI and re-optimizing the grid voltage profiles. These steps can be done by balancing real and reactive demands in their respective grids. The interaction between different actors and content for information exchange during intentional disconnection is summarized in the table in subsection 2.1.8.

- To reconnect to the grid, the microgrid should notify the DMS and receive a confirmation message. Once confirmation is received, the microgrid can start the resynchronization process. The information exchange between different actors during reconnection is summarized in the table in subsection 2.1.7.

1.3.3 Summary of Information Exchange

Figure 2 [3] is a summary of data communication and function mapping between a micro EMS and a DMS to highlight the different functions in each under both normal and fault conditions. As shown in Figure 2, in the grid-connected operation mode, the functions in the micro EMS and DMS are coordinated with each other to ensure effective integration between the two control systems.

Considering the data communication and interactive control functions between a micro EMS and a DMS, the microgrid can be seamlessly integrated and treated as an energy asset to improve the operation of the distribution grid. Control signals are generated by different advanced applications in the DMS to change the status of the microgrid according to the operation condition and requirements, as shown in Figure 3.[3]

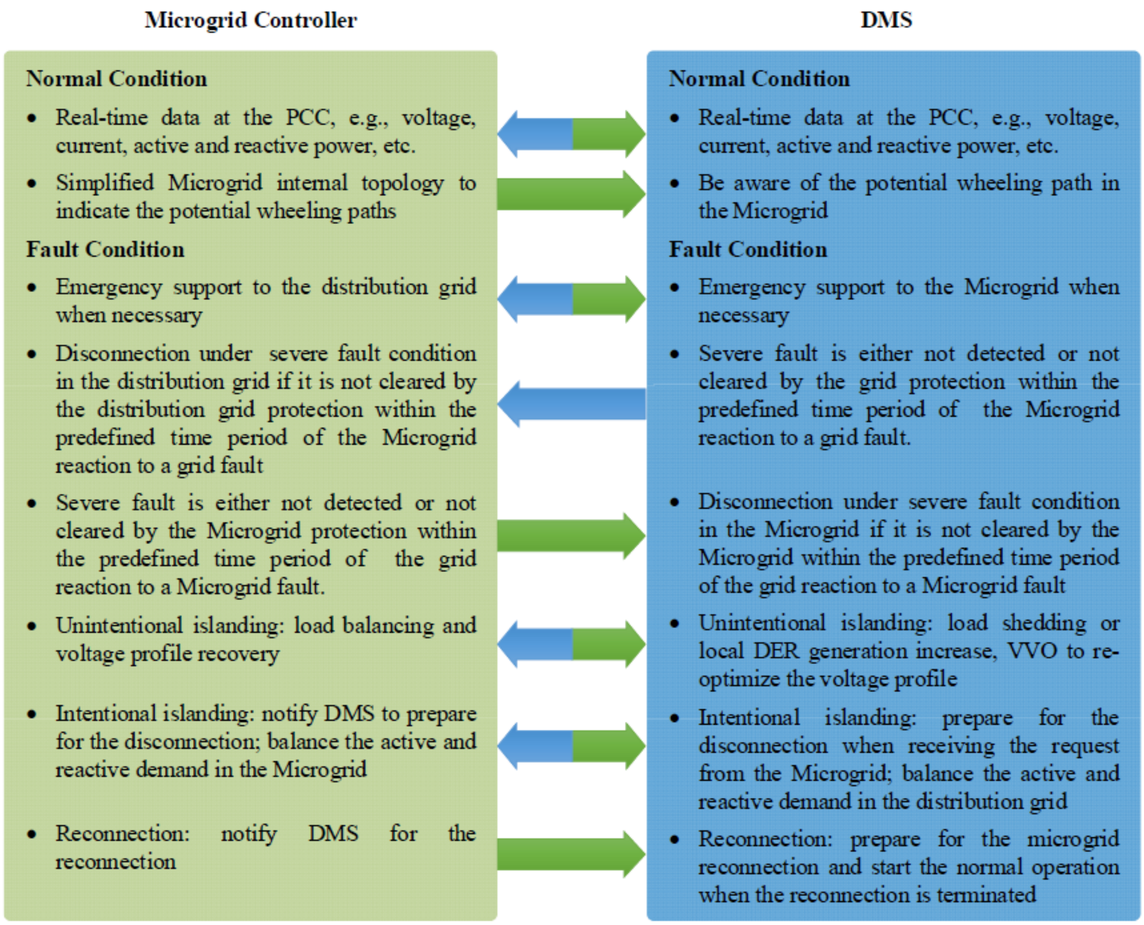

Figure 2 Data Communication and Function Mapping between a Microgrid Controller and a DMS.

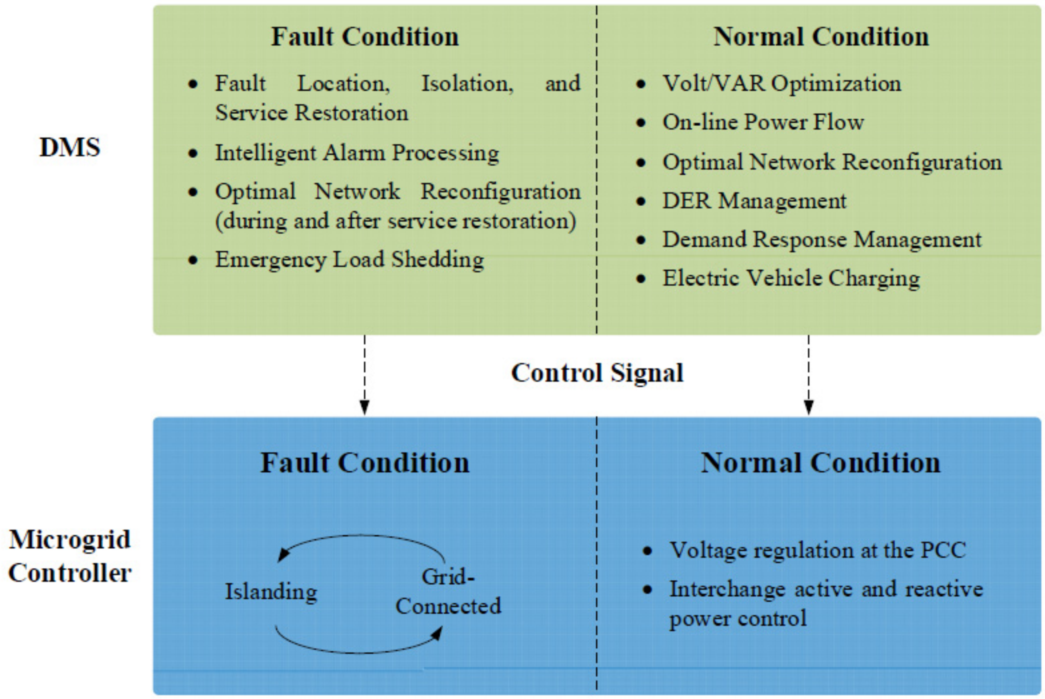

Figure 3 Control Signals Generated by Advanced Applications to Adjust Operation of a Microgrid.

1.3.4 Issues with Communicated Data

The quality and availability of the data to be exchanged between the field devices or sensors and the controllers are the major issues associated with the data communication. The main challenges include data loss, latency and bad data. Missing data and latency may cause the system to lose observability. Bad data can also cause the system to become non-observable when it is rejected by the bad data detection algorithm. In addition, bad data can lead to significant impact to the system stability. Undetected bad data can cause an incorrect control action by the controller, which in turn may result in system instability. In view of this, both the DMS and microgrid controller functions should be robust against bad data, data loss, and data latency and should meet the following requirements:

1. Controllers should have adequate data buffer to execute different functions. The life span of buffer data should be capable of spanning milliseconds to minutes, depending on the time criticality of the control (primary, secondary etc.)

2. Controller functions and algorithms should be able to compensate for data latency by using, for example, a compensator or Padé approximation.

3. Data should be preprocessed using statistical characteristics to identify bad data.

4. The elimination of bad data or missing data due to communication errors should not cause any observability issue, and measurement redundancy should be included to ensure system observability.

5. If required, the controller should be equipped with a system state observer or state estimator, such as a Kalman filter, so that missing data can be estimated.

6. The controller needs to be properly tuned to address the issues of missing data, delay or bad data.

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SECTION II – INTERNAL OPERATION OF A MICROGRID THAT IMPACTS DISTRIBUTION SYSTEM OPERATION

II-A INTERACTIONS BETWEEN MICROGRIDS AND DISTRIBUTION SYSTEMS UNDER NORMAL AND FAULT CONDITIONS

An advanced microgrid is considered to be a sub-power system comprising distributed generation/storage and load. It uses its internal controlling devices for different control and operation objectives, such as different step-wise and/or continuous voltage and VAR controllers (VVC), remedial action schemes (RAS), under-frequency/voltage load shedding, and elements of information communications technology (ICT). An advanced microgrid can operate in grid-connected mode or in island mode. It can also provide various ancillary services. The operation of microgrids in different modes has a significant impact on the operation of the DMS and the distribution networks, and we analyze this impact through the identified twenty-one use cases in this chapter. The use cases generally fall into two categories: normal operation (Category A) and emergency operation (Category B). Detailed analyses for each identified use case include the operation rules and control strategies of microgrids and micro EMS, the operation rules and control strategies for distribution system and DMS, and the interactions and operation impacts on both microgrids and distribution systems.

2.1 USE CASES UNDER NORMAL OPERATIONS

2.1.1 A-1: Frequency Control with Supply and Demand Side Variations in Both Microgrids and Distribution Systems

A. Description

This use case analyzes system frequency regulation in both microgrids and distribution systems, taking into account the impact of both supply and demand side variations. Note that the supply and demand sides are defined in both distribution systems and microgrids. The supply side represents the energy sources in either system, such as DERs, while the demand side represents loads, including common loads and distributed loads. The critical components responsible for regulating the system frequency will be identified and the corresponding controllers with effective impact to the performance of frequency regulation will be discussed.

With the connection of microgrids to the distribution grid, system frequency regulation can no longer rely solely on the upstream transmission system. The microgrids, as active sub-networks in the modern distribution system, can participate in system frequency regulation or support in certain operation modes. Both DER and load variations in the microgrid and distribution system are taken into account. When the microgrid operates in grid-connected mode, its DERs may participate in frequency regulation although system frequency is dominated by the distribution system and relies mainly on the frequency regulation of the upstream transmission system.

When the microgrid operates in island mode, the energy storage systems (ESSs) in the microgrid can operate in droop control mode and can thus be responsible for regulating the frequency. In some cases other DERs, such as photovoltaics (PVs) or wind turbines, can also be used to regulate the microgrid frequency.

An energy storage system (ESS) can be employed to resolve intermittency issues. Secondary control for DER generation, or automatic generation control (AGC) for maintaining the area frequency error close to zero, should be considered as well. DER scheduling or load shedding can be utilized if necessary.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• AGC (control system) • DER interface inverter controller[1] (control system) • Microgrid energy management system (micro EMS) (control system) • Distribution management system (DMS) (control system)	• Upload monitoring data from supply and demand sides to micro EMS and DMS. • Use AGC and DER interface controller to maintain area frequency control error close to zero. • Schedule DER or load shedding in emergency conditions if necessary. • Send frequency control command to the devices.	• Supply side monitoring data • Demand side monitoring data • Area frequency • Frequency control command

C. Impact Analysis

The interconnection of microgrids will have an impact on the system frequency regulation mechanism of conventional distribution systems, which is commonly dominated by the upstream transmission system and usually not reachable by the DMS. However, with the integration of microgrids, system frequency can be manipulated in certain levels with the active devices in microgrids, depending on their total generation capacity.

Frequency regulation applies to both grid-connected and island operation modes. In grid-connected operation mode, the capacity of a microgrid might not be significant compared to that of the distribution system in most cases. Thus the frequency of the combined system is mainly maintained by the distribution system, while the microgrids may only be able to provide limited help. In fact, the active devices in microgrids, such as PVs, wind turbines, and ESSs, usually follow the distribution grid frequency in grid-connected mode and may not actively participate in frequency regulation in most cases.

[1] DER interface inverter refers to conventional inverters that are used for DERs, including battery inverters, PV inverters, etc.

When a microgrid is disconnected from the distribution system, it will switch to an autonomous operation mode in which the frequency of the microgrid is regulated by the active devices within it, such as ESSs. These active devices are usually used for frequency regulation and have stable output that is not significantly influenced by external conditions. ESSs and DERs with relatively large capacity are good candidates for this purpose. In some cases PVs, wind turbines and other DERs may also be considered for frequency regulation. However, these devices' inevitable intermittence problem must be properly tackled to avoid severely degrading system operation reliability.

2.1.2 A-2: Coordinated Volt-VAR Control and Optimization

A. Description

This use case analyzes the impact of coordinated volt-VAR optimization (VVO) functions with microgrid controllers on distribution system operation. In addition, this use case will determine the requirements for information exchange between the microgrid and EPS operators for the coordinated VVO.

VVO is a very important application in a DMS. It is used to adjust the feeder voltage profile and reactive power flow during normal operation. VVO usually refers to the integrated control of conventional controllable devices, such as capacitor banks in a substation and along a feeder, on-load tap changers (OLTC) of substation transformers, voltage regulators on feeder sections, and smart inverter interfaced DERs. VVO usually executes at 5-, 10- or 15-minute intervals. For each control cycle, the VVO solves an optimization problem: determining the optimal control settings for each of the controllable devices. Specifically, this use case will use an aggregated microgrid model to identify the reactive power support capability of each microgrid to achieve the coordinated VVO objectives with the micro EMS and the conventional controllable devices.

Volt-VAR optimization involves multiple types of conventional controllable devices, such as substation transformer load tap changers, capacitor banks, voltage regulators, and smart inverter interfaced DERs, and an aggregated microgrid model is used to identify the reactive power support capability of each microgrid. The operation of microgrid and conventional controllable devices and smart inverter interfaced DERs should be coordinated for voltage profile regulation, and interactive operation between micro EMS and DMS should be achieved.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Controllable devices, e.g., load tap changer, capacitor bank, smart inverter, etc. (power hardware devices) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data to micro EMS and DMS. • Run the VVO algorithm in DMS. • Send control commands to each controllable device. • Conventional devices respond to the control commands. • Micro EMS coordinates its sources and loads in the microgrid and generates required amount of reactive power at its POI.	• Local voltage amplitude • Local current amplitude • Local power factor • Local real/reactive power • Command signals for reactive power control • Generation and load forecast data

C. Impact Analysis

With the microgrids' connections to the distribution grid, the voltage profile of a feeder circuit will be impacted not only by the OLTC, voltage regulators, and capacitor banks, but also by the active and reactive power outputs from the DERs and microgrids at different locations along the feeder circuit. The impact of microgrids on the VVO function will be discussed separately and depends on whether the micro EMS is able to dispatch its internal DERs or not. Dispatchable DERs are either DERs paired with energy storage units or distributed generators, such as diesel generators or micro turbines.

In island mode, a microgrid is disconnected from the distribution grid and, therefore, will have no impact on the VVO function of the distribution grid other than the microgrid's own voltage control.

In grid-connected mode, the micro EMS can provide the aggregated schedule of its active power and offer its reactive power capacity to the DMS for the overall VVO of the distribution grid. The VVO formulation can treat the power factor of each microgrid as a decision variable in addition to the conventional decision variables. The DMS can send out the power factor or reactive power set-point for each microgrid to maintain at the individual point of interconnection (POI) by controlling its internal DERs.

2.1.3 A-3: Short-term Operations Planning for Interchange Schedule

A. Description

This use case analyzes the impact of the presence of microgrids on the distribution system's short-term planning. More specifically, this use case will use aggregated microgrid models to identify the aggregated DER and load for each microgrid in order to achieve short-term power interchange that mitigates the intermittency caused by renewable energy sources (RES). In addition, this use case will determine the requirements for information exchange between the microgrid and EPS operators for short-term planning.

A microgrid can be used as an energy resource in short-term distribution system operation planning to mitigate the intermittency caused by the increasing penetration of DERs. The following points need to be considered for short-term operation planning for interchange schedules.

- Short-term planning is used for mitigating the influence of intermittency caused by RES.
- DERs in both microgrids and distribution systems should be taken into account.
- An aggregated model of each microgrid is used for short-term planning.
- DER and load forecasting should be considered for each microgrid and the distribution grid.
- Power interchange should be scheduled based on the predicated DER and load trends.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Device level on/off switch (power hardware device) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data to micro EMS and DMS. • Conduct source and load prediction in both microgrids and distribution systems. • Update predicted power availability of microgrids in DMS. • Schedule power interchange when necessary based on predicated DERs and load trends.	• Model update information of microgrids • DER and load side data monitoring • Device level forecasting data • On/off command signals for DERs and loads

C. Impact Analysis

The interconnection of microgrids will affect the short-term operational planning of a distribution system by mitigating the intermittency induced by RES. Two scenarios will be discussed: when the intermittency issue is originated from the microgrid side and when the issue is originated from the distribution grid side. The distribution grid can provide support to mitigate the intermittency in a microgrid and vice versa. For example, if the distribution grid forecasts a large increase in its DER generation, a microgrid can be scheduled to export less power to or import more power from the distribution grid to mitigate the intermittency issue. The microgrid can do so by sending out control commands to turn off some of its DERs, start charging its batteries, and so on. On the other hand, if the distribution side forecasts a large decrease in its DER generation, the microgrid may be scheduled to export more power to or import less power from the distribution grid to alleviate the intermittency. The microgrid can do so by turning on its own DERs, shedding some of its non-critical load, or starting to discharge EES batteries to meet the schedule.

Similarly, if the microgrid side forecasts a large increase in its DER output, the distribution grid can be scheduled to export less power to or import more power from the microgrid to mitigate the intermittency issues. The distribution grid can send out control commands to turn off some of its DERs, start charging its ESS batteries, and so on. If the microgrid forecasts a large decrease in its DER output, the distribution grid can be scheduled to export more power to or import less power from the microgrid to alleviate the intermittency. The distribution grid can turn on its own DERs, shed some of its non-critical load, or start to discharge its ESS batteries to meet the schedule.

2.1.4 A-4: On/Off Schedule of DERs

A. Description

This use case analyzes the impact of microgrids on the on/off schedule of DERs, which are used to balance power within each microgrid and throughout the entire distribution system. The following considerations need to be taken into account when scheduling DERs in microgrids and in the distribution system:

- The system frequency and the voltage profile throughout the system should be maintained within the acceptable range.

- Sufficient spinning reserve should be provided as ancillary services.

- Power balance in the individual microgrids and the distribution grid must be ensured.

- Short-term planning results should be considered for the on/off schedule of DERs.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Device level on/off switch (power hardware device) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data to micro EMS and DMS. • Conduct source and load prediction in micro EMS and DMS. • Micro EMS determines the on/off schedule of DERs inside microgrid. • DMS determines the on/off schedule of DERs outside microgrids.	• DER and load side data monitoring • Generation and load forecast data • On/off command signals for DERs

C. Impact Analysis

The interconnection of microgrids can have a significant impact on the on/off schedule of DERs. The micro EMS and DMS need to plan and commit the on/off schedule for dispatchable DERs, based on load and energy resource forecasting, as well as coordinate with the committed interchange schedules of the distribution grid and the microgrids. We will discuss the impact of a large load change predicted on both the microgrid side and the distribution grid side.

When the distribution side forecasts a large load decrease, the microgrid can be scheduled to shut down some of its DERs exporting power to the distribution grid. The microgrid can send out control commands to turn off some of its DERs, start charging its ESS batteries, and so on. DERs in the distribution system side may be scheduled to be off to help balance the power. If the distribution side then forecasts a large load increase, the microgrid can be scheduled to turn on new DERs to export more power to the grid or to import less power from the grid to help balance the power in the distribution grid. The microgrid can turn on its own dispatchable DERs and/or discharge ESS batteries to meet the schedule. The distribution system can also turn on its dispatchable DERs to maintain the power balance.

If the microgrid side forecasts a large load decrease, the distribution grid can schedule some of its DERs to export less power to or import more power from the microgrid. The distribution grid can send out control commands to turn off its DERs, start charging its ESS batteries, and so on. The microgrid may also turn off its own DERs to help balance the power. If the microgrid then forecasts a large load increase, the distribution grid can be scheduled to export more power to or import less power from the microgrid. The distribution grid can turn on its own dispatchable DERs and/or discharge its ESS batteries to meet the schedule. The microgrid may also turn on its dispatchable DERs to maintain the power balance.

2.1.5 A-5: Harmonic Monitoring and Compensation with Microgrid Participation

A. Description

This use case analyzes the harmonic distortion and compensation in distribution system with microgrids. Different mechanisms will be discussed in terms of harmonic characteristics in conventional distribution system and modern distribution system with microgrids and the harmonic compensation approaches will be investigated.

With the increasing penetration of inverter-interfaced DERs, the harmonic distortion problem in the modern distribution systems is dramatically reduced. Harmonic compensation is an interactive function that is achieved by both the micro EMS and local controller/power hardware devices. Harmonic monitoring and compensation should be achieved in a coordinated way by considering impacts from both conventional devices and interface inverters. The following should be taken into account:

- The harmonic sources in both microgrid and distribution system should be identified and analyzed.
- Harmonic mitigation for critical loads takes priority over mitigation for non-critical loads.
- The harmonic content after compensation should comply with the relevant industry standards, e.g., IEEE Standard 1547.
- Stability in both microgrid and distribution system during harmonic compensation should be guaranteed.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Active devices, e.g., active power filter (APF) (power hardware device) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data, especially for low-order harmonics, to micro EMS. • Micro EMS and DER interface inverter controller work together to eliminate harmonics. • If necessary use hardware devices, e.g., APFs, to alleviate local harmonics for critical loads. • Compare harmonic contents with certain standards to check whether they meet requirements.	• Device level data monitoring • Command signals for active devices

C. Impact Analysis

In conventional distribution systems, harmonic sources include mainly industrial loads with relatively large power and non-linear characteristics, such as steel mills and arc furnaces. Harmonic compensation is usually implemented by installing local harmonic compensation devices, such as active power filters (APFs). However, with the integration of microgrids, the harmonic characteristics in a distribution system are significantly changed. Since many of the various types of DERs in microgrids are interfaced by using power electronic inverters, the microgrids themselves are potential harmonic sources due to the high-frequency switching nature of power electronic inverters. However, since smart interface inverters are generally highly controllable, they can play a significant role in eliminating harmonic distortion, and the harmonics inside microgrids can usually be compensated locally by using smart interface inverters. Interactive operation between local inverter controllers and a high-level controller, such as a micro EMS, should be also achieved to ensure that a wide harmonic frequency range can be reduced to an acceptable level.

The emerging harmonic compensation schemes in the local interface inverters, when coordinated with conventional harmonic compensating devices, such as APFs, can eliminate overall harmonic distortion throughout the distribution system. Harmonic compensation should comply with the corresponding industry standards, such as IEEE Standard 1547. Note that since the control scheme is modified to add the additional control function of harmonic compensation, operation stability should be maintained to guarantee that harmonic compensation does not conflict with conventional control and operation requirements.

2.1.6 A-6: Unbalance Compensation with Microgrid Participation

A. Description

This use case investigates unbalance characteristics and corresponding compensation approaches in distribution systems with microgrids, and identifies the differences in unbalance distortion between a conventional distribution system and the modern distribution system with microgrids.

Unbalance in distribution systems is mainly attributed to uneven load distribution among the three phases of a three-phase power system. The increasing penetration of DERs makes the unbalance issue more complicated than in conventional passive distribution systems. Unbalance compensation can be achieved by optimally placing sources and loads among three phases and implementing local unbalance mitigation strategies, taking the following into account:

- Unbalance compensation is an interactive function that is achieved by both the micro EMS and local controller/power hardware devices.

- Unbalance mitigation for the critical loads has priority over mitigation for non-critical loads.

- Voltage/current unbalance after compensation should meet the corresponding industry standards.

- Constant asymmetrical voltage/current (usually with a small unbalance ratio) and transient asymmetrical voltage/current (usually with a large unbalance ratio) should be differentiated.

- Stability in both the microgrid and the distribution system during unbalance compensation should be guaranteed.

- The asymmetry problem should be mitigated by using the interface inverters and placing the sources and loads as evenly as possible among three phases.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data, especially for voltage and current unbalance, to micro EMS. • Distinguish constant asymmetrical voltage/current unbalance and transient asymmetrical voltage/current unbalance. • Micro EMS and DER interface inverter controller work together to eliminate voltage/current unbalance. • Check whether voltage/current unbalance should meet requirements of certain standards.	• Device level data monitoring • Command signals for active devices

C. Impact Analysis

Voltage or load unbalance is a common problem in both conventional and modern distribution systems. It is generally attributed to the unbalanced distribution of loads and/or DER resources among the three phases of a three-phase power system. When microgrids are integrated into a distribution system, the unbalance issue could be further exacerbated, since both distributed energy resources and loads may be connected in an unbalanced way among the three phases.

The conventional approach to compensating system unbalance is to place the resources and loads as evenly as possible among phases, an approach also feasible in the modern distribution system with microgrids. Meanwhile, since more active devices with interface inverters are connected to the system, local unbalance compensation can also be achieved in the control scheme of the interface inverters themselves. Thus interactive unbalance compensation can be realized with local controllers of DER interface inverters and with a high-level central controller, such as a micro EMS. As with harmonic compensation, since the control scheme of interface inverters is modified to add the additional control function of unbalance mitigation, system stability should be still maintained to make sure that this additional control objective does not conflict with conventional operation requirements.

2.1.7 A-7: Microgrid Mode Transition from Intentional/Unintentional Island Operation to Grid-Connected Operation

A. Description

This use case determines the impact of microgrid mode transition from island mode to grid-connected mode. For a seamless transition, the microgrid must be synchronized as closely as possible with the main grid before the interconnection, and the synchronization criteria should meet IEEE Standard 1547 requirements. Active devices can be used to alleviate the transient voltage/current spikes during operation mode transition.

The microgrid and DMS should ensure that the following steps take place during the transition process:

- The DMS and micro EMS coordinate with each other to perform interactive actions during microgrid mode transition.
- The DMS is aware of microgrid mode transition.
- The model of microgrid should be updated in DMS for their different operation modes.
- The transition process should meet the transient voltage and frequency requirements.
- Power balance in both microgrid and distribution system should be maintained before and after microgrid mode transition.

B. Technical Details

Details of the various actors, their roles and the information exchange among them are summarized in the following table.

Actor & Actor Type	Action	Contents of Information for Exchange
• Static switch at the microgrid POIs (power hardware device) • Protection relay (power hardware) • POI circuit breaker (power hardware) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system) • Active devices to alleviate transient spikes (optional) (power hardware device)	• Micro EMS sends request of connecting microgrid to distribution system to DMS. • DMS evaluates current status based on monitoring data and approves request for mode transition. • DMS sends control command to static switch at microgrid POI to trigger mode transition. • Alternatively, POI relay performs a sync check and sends control command to POI breaker to close circuit breaker. • Micro EMS coordinates devices inside microgrid to ensure smooth mode transition. • Micro EMS updates status of mode transition to DMS. • DMS updates model of microgrid after mode transition if necessary. • DMS triggers on/off changes of sources and loads to balance power if necessary.	• Microgrid mode transition signal • Transient frequency and voltage signals • Device level data monitoring to meet the requirements of power balancing • Control signals for active devices (optional)

C. Impact Analysis

In the process of mode transition from islanded mode to grid connected mode, the microgrid needs to be resynchronized with the main grid. This impacts the operation of the microgrid. One of the main impacts is the change of microgrid operation control from droop control mode to PQ control mode. This is mainly because the microgrid will be tied with grid frequency and grid voltage after the interconnection. Another impact is that the microgrid needs to respond to the external faults according to IEEE Standard1547 requirements. Transition may also require a provision for black start. Moreover, the functions of load balancing and/or DER curtailment cannot be facilitated by the micro EMS because the power change in the microgrid can be balanced by drawing from or supplying to the main grid. In addition to this, the battery energy storage can be optimized and the need for energy storage can be reduced. Overall stability of microgrid is improved because it becomes part of the main grid electrically. However, during mode transition, severe electrical transients may occur if the control process is not properly executed. Unless all loads in a microgrid are critical, the grid connected operation may allow for reduced investment in local generation to cover only the sensitive industry loads for maintaining continuous and uninterrupted power supply in the island mode.

2.1.8 A-8: Microgrid Mode Transition from Grid-Connected Operation to Intentional Island Operation

A. Description

This use case determines the impact of microgrid mode transition from grid-connected operation to intentional island operation. Intentional islanding is the process in which one or more sections of a utility distribution system are purposely isolated from the distribution grid following a widespread disturbance in the utility distribution grid or to fulfill a dispatch order during normal operation. Each of the isolated microgrids can operate in island mode and maintain its own power balance.

Intentional islanding can be formed because of a scheduled maintenance/dispatch order or scheduled load/generation shedding. To ensure a smooth mode transition, the DSO should notify each microgrid to be islanded to prepare itself, maintaining its own energy balance as well as optimizing its DERs' operation. Active devices are used to alleviate the transient voltage/current spikes during operation mode transition if necessary.

The following steps are required during this mode transition.

- The DMS and micro EMS should coordinate with each other to perform an interactive process during microgrid mode transition.
- The model of the microgrid should be updated in DMS for the operation mode change.
- The transition process should meet the transient voltage and frequency requirements.
- Power balance in both microgrid and distribution system should be maintained before and after microgrid mode transition.

B. Technical Details

Various actors, their roles and the content of information exchange to achieve this mode transition are shown in the following table.

Actor & Actor Type	Action	Contents of Information for Exchange
• Static switch at microgrid POIs (power hardware device) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system) • Active devices to alleviate transient spikes (optional)	• DMS evaluates current status based on monitoring data and schedules intentional mode transition of microgrid. • DMS notifies micro EMS and sends control command to static switch at microgrid POI to trigger mode transition or let micro EMS start mode transition. • Micro EMS coordinates devices inside microgrid to ensure smooth mode transition. • Micro EMS updates status of mode transition to DMS. • DMS updates model of microgrid after mode transition if necessary. • DMS triggers on/off changes of sources and loads to balance power if necessary.	• Microgrid mode transition signal • Transient frequency and voltage signals • Device level data monitoring to meet requirements of power balancing • Control signals for active devices (optional)

C. Impact Analysis

Intentional islanding allows system operators to flexibly control and manage the grid operation, which can improve system reliability and reduce the chances of emergency outages and customer interruption time due to unintentional loss of supply.

Intentional islanding requires each islanded microgrid to maintain its own voltage and frequency, which requires the microgrid to change its control mode from PQ control to droop control mode. Before islanding is initiated, it should be confirmed that critical loads can be served and DERs can be coordinated to balance the energy within the microgrid after it is disconnected from the distribution grid. It should also be ensured that any disconnection of loads or connection of DERs during the transition will not cause dynamic stability problems. In the case of excessive generation, i.e., there is not enough load to serve or energy storage capacity to store the excess energy, corresponding output from the DERs will be curtailed. In the case of insufficient power output from the DERs, the load shedding scheme can be triggered to balance the power after islanding. This may result in disconnection of critical loads and additional outage cost.

Island mode operation increases the need for storage to compensate for the impact of intermittent power output from the DERs. Maintaining storage has a significant economic impact on microgrid and distribution system operations.

2.1.9 A-9: Coordinated Energy Management for Economic Dispatch

A. Description

This use case determines the impact of coordination between different energy resources for economic dispatch. The impact will be analyzed for both grid-connected and island modes of operation.

Coordinated energy management in economic dispatch of microgrid resources minimizes the overall operation cost of the microgrids. The coordinated energy management problem in economic dispatch is formulated with the objective of minimizing the overall operation cost of the participated microgrids and the distribution grid by meeting load requirements over a period of time and satisfying specific operational and physical constraints (i.e., generation constraints, ramping constraints, and energy storage constraints). Coordinated energy management is a two-level dispatch problem: level one is at the system level, in which each microgrid can be modeled as an aggregated unit, and level two is how to dispatch the individual DERs in each microgrid based on its target, defined in level one. The solution of the level one problem determines the dispatch from each microgrid at the system level, and the optimal solution of the level two dispatch problem includes both how much power each DER needs to generate at a given time interval and how much power needs to be taken from or supplied to the energy storage and power grid. Coordination between the energy resources should take into account the following:

- Economic dispatch is achieved with the interaction between the micro EMS and DMS.
- The sources and loads in a microgrid are regarded as an aggregated unit for coordinated energy management.
- Available power and load demand in the microgrid and distribution system should be taken into consideration.
- Data communication between DMS and micro EMS should be used to achieve coordinated energy management.
- The assets in each microgrid and distribution system should be managed in coordination to achieve economic dispatch.

B. Technical Details

The role of actors, their types, action taken and content for information exchange for coordinated energy management are shown in the table.

Actor & Actor Type	Action	Contents of Information for Exchange
• Micro EMS (control system) • DMS (control system)	• Upload monitoring data to DMS. • DMS schedules economic dispatch. • DMS runs optimization algorithm and sends control signals to devices, including microgrids. • Micro EMS coordinates its sources and loads to deliver required power.	• Device level data monitoring in both microgrids and distribution system • Commands for economic dispatch

C. Impact Analysis

Coordinated energy management is essential for optimal utilization of energy resources. With optimal energy management, the DSOs and microgrid owners can determine how much power each DER should generate and how much energy should be taken from or supplied to storage and/or the distribution grid in a given time interval. Without optimal energy management, the overall operation cost of the microgrids could be excessively high, and without coordination, the capacities of DERs may not be fully utilized in satisfying the operational constraints of the microgrids. DSOs and microgrid owners can maximize their profit in transactive energy markets by optimally scheduling their resources through coordination between them. Optimal energy management of resources can reduce the need for storage, resulting in lower storage costs.

2.1.10 A-10: Microgrid Model Update and Verification for Different Grid Operation Conditions

A. Description

This use case determines the impact of microgrid model update and verification on different grid operating conditions. It is particularly important in determining the appropriate control actions to deal with changes in system operating conditions.

Model update and verification is an important requirement for secure and reliable operation of the microgrid and the distribution system. If microgrid models are not updated according to their changes in system operating conditions, incorrect control actions by the controller and system instability may result. Typically, models can be updated using the field measurements. In the case of "brown field" sites, where the parameters of different components are unknown, a system identification technique can be adopted to identify the system parameters and update the models. The following are key for model update and validation:

- A simplified model of each microgrid is necessary in the DMS to enable it to perform certain functions, such as frequency control, volt-VAR optimization, etc.

- This simplified microgrid model should be updated if grid operation condition changes.
- Potential wheeling paths caused by the microgrid should be visible in DMS.

B. Technical Details

The technical details of this use case describing the role of different actors along with information exchange is given in the following table.

Actor & Actor Type	Action	Contents of Information for Exchange
• Micro EMS (control system) • DMS (control system)	• DMS determines changes in grid operation conditions based on monitoring data. • DMS updates microgrid model according to different operation conditions. • Identify and highlight potential wheeling paths in distribution systems	• Models of microgrids • Operation mode changes • Potential wheeling loops between microgrids and distribution system

C. Impact Analysis

Managing the control and operation of the distribution systems in the DMS requires the DMS to know the current operation status and corresponding simplified models of each microgrid. When the operation modes of the microgrids change, these simplified models in the DMS should be updated accordingly to reflect the current status. It should be noted that rather than focusing on detailed dynamic responses, these simplified microgrid models are used to show basic operation information, including simplified microgrid topologies, aggregated DER capacity curves, dispatchable load information, etc. It is important for the DMS to use these simplified microgrid models to fully understand the operation status of each microgrid and analyze its impact on the distribution system. One example is using the simplified microgrid model to identify potential wheeling loops in distribution systems when multiple microgrids are connected to the distribution feeder simultaneously. If no accurate microgrid models are used in the DMS, these wheeling loops may not be visible and may cause damage in the distribution system.

2.1.11 A-11: Distribution System Reconfiguration with Multiple Microgrids

A. Description

This use case determines the impact of distribution system reconfiguration when multiple microgrids are connected to the distribution grid. Network reconfiguration with multiple microgrids connections is particularly useful for enhanced power quality, reduced network power losses, and improved grid resiliency in the event of natural disasters or fault conditions by isolating the faulted segments of the network.

Reconfiguring a distribution system with multiple microgrids provides an alternate power rerouting scheme in order to maximize DER output power, reduce network power losses, or restore loads interrupted in a faulted scenario. The rerouting is performed through multiple switching operations. The following points need to be taken into consideration for network reconfiguration with multiple microgrids:

- When multiple microgrids are connected to the distribution system, consider their impact and contribution to the optimal network reconfiguration.
- Short-term DER and load forecasting data can be used to support the network reconfiguration.
- Available power is supplied not only by feeders but also by connected microgrids with high available power.
- Ensure power balance after network reconfiguration, and ensure that no new loops are formed and no new segments are de-energized after the reconfiguration.

B. Technical Details

The role of actors, actions to be taken and contents of information exchange in this use case are summarized in the following table.

Actor & Actor Type	Action	Contents of Information for Exchange
• Micro EMS (control system) • DMS (control system) • Smart switches (power hardware devices) (optional)	• Upload monitoring data to DMS. • DMS determines if network reconfiguration is necessary. • DMS determines optimal network reconfiguration considering available power from both feeders and microgrids. • DMS sends control signals to trigger optimal network reconfiguration. • Adjust the status of smart switches if necessary to enhance flexibility of network reconfiguration.	• Network configuration • Device level data monitoring • Device level forecasting data • Control signals to smart switches (optional)

C. Impact Analysis

Network reconfiguration may provide the best alternative paths for uninterrupted power supply to parts of the network with excessive power losses and/or poor voltage profile or that are isolated from the main grid due to faults or natural events. A distribution system reconfiguration scheme with multiple microgrids can help improve the resiliency of the system in such cases. In the event of natural disasters, it can help restore power for critical loads such as transportation, hospitals, supermarkets, fire stations, etc. The absence of a network reconfiguration scheme where multiple microgrids are connected may lead to detrimental impacts on the operation of the distribution network. For example, some critical loads may not be served, or part of the network may have bad voltage quality or excessive power losses. All these can lead to reduced revenue and increased customer interruption time for DSOs.

2.2 USE CASES UNDER EMERGENCY OPERATIONS

2.2.1 B-1: Coordinated Load Shedding with Load and DER Variations in Both Microgrids and Distribution Systems

A. Description

This use case determines the impact of coordinated load shedding in microgrids and distribution systems considering the significant variations in loads and DERs.

Load shedding is required to maintain system frequency and voltage within their limits when there is a generation deficit in the system. Coordinated load shedding can determine how many and which loads need to be disconnected at a given time following an event of major variation in load and/or DER output. The following points need to be taken into consideration for coordinated load shedding.

- The purpose of load shedding is to maintain the frequency stability throughout the distribution system.
- The DMS and micro EMS should cooperate interactively to perform proper load shedding.
- Power balance in both microgrids and distribution system must be maintained.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• AGC (control system) • Device level on/off switch • Micro EMS (control system) • DMS (control system)	• Upload monitoring data to DMS. • DMS determines if load shedding should be triggered based on monitoring data and predicted data for both sources and loads. • If emergency load shedding is triggered, DMS sends control commands to micro EMS and individual devices to disconnect load. • If micro EMS receives load shedding command, it sends commands to device level on/off switches to disconnect certain devices based on their power availability.	• Supply side monitoring data • Demand side monitoring data • Frequency signals • On/off status of devices

C. *Impact Analysis*

Load shedding is essential for stable operation of the power network when there is not enough generation to supply the load. Coordinated load shedding ensures that critical loads are given priority. Lack of proper coordination in the load shedding scheme can interrupt the supply to critical customers, which can lead to severe consequences for the customers and high penalties for the utility. If the load shedding scheme is not well coordinated, based on load demand and generation availability, it may cause the grid to collapse.

2.2.2 B-2: Coordinated Microgrid Protection

A. *Description*

This use case investigates coordinated protection schemes in distribution systems with microgrids. It is commonly known that microgrid protection is significantly different from the protection schemes in the conventional distribution grid due to the existence of inverter-interfaced DERs.

Conventional protection schemes for distribution systems are generally not suitable for modern distribution systems with DERs and microgrids connected, primarily because of the low fault current contributed by the inverter-interfaced DERs in the microgrids and the distribution grid. The operation modes of microgrids should be considered in identifying suitable protection schemes:

- Protection of a microgrid is more challenging than conventional protection schemes for distribution systems due to the considerably lower fault current.

- Protection of microgrids must consider the fault current contribution from both the microgrid side and the distribution system side, which requires coordination between micro EMS and DMS.

- Diversified protection schemes and directional protective relays should be used in the protection schemes of microgrids.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Protective relay (power hardware device) • Micro EMS (control system) • DMS (control system)	• Depending on fault location, either micro EMS or DMS identifies fault. • Protective devices triggered automatically to isolate fault. • Use different types of protection schemes, e.g., current-based protection as the primary protection scheme and voltage protection as the backup protection scheme. • Update relay settings in different microgrid operation modes. • Send status of fault occurrence and isolation to micro EMS and DMS. • If necessary, trigger follow-up behaviors in DMS, e.g., service restoration enabled by FLISR, etc.	• Device level data monitoring (mainly localized monitoring for protection purpose) • Microgrid and distribution system condition (normal or fault condition)

C. Impact Analysis

The two-direction fault current contribution is the key feature of the protection schemes in distribution systems with DERs and microgrids. In conventional distribution systems, the fault current is always one-way and solely from the upstream feeder; no fault current is from the downstream feeder sections. Since the short-circuit capacity at the main feeder is very large, the settings of downstream protective relays are usually set accordingly: non-directional with relatively large values. However, DERs and microgrids as active sources can also contribute fault current from the downstream side to the fault, but with much lower fault current compared with that from the upstream feeder. With lower fault currents from the DERs and non-directional high relay settings, the existing protection scheme will not be not able to isolate the fault in the distribution grid.

Coordinated microgrid protection should consider the maximum fault current capabilities of different DER devices and fault current flows and change the protective relay settings accordingly.

Meanwhile, for the protection of the circuits and devices inside the microgrid, different operation modes should be considered when determining the relay settings. In particular, for grid-connected operation mode, the relay settings should be directional, with different values for each direction, since the fault current is contributed in two ways by both DERs and upstream distribution system. In island operation mode, the fault current is solely contributed by the DERs.

The fault current may still be two-way, but at a lower level in each direction compared with the grid-connected mode, and thus different relay settings should be used.

Coordinated protection of distribution systems with microgrids should consider multiple functionalities and be implemented as an integrated solution. The fault ride-through capability of DER interface inverters and the protection relays inside and outside the microgrids should be coordinated to avoid malfunction of the protection schemes.

2.2.3 B-3: Power Outage Mitigation Using Multiple Microgrids Integrated with DMS

A. Description

This use case determines the impact of multiple microgrids integrated with a DMS in mitigating power outages. When a fault in a segment of the network is detected, the DMS can isolate the faulted segment and coordinate with its microgrids to supply power to the faulted segment. The following steps can be taken to ensure effective power outage mitigation using multiple microgrids.

- Microgrids can be used as effective assets to mitigate the impact of a power outage.

- The micro EMS in each microgrid should work in a coordinated way with the DMS to isolate the fault area and restore service.

- The desired voltage profile and system frequency throughout the system should be maintained within limits if the affected feeder segments are islanded with one or more microgrids.

- The availability of DERs for emergency power support should be identified.

- The necessary data exchange between micro EMS and DMS during power outage mitigation should be identified.

- Power balance inside each microgrid must be ensured.

B. Technical Details

The details of various actors, their roles and information required are given in the following table.

Actor & Actor Type	Action	Contents of Information for Exchange
• DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Detect power outage and inform DMS of fault area. • DMS runs optimization algorithm to isolate areas with faults and uses microgrids as assets for restoration. • DMS sends out control commands to each microgrid and other devices. • Store and update status of power outage and service restoration in DMS.	• Device level data monitoring • Power outage information, e.g., location, severity, etc. • Control commands for each microgrid.

C. Impact Analysis

If a power outage takes place in a segment of the network, multiple microgrids in coordination with the DMS can help mitigate it. When an outage is detected, the DMS can determine an alternative path for rerouting the supply through other microgrids in the system. This rerouting helps in the resilient operation of the grid, reduces customer service interruption time, enables the efficient use of energy resources, and ensures the power supply to critical loads. All these help mitigate outage impacts and improve the power delivery service of the utility, as well as reduce the overall cost of additional backup generations in the microgrids.

2.2.4 B-4: Virtual Microgrid Implementation and Energy Management Scheme for Emergency Power Support

A. Description

This use case investigates an emergency service restoration approach: using virtually formulated microgrids when a fault occurs in the distribution system. These virtually formulated microgrids are used to isolate the fault and prevent possible further cascading of the power outage to a wider area.

Using virtual microgrids to enhance the resilience of a distribution system is an emerging approach and is achieved by dynamically configuring the distribution system to isolate the faults and then facilitating a service restoration strategy. Several microgrids can be dynamically formed into a virtual microgrid to supply power and maintain the frequency and voltage stability of the islanded part of the distribution network. The interactions between the micro EMS and DMS are used to determine the location and size of each virtual microgrid.

These microgrids can be virtually implemented, i.e., with dynamic boundaries based on the location and severity of the power outage. When the power outage is cleared, the virtual microgrids can be reconnected to form the original distribution system configuration. The following should be considered:

- Decentralized energy management for each virtual microgrid should be achieved.
- Necessary data exchange between the micro EMS and DMS should be identified during power outage mitigation.
- Power balance inside each microgrid must be ensured.
- The frequency and voltage throughout the system should be maintained in the acceptable range.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Smart switches (power hardware device) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Detect power outage and inform DMS of fault area. • DMS runs optimization algorithm to form several virtual microgrids to isolate fault and restore service. • DMS sends control signals to corresponding smart switches to form dynamics microgrids. • Monitor frequency, voltage and other critical indices throughout distribution system to determine if the power outage has been successfully cleared. • When power outage is successfully cleared, DMS sends control signals to smart switches to reconnect virtual microgrids and form the original distribution system configuration.	• Device level data monitoring • Power outage information, e.g., location, severity, etc. • Control commands for smart switches • Local frequency and voltage information for disconnection and resynchronization

C. Impact Analysis

Virtual microgrids can be regarded as an emergency application of microgrids for fault isolation and service restoration in distribution system. These virtually formulated microgrids can significantly improve the reliability and resilience of a distribution system: When a fault occurs in a distribution system, multiple microgrids will be implemented to isolate the fault and prevent the further power outage in a wider area. When the fault is cleared, these virtual microgrids can be re-combined to form the original distribution system configuration, thus providing a flexible way to maintain service in a distribution system.

When formulating the virtual microgrids, the power in each microgrid must be balanced to maintain the frequency and voltage stability in each section of the system. Meanwhile, to facilitate the interconnection of the microgrids, smart switches are used to detect the fault occurrence and conduct the effective disconnection and resynchronization.

2.2.5 B-5: Fault Isolation for Grid-Side Faults

A. Description

This use case analyzes the impact of connected microgrids on fault isolation of grid-side faults. Connection of microgrids and DERs to the distribution system complicates the fault isolation process for permanent grid-side faults. Proper coordination is needed between the microgrid protection devices and distribution grid protection devices. The following points should be considered when isolating grid-side faults:

- The DMS is the main actor in detecting and isolating the faults occurring at the grid side.
- Fault location, isolation, and service restoration (FLISR) and other applications in DMS should be used to support the fault isolation.
- The microgrids should participate in the fault isolation process.
- Frequency and voltage in each microgrid and the distribution system should be maintained within the acceptable ranges.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Protective relay (power hardware device) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data to DMS. • When fault occurs, protective devices should isolate fault automatically, then local devices should inform micro EMS and DMS of fault occurrence. • DMS utilizes FLISR or other applications to prevent further fault propagation. • Micro EMS receives command from DMS to participate in fault isolation. • Microgrids should be disconnected if they are in faulted feeder section.	• Device level data monitoring • Present condition of microgrid and distribution system

C. *Impact Analysis*

The interconnection of microgrids will have an impact on fault isolation for permanent grid-side faults. The short-circuit protection devices on the grid side should coordinate with microgrid interconnection switches and their own protection schemes to help isolate grid-side faults.

Which mechanism to be used regarding how a microgrid will participate in the grid-side fault isolation process depends mainly on its location relative to the actual fault location — upstream, in the middle, or downstream of the faulted section (bounded by two adjacent switches of the fault location).

When a fault occurs, the closest upstream protection device on the distribution grid side interrupts the fault. The microgrids and DERs on the faulted section and downstream of the faulted section will be disconnected from the grid triggered by their own protection schemes. The adjacent switches of the faulted section will then be opened automatically by the FLISR to isolate the fault. The microgrids and DERs on the faulted section will remain disconnected until the crew repairs the faulted component. Throughout the isolation process, via their own protection schemes, the DERs and microgrids upstream of the faulted section will ride through the fault and remain connected without any service interruption.

2.2.6 B-6: Post-fault Recovery for Grid-Side Faults

A. *Description*

This use case analyzes the impact of microgrids on post-fault recovery for permanent grid-side faults. microgrids and DERs can be used as resources for post-fault recovery for permanent grid-side faults. While the DMS is the main actor in detecting and isolating faults occurring on the grid side, and the FLISR in the DMS is the main application in post-fault recovery for grid-side faults, microgrids should also participate in restoring the service. The following points should be considered during the post-fault recovery process:

- The frequency and voltage in each microgrid and the distribution system should be maintained within the acceptable range.

- Effective data communication between DMS and micro EMSs should be ensured to coordinate the operation of the microgrids and the distribution system during fault isolation and service restoration.

- DERs inside and outside of microgrids should be used to balance power demand during post-fault recovery procedure.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Micro EMS (control system) • DMS (control system)	• Upload monitoring data to DMS. • DMS uses FLISR to restore service in post-fault procedure. • Microgrid participates in service restoration as an aggregated asset. • Micro EMS coordinates sources and loads inside microgrid during service restoration. • Notify interrupted microgrids to reconnect to the distribution grid if corresponding feeder sections are reenergized by FLISR.	• Device level data monitoring • Present condition of microgrid and distribution system

C. Impact Analysis

The interconnection of microgrids will have some impact on post-fault recovery for permanent grid-side faults, as short-circuit protection devices on the grid side should coordinate with microgrid interconnection switches and their own protection schemes to isolate grid-side faults and restore service to customers as quickly as possible.

Which mechanism to be used regarding how a microgrid will participate in grid-side fault isolation and post-fault recovery depends mainly on its location relative to the actual fault location — upstream, in the middle, or downstream of the faulted section (bounded by two adjacent switches of the fault location).

When a fault occurs, the closest upstream protection device on the distribution grid side interrupts the fault. The microgrids and DERs on the faulted section and downstream of the faulted section will disconnect from the grid, triggered by their own protection schemes. The adjacent switches of the faulted section will then be opened automatically by the FLISR to isolate the fault. Then the normally open tie switch connecting to the adjacent feeder will be closed by the FLISR to restore service to the customers downstream of the faulted section. All of the DERs and microgrids downstream of the faulted section that were previously disconnected by their own protection schemes can then reconnect back to the grid. The microgrids and DERs on the faulted section will remain disconnected until a crew repairs the faulted component and the feeder section is re-energized. Throughout the entire isolation and restoration process, via their own protection schemes, the DERs and microgrids upstream of the faulted section will ride through the fault and remain connected without any service interruption.

Since feeder configurations are changed due to fault isolation and service restoration, the power inside and outside the microgrids need to be re-balanced, and the frequency and voltage in each microgrid and the distribution system should be maintained within acceptable range. The DMS and energized microgrids should communicate among each other to coordinate the DERs and loads inside and outside the microgrids and balance the power demand during the post-fault recovery procedure.

2.2.7 B-7: Fault Isolation for Microgrid-Side Faults

A. Description

This use case analyzes the impact of connection to the distribution system on fault isolation for permanent microgrid-side faults. Proper coordination between microgrid protection devices and distribution system protection devices is needed. The micro EMS is the main actor in isolating microgrid-side faults, and the FLISR and other applications in the DMS prevent further fault propagation. The following points should be considered when isolating microgrid-side faults:

- The frequency and voltage in each microgrid and the distribution system should be maintained within the acceptable range.
- Effective data communication between the DMS and the micro EMS should be ensured to coordinate the operation of the microgrids and the distribution system during fault isolation.
- The microgrid with the fault should be disconnected if necessary.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• Protective relay (power hardware device) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data to DMS. • When fault occurs, protective devices should isolate fault automatically, and then local devices should inform micro EMS and DMS of fault occurrence. • Micro EMS coordinates sources and loads inside microgrid to maintain power balance. • FLISR application in DMS is used to prevent fault propagation. • Prepare DMS to provide emergency power support to maintain frequency and voltage stability inside microgrids.	• Device level data monitoring • Present condition of microgrid and distribution system

C. Impact Analysis

Short-circuit protection devices from the grid side should coordinate with the microgrid interconnection switch and protection devices to help isolate permanent microgrid-side faults.

When a fault occurs in a microgrid, the local protection schemes of the microgrid should trip the corresponding switch automatically to interrupt the fault current and notify its micro EMS and the DMS of the fault occurrence with the corresponding switch operations. With proper protection coordination, the microgrid protection devices will be activated first while the protection devices on the distribution side will not operate, and thus other microgrids and all the DERs connected to the distribution system side will remain connected. The micro EMS will then apply a FLISR-like function to isolate the faulted section within the microgrid.

If the protection device that interrupts the microgrid internal fault happens to be the circuit breaker at the microgrid's POI, the microgrid will be disconnected from the main grid. The protection devices and the operated circuit breaker will notify the micro EMS and DMS of the fault occurrence. The micro EMS then will start its unintentional islanding process and isolate the faulted segment. Due to the designed fast action of the microgrid protection devices, the protection devices on the distribution side will not operate, and thus other microgrids and all the DERs connected to the distribution system side will remain connected.

If the responsible nearest switches fail to isolate the faulted section within the microgrid, the backup protection scheme in the distribution grid may react to isolate the feeder section on which the microgrid is connected. The distribution system protective devices will then notify the micro EMS and DMS of its operation. At the same time, the micro EMS will disconnect the interconnection switch between the microgrid and the distribution system and go out of service.

2.2.8 B-8: Post-fault Recovery for Microgrid-Side Faults

A. Description

This use case analyzes the impact of connection to a distribution system on post-fault recovery for permanent microgrid-side faults. In post-fault recovery for microgrid-side faults, the micro EMS is the main actor in detecting and isolating the fault, and the FLISR in the DMS participates in post-fault recovery. The following points should be considered:

- The frequency and voltage in each microgrid and distribution system should be maintained within the acceptable range.
- Data communication between the DMS and micro EMS should be ensured to coordinate operation between multiple microgrids and distribution system during fault isolation.
- DERs inside and outside microgrids should be used to balance the power demand during post-fault recovery procedure.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Upload monitoring data to micro EMS. • Micro EMS coordinates sources and loads inside microgrid to balance power and maintain frequency and voltage stability. • DMS supports microgrid for service restoration if necessary.	• Device level data monitoring • Present condition of microgrid and distribution system.

C. Impact Analysis

Short-circuit protection devices from the grid side should coordinate with the microgrid interconnection switch and protection devices to isolate permanent microgrid-side faults and carry out post-fault service restoration.

When a fault occurs in a microgrid, its local protection schemes should trip the corresponding switch automatically to interrupt the fault current and notify its micro EMS and the DMS of the fault occurrence with the corresponding switch operations. With proper protection coordination, the microgrid protection devices will be activated first while the protection devices on the distribution side will not operate, and thus other microgrids and all the DERs connected to the distribution system side will remain connected. The micro EMS will then apply its FLISR-like function to isolate the faulted section within the microgrid. When the faulted section is isolated, the micro EMS will reconfigure the circuit and coordinate its sources and loads to maintain power balance. In case of an emergency, the DMS may provide emergency power support to maintain power balance and voltage quality in the microgrid. If the power imbalance and/or voltage violation in the microgrid persists, it will be disconnected from the distribution system.

If the protection device that interrupts the microgrid internal fault happens to be the circuit breaker at the microgrid POI, the microgrid will be disconnected from the grid and the protection devices and operated circuit breaker will notify the micro EMS and DMS of the fault occurrence. The micro EMS will then start its unintentional islanding process, isolate the faulted segment and restore service to the rest of the microgrid. Due to the designed fast action of the microgrid protection devices, the protection devices on the distribution side will not operate, and the other microgrids and all the DERs connected to the distribution system side will remain connected. The DMS and remaining micro EMSs then maintain the voltage and frequency in each remaining microgrid and the distribution system.

If the nearest responsible switches fail to isolate the faulted section within the microgrid, the backup protection scheme in the distribution grid may react to isolate the feeder section to which the microgrid is connected. The distribution system protective devices will then notify the micro EMS and DMS of its operation. At the same time, the micro EMS will disconnect the interconnection switch between the microgrid and the distribution system, and the microgrid will go out of service. The DMS will then restore service to the isolated section by closing the operated switches. The DMS and remaining micro EMSs will then coordinate their sources, including DERs, and loads to maintain the voltage and frequency in each remaining microgrid and the distribution system.

2.2.9 B-9: Microgrid Mode Transition from Grid-Connected Operation to Unintentional Island Operation

A. Description

This use case determines the impact of a microgrid mode transition from grid connected mode to island mode when a section of the utility distribution grid is disconnected from the main grid following a fault on the main grid side.

Unintentional islanding is usually triggered by a fault condition, such as anti-islanding protection. The DMS should be aware of the operation mode transition and the cause for the unintentional islanding operation. The micro EMS and DMS should ensure power balance in the islanded microgrid and the distribution system, respectively, after mode transition.

The following steps needs to be considered for this use case:

- The transient frequency and voltage requirements for operation mode transition should be met.

- Active devices should be used to alleviate the transient voltage/current spikes during operation mode transition if necessary.

B. *Technical Details*

Actor & Actor Type	Action	Contents of Information for Exchange
• Static switch at the microgrid POIs (power hardware device) • DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system) • Active devices to alleviate transient spikes (optional) (power hardware device)	• Protective behavior triggers operation mode transition from grid-connected to unintentional island mode. • Micro EMS conducts mode transition and informs DMS of cause for unintentional behavior. • Micro EMS coordinates sources and loads inside microgrid to keep power balance. • DMS maintains power balance throughout the distribution system and updates microgrid model if necessary.	• Microgrid mode transition signal • Fault information that triggers unintentional microgrid islanded operation • Transient frequency and voltage signals • Device level data monitoring to meet requirements of power balancing • Control signals for active devices (optional)

C. *Impact Analysis*

Unintentional islanding may result in a power imbalance in the microgrid, which may cause microgrid instability or blackout and damage the devices inside the microgrid. The unintentional islanding operation requires a microgrid with sufficient energy storage capacity to balance power during the mode transition and persistent islanding operation, which is an additional cost to the microgrid owner. During the transition, the micro EMS may shed non-critical loads to balance the power within the microgrid. Another impact of unintentional islanding is possible end-user equipment damage due to abnormal voltage and frequency violations during the islanding. Crew safety can be significantly impacted by unintentional islanding — the repair crew may be exposed to unexpected live wires.

2.2.10 B-10: Fault Ride-Through Capability of Microgrids

A. *Description*

This use case investigates the fault ride-through capability of microgrids. The requirements of fault ride-through capability should coordinate with the conventional protection scheme throughout the distribution system.

Conventionally, microgrids are usually disconnected from the grid to stop energizing the distribution system when a fault occurs; however, the microgrid need not be always disconnected in emergency conditions to achieve a resilient distribution system. Implementing the fault ride-through capability on microgrids can enable some desirable responses for different types of faults, avoiding unnecessary disconnection and resynchronization. The microgrid should be capable of identifying the type of fault and determine whether to trigger a disconnection or ride through the fault. The following points should be considered:

- The system stability of microgrid and distribution system should be guaranteed during fault ride-through.
- The micro EMS should be used to coordinate the devices inside microgrid to ride through the fault.
- Frequency and voltage must be kept within the acceptable range during fault ride-through.

B. Technical Details

Actor & Actor Type	Action	Contents of Information for Exchange
• DER interface inverter controller (control system) • Micro EMS (control system) • DMS (control system)	• Micro EMS and DMS detect fault and determine type of fault. • If disconnection of microgrid should be triggered, send control command to static switch at microgrid POI to transfer to island operation mode. • If fault is not severe and only a fault ride-through is required, micro EMS sends out commands to DER interface inverter controllers to trigger fault ride-through control algorithm so that fault influence can be mitigated.	• Device level data monitoring • System condition (microgrid or distribution system) in case of longer term fault (identified based on the standard)

C. Impact Analysis

The fault ride-through capability of microgrids can be regarded as an enhanced feature, making the system operate in an intelligent way without involving unnecessary disconnection and reconnection. Conventionally, a microgrid may have to disconnect from the distribution system when a fault occurs either on the microgrid side or the distribution system side because it lacks fault ride-through capability. When the fault is cleared, the microgrid will be reconnected and resynchronized to the distribution system. By implementing the fault ride-through function, the microgrid is able to identify the type of fault and its relative location to the fault and decide whether to ride through it or disconnect itself from the distribution system. Since most of the faults in distribution system are single-phase and temporary faults, the micro EMS should be able to identify such faults and ride through them with very limited fault current contribution. If certain types of severe or permanent faults are detected, e.g., three-phase faults, the micro EMS can disconnect the microgrid from the grid instantaneously, via the corresponding protection scheme, to prevent the fault from damaging devices inside the microgrid. If the microgrid is upstream of the fault, it should coordinate with the FLISR to ride through the fault.

II-B POWER QUALITY CONSIDERATIONS INTERNAL TO THE MICROGRID

There is a growing interest in online power quality monitoring and analysis that will enable microgrids to collect high-resolution voltage and power quality data and perform forensic engineering analysis with it. One reason for this increased emphasis on power quality is the growing penetration of electrical and electronic devices whose operation may be adversely impacted by the presence of harmonics and nonlinear voltage waveforms. The foreseeable increasing penetration of inverter-interfaced DERs will no doubt aggravate power quality problems in microgrids and the distribution grid. As a result, new power quality sensors may be added at critical locations, along with analytical tools for processing the data from the sensors to form actionable information.

This chapter includes the following analyses: a) identification of operation quantities for online microgrid power quality monitoring, b) identification of online monitoring strategies for microgrid power quality, and c) evaluation of the effectiveness and efficiency of online monitoring strategies.

2.3 MICROGRIDS OPERATION QUANTITIES FOR ONLINE POWER QUALITY MONITORING

The most critical power quality indices that will be monitored in real time are as follows:

- **Harmonics**. The dominance of inverter-interfaced DERs may result in harmonic distortion or high-frequency disturbance induced by pulse width modulation in the microgrid. The wide use of inverters can potentially activate interaction with other devices and possibly trigger resonances.[6] Depending on the number of paralleled DER inverters, the resonant frequencies may vary in a wide spectrum.

- **Unbalance**. A major source of voltage unbalance is the connection of unbalanced loads, i.e. single-phase load connection between two phases or between one phase and the neutral. In addition, most DERs, such as PVs, are interconnected to the microgrids in an unbalanced way. Most DERs are subject to weather conditions, such as cloud cover, solar irradiation and ambient temperature. The stochastic nature of weather conditions creates significant volatility in the DER output. As a result, intermittent DER power output can exacerbate voltage unbalance among the three phases, especially with a large number of single-phase DERs connected to the microgrid. Voltage unbalance can cause adverse effects on equipment such as induction motors, power electronic converters and adjustable speed drives (ASDs). In addition, under unbalanced conditions, the microgrid will be subject to more losses and be less stable. [7]

- **Voltage Violations**. With the increasing penetration of DERs, especially residential PVs, the voltage profile in a microgrid will be influenced not only by the loading condition but also by the generation of DERs. However, the intermittent nature of DERs may induce voltage violations, such as voltage sags and swells, which may cause power equipment and/or abnormal load trips. In addition, a rapid change in power flow direction due to fluctuating DER output may cause excessive operation of the voltage regulating devices, such as the voltage regulator and switched capacitor banks, shortening their life spans and increasing maintenance requirements.

With the challenges that large-scale integration of DERs may inflict on microgrids, the online monitoring of power quality for microgrids must include harmonics, unbalance, and voltage violations.

2.4 IDENTIFICATION OF ONLINE MONITORING STRATEGIES FOR MICROGRID POWER QUALITY

To guarantee that the microgrid controller can effectively monitor and evaluate the impact of DERs on power quality, it should be capable of gathering power quality status information from DERs directly. Effective approaches to eliminating power quality problems from DERs should be deployed in the microgrid controller to alleviate the DER's influence and comply with related standards (e.g., IEEE Standard 1547). Meanwhile, individual DERs should have the ability to mitigate the impact of power quality issues by themselves. To effectively enhance the power quality in microgrid operations, the power quality data acquisition and analysis system should adopt a hybrid architecture in which some components may be decentralized and some others centralized. Online monitoring strategies for the three identified power quality problems, harmonics, unbalance and voltage violations, will be separately discussed in the following subsections.

2.4.1 Online Monitoring Strategy for Microgrid Harmonics

We propose a hybrid harmonics monitoring and compensation scheme that utilizes both local device controllers and the central controller. On the device level, local harmonics are monitored and compensated at both critical loads and DER interface inverters. Critical loads may include industrial loads with relatively large power and non-linear characteristics that can be major harmonic sources. High-fidelity PQ sensors can be installed at those critical loads, and the harmonics can be locally compensated by installing harmonic compensation devices, such as APF. Another major harmonic source in microgrids is inverter-interfaced DERs, because of their high frequency switching behaviors. Because the controllability of the interface inverters is high enough to achieve harmonic compensation, they can also play a significant role in eliminating harmonic distortion in microgrids. As a result, the harmonics induced by DERs are usually locally monitored and compensated by the interface inverters.

Central power quality monitoring, analysis and control systems perform the following functions:

a) Interact with local harmonic monitoring and compensation systems
b) Coordinate the inverter controllers and conventional harmonic compensation devices such as APF

The central microgrid power quality monitoring, analysis and control system employs a secondary harmonic compensation scheme to avoid the “whack-a-mole” problem in harmonic distortion, i.e., the elimination of certain orders of harmonics leading to the rise of other orders of harmonics. The hierarchical harmonic monitoring and control system design ensures that overall harmonic distortion throughout the entire microgrid can be eliminated.

2.4.2 Online Monitoring Strategy for Microgrid Unbalance

We propose a hierarchical unbalance monitoring and compensation scheme with two levels: primary and secondary.[8] Unbalance data acquisition, analysis and control at the primary level resides in the local DER interface inverter controller and critical load controller. The local DER inverter employs proper control strategies to eliminate negative sequence voltage/current and achieve local voltage unbalance compensation. For critical loads, the voltage/current unbalance is alleviated by APF through the injection of negative sequence voltage/current.

Unbalance control on the secondary level is envisioned to be one of the functions of the microgrid controller. The microgrid controller is mainly responsible for managing unbalance at the POI. This is achieved mainly through the following sub-functions: a) dynamic allocation and optimal switching of DERs and loads within the microgrid, based on the forecasting data, to make the net power among the three phases as balanced as possible, and b) interaction and coordination with the local DER inverter and critical load unbalance monitoring and control system.

2.4.3 Online Monitoring Strategy for Voltage Violations

We propose a coordinated hierarchical online monitoring and control architecture to eliminate voltage violations in a microgrid. In the device monitoring and control layer, voltage sag/swell compensation is realized by using DER inverter reactive power generation/absorption capabilities. The DER inverter monitors the local voltage and may implement either a constant power factor or volt-VAR droop control to continuously adjust its reactive power output to mitigate local voltage violations. The local control is autonomous and receives the control set points from the microgrid controller.

The microgrid controller formulates a unified optimization problem that can hierarchically integrate the control effects of DER inverters and other conventional voltage regulating devices with different time scales. It receives local voltage monitoring data as well as DER generation and load forecast data as input and determines the optimal control commands, such as active power and power factor or volt-VAR droop control set points for DERs, and switching operations for voltage regulators and capacitor banks. The two-layer monitoring and control strategy is designed to optimize the voltage profile and eliminate voltage violations for the entire microgrid.

2.5 EVALUATING THE EFFECTIVENESS OF ONLINE POWER QUALITY MONITORING STRATEGIES

Online harmonic monitoring and compensation strategies should be evaluated using existing standards, such as IEEE Standard 1547.[2] It should be noted that since the control diagram is modified to achieve the additional control function of harmonic compensation, system operation stability should be maintained to guarantee that the harmonic compensation does not conflict with the conventional control and operation requirements.

The performance of online unbalance monitoring and compensation strategies should conform to International Electrotechnical Commission (IEC) standards, which recommend the limit of 2 percent for voltage unbalance in electrical systems.[7]

Online voltage violation monitoring and compensation strategies should maintain the voltage profiles within the boundaries specified by ANSI C84.1.[1]

SECTION III – IMPACT OF MICROGRID OPERATION ON THE DISTRIBUTION SYSTEM AND DMS OPERATION

III-A POWER EXCHANGES BETWEEN MICROGRIDS AND DISTRIBUTION SYSTEMS – ELECTRICITY MARKETS

One of the potential benefits of microgrids is that they can reduce the additional costs associated with utility-supplied electric energy, which include the cost of network losses, expenditure on marketing and customer support, and the costs associated with network congestion and various government-imposed taxes. In addition, the owner can sell excess electric energy to the market or store it for future use in certain situations, such as when the microgrid has to operate in island mode or when the cost of electric energy is high. Microgrids can also help ensure the safe and reliable operation of the distribution grid by dispatching power under normal and emergency conditions to the main grid as well as the other microgrids in the network.

This chapter focuses on a) defining microgrid pools (multiple microgrids) participating in joint power dispatch, b) defining the dispatch and operation rules applied to microgrid pools by distribution utilities and markets, and c) analyzing the interaction of microgrid pools with distribution utilities and markets in power dispatch.

3.1 DEFINITION OF MICROGRID POOLS PARTICIPATING IN JOINT POWER DISPATCH

A microgrid pool is an energy exchanging platform that facilitates the dispatch of energy, both internal and external, to a microgrid. Internal dispatch is basically the circulation of energy among all the components within a microgrid, and external dispatch includes the exchange of energy with other microgrids in a multiple-microgrid system and/or the DSO. Each microgrid pool may consist of a microgrid power-supplying network, local DERs, loads, and energy storage. The micro EMS can act as an energy exchanging platform. A schematic of microgrid pools in a multiple microgrid system is shown in Figure 4.

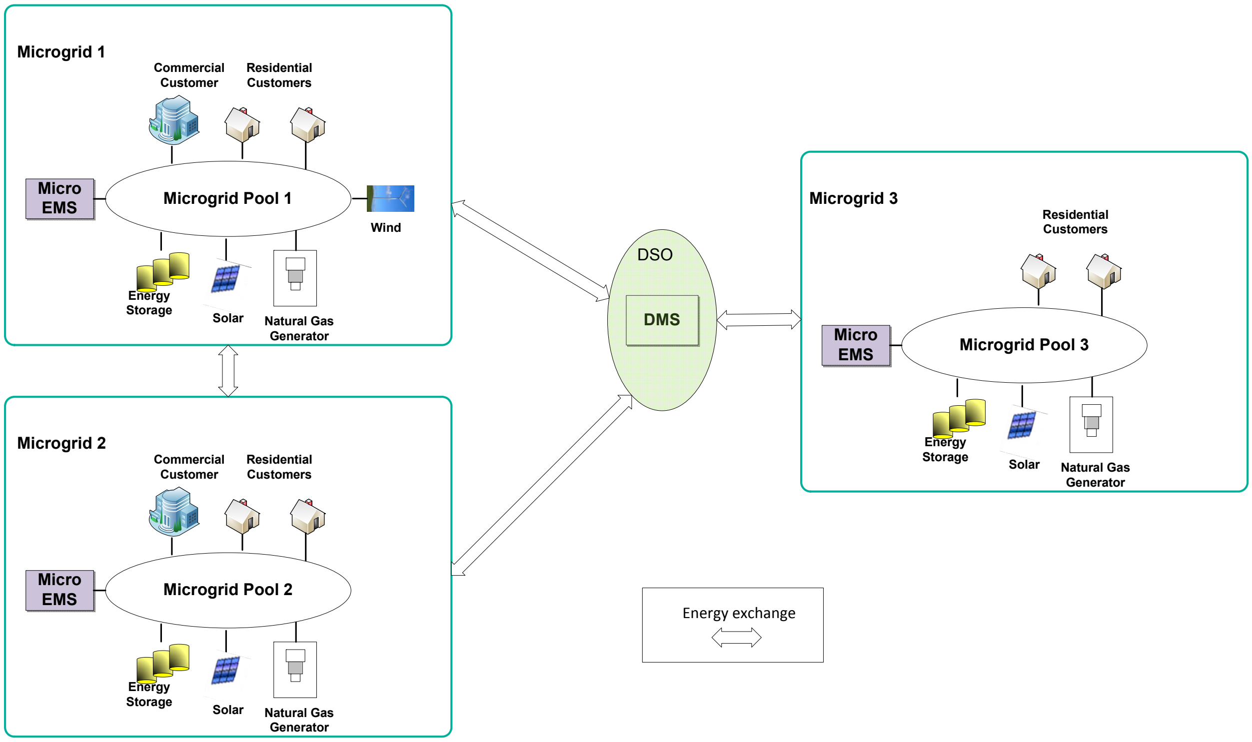

Figure 4 Schematic of Microgrid Pools.

Power dispatch from multiple microgrids to distribution grids and markets is a coordinated energy management scheme for economic dispatch of microgrid resources, essential for minimizing the operating cost of the microgrids as well as the distribution grid. The coordinated energy management problem for economic dispatch is solved with an objective of meeting certain load requirements over a period of time while minimizing overall cost and satisfying operational and physical constraints (generation constraints, ramping constraints, and energy storage constraints). The dispatch problem can be formulated as a two-stage optimization problem. The first stage determines the optimal power dispatch from multiple microgrids within the multiple-microgrid pool, considering each microgrid as an aggregated single entity (load, generation). The second stage optimizes the resources within each microgrid in order to meet the requirements from the first stage while satisfying the local constraints. The solution of the dispatch problem is used to decide the following:

- The amount of power each DER must generate at a given time in order to meet the local demand.
- The available excess power within the microgrid that can be exported to the distribution grid as well as other microgrids, for their secure and stable operation under normal and emergency conditions.
- The available excess power for market transactions.

- The amount of power that must be imported from energy storage, distribution grid and other microgrids in the system.

Different market models can be adopted for dispatch from microgrids: [9]

- **Pool market model**. The pool model is a centralized marketplace model in which individual microgrids can buy electricity from or sell electricity to the pool using a bidding system. The DSO can be the regulatory body for this type of market.

- **Bilateral/ multilateral contract model**. In this model, different microgrids can have contractual agreements with each other for selling and buying electricity. These transactions can be independent of DSOs.

- **Hybrid market model**. The hybrid model is similar to the bilateral model except that all the transactions between different microgrids need to be evaluated by the DSO before they are scheduled. Since the primary focus of dispatch is the secure and reliable operation of the entire grid, the DSO needs to make sure that such transactions do not impact network operating conditions, and that if required, power can be dispatched to non-contractual players (those who do not have a power transaction agreement) to ensure system security and stability.

The hybrid model is more appropriate for power dispatch from multiple microgrids to distribution utilities and markets because it involves the coordination between microgrids and DSOs.

3.2 MICROGRID DISPATCH RULES AND OPERATION STRATEGIES

Microgrid dispatch rules need to be defined for both import to and export from the distribution grid and other microgrids. Some of the rules applicable within the pool as well those imposed by the DSO and the market are identified in this section. [9]-[12]

3.2.1 General Rules

- In the pool market model, the DSO will manage the pool.

- Bilateral contracts can be made between the microgrid owners, but the DSO should ensure that network constraints are not violated.

- In an emergency, other microgrids should be able to supply power to the affected microgrid in order to ensure the reliability and stability of the entire system. Critical loads in the affected microgrid should always be served.

- Power transactions for economic benefit should not compromise the secure and reliable operation of the individual microgrid or the distribution grid.

- Optimal dispatch from multiple microgrids to the distribution grid is a two-level dispatch problem. Level one is the system level, in which each microgrid can be modeled as an aggregated unit, and all microgrids are optimized and coordinated to achieve the overall minimum generation cost under various operating conditions.

- System level optimization can set a dispatch target for each microgrid.

3.2.2 Optimal Scheduling Strategy within the Microgrid

Level two of the optimal dispatch problem is to dispatch each individual DER in each microgrid based on its target, defined in level one. The optimal scheduling strategy of resources within a microgrid is summarized in Table 1.

Table 1 Dispatch Strategy for Multiple Microgrids

Microgrid Operating Condition	Distribution Grid Operating Condition	Action by Microgrid
Active power > Load + losses	Peak load	Discharge battery to sell power to distribution grid, other microgrids and market
	Valley load	Purchase power from market to charge battery
	Distribution grid-side fault	Dispatch power to restore distribution grid
Active power < Load + losses	Peak load	• Disconnect non-critical loads • Discharge battery to supply microgrid critical loads and losses
	Valley load	Purchase power from market and other microgrids to supply critical loads and losses

The following general rules should be observed:

- Operate renewables at their maximum capacity as much as possible.

- Maintain the voltage at the point of interconnection with the distribution grid and other microgrids within the range.

- Maintain the frequency of the microgrid within the limit.

- When the microgrid is islanded from the main distribution grid, the priority of a microgrid should be to meet local load demand (if required, by shedding the non-critical loads) rather than economic benefit. The objective of the dispatch should be to minimize the outage and customer interruption time.

3.2.3 Dispatch Rules from Distribution Grid and Market

- DSO and market will provide fair market access to all players (microgrids)

- The DSO can ask the microgrids to increase or decrease production on a non-discriminatory basis in order to ensure system stability.

- The microgrids should assure the DSO that use of renewables has priority over non-renewables (EU Renewable Dispatch Directive).[13]

3.3 POWER DISPATCH INTERACTION BETWEEN MICROGRID POOLS, DISTRIBUTION UTILITY AND MARKETS

Economic dispatch is achieved with the interaction between microgrid controllers, the DMS and the DSO. Data communication between the DMS and microgrid controllers is used to achieve coordinated energy management. The assets in each microgrid and distribution system should be managed in coordination to achieve economic benefits. The role of actors, their types, actions taken, and content for information exchange for coordinated economic dispatch are shown in Table 2.

Table 2 Interaction and Information Exchange in Microgrid Scheduling

Actor & Actor Type	Action	Contents of Information for Exchange
• Microgrid controller (control system) • DMS (control system) • DSO (market transaction)	• Upload monitoring data from all microgrids to DMS. • DMS schedules economic dispatch. • DMS runs optimization algorithm and sends control signals to the devices, including microgrids. • Microgrid controller coordinates its sources and loads to deliver required power. • DMS updates microgrid controllers with system load information. • Each microgrid controller updates availability of excess power to DMS and market. • Market participants place bids. • Microgrids make transactions based on bidding. • DSO in coordination with DMS ensures that any transaction does not impact system reliability and stability. • DMS gives preference to reliability and stability over economic benefits in supplying power. • Microgrids exchange energy with each other based on their contractual agreements once these transactions are cleared by the DSO.	• Device level data monitoring in both microgrids and distribution system • Commands for economic dispatch • Market pricing signals • Availability of excess power information from microgrid controllers to DMS and market • Load data from DMS to individual microgrid controllers • Tie-line power between microgrids and distribution networks

III-B PROTECTION COORDINATION BETWEEN MICROGRIDS AND THE DISTRIBUTION SYSTEM

In this section we will a) identify the protection schemes of a DMS in an active distribution network, b) identify the protection schemes of a micro EMS, c) define the requirements for micro EMS and DMS protection functions to coordinate with each other, and d) analyze the protection coordination between DMS and micro EMS in various event scenarios.

3.4 PROTECTION SCHEMES OF DMS IN ACTIVE DISTRIBUTION NETWORKS

Overhead distribution systems are common in rural areas, while underground distribution systems are widely adopted in urban areas. Regardless of the variations in distribution system composition, overcurrent protection is the most widely adopted protection scheme for distribution systems. It relies on measured currents to distinguish faults from nominal load currents. The most-used protection devices in distribution system protection include overcurrent relays, reclosers, sectionalizers, and fuses. These devices, except sectionalizers, all implement a set of time/current curves, which have a time-inverse characteristic and provide different operation times, depending on the fault current level, i.e., the larger the fault current, the shorter the operation time will be.

The basic requirements for a protection device include selectivity, sensitivity, operating time and stability. The relay settings are very important in ensuring selectivity and sensitivity. Traditionally, because of the passive nature of distribution networks, the power flow in the distribution network is one-way, i.e., from the distribution substation to customers. When a fault occurs in the distribution system, the main source feeding the fault is the transmission system. Conventional protection devices are set up and coordinated on the basis of one-way power flow, ensuring that the upstream protection device closest to the fault reacts first to clear the fault. Each relay provides backup to the next downstream relay with a time delay. An upstream relay will not react to the fault current unless its downstream relay fails to react within the setting time. The basic coordination scheme is illustrated in Figure 5.[3]

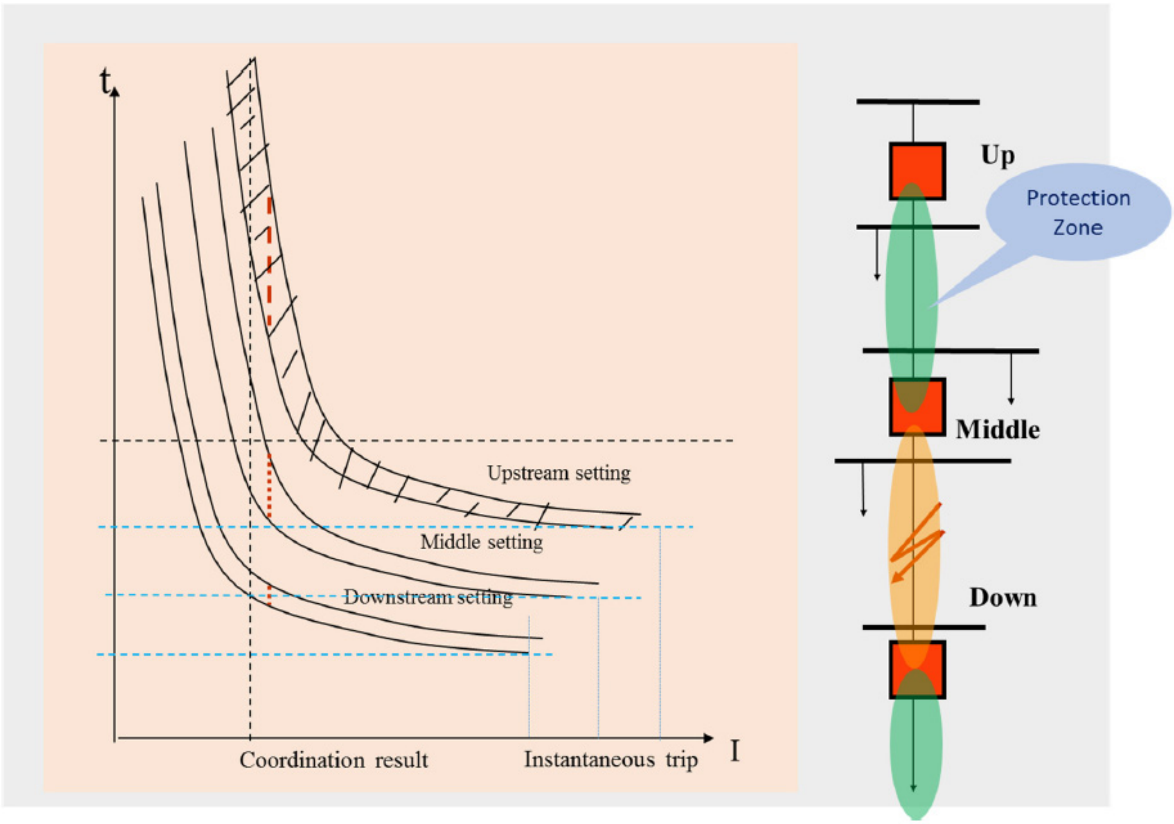

Figure 5 Distribution System Basic Protection Coordination Scheme.

Conventional distribution system protection devices, their protection schemes, and operation mechanisms are summarized in Table 3.

Table 3 Summary of Distribution System Protection Devices

Device	Protection Schemes	Operation Mechanism
Recloser	Overcurrent protection by implementing a set of time/current curves.	Interrupts current and automatically recloses. If fault is temporary, the reclosing will hold within preset number of operations after the fault is cleared. If fault still exists after preset number of operations, final operation is lockout.
Sectionalizer	Automatically isolates faulted sections of a distribution circuit once an upstream recloser has interrupted the fault current after set number of recloser operations.	Without current interrupting capability. Must be used together with a back-up device that has fault current interrupting capacity, e.g., a recloser or a circuit breaker.

Table 3 (Cont.)

Device	Protection Schemes	Operation Mechanism
Fuse	Overcurrent protection with a time/current curve characteristics.	Interrupts current; for one-time only use.

Note that the circuit breaker installed at the feeder head may also be a recloser.

3.5 PROTECTION SCHEMES OF MICRO EMS

There are two main issues in microgrid protection: [14] 1) identifying external abnormal conditions and selecting the corresponding protection scheme, e.g., anti-islanding or fault ride-through, and 2) providing a properly coordinated and reliable protection scheme for internal faults. The microgrid's protection scheme must have current interrupting capabilities and be able to distinguish an island condition from upstream/transmission and adjacent fault conditions.

The specific technical challenges for the microgrid protection include:

- Bi-directional power flow
- Two operational modes: grid-connected and island
- Topological changes due to switch operations in the network and connection/disconnection of DERs and loads
- Intermittence in the generation of DERs connected to the microgrid
- Relatively lower fault current in island mode due to inverter-interfaced DERs

The last point above has been a key research issue in the past few years. The characteristics of most protective devices used in microgrids are usually similar to those used in distribution networks, which are based on large fault currents. However, in island operation, the fault current is from the inverter-interfaced DERs, which generally can only provide very limited fault current, e.g., only about 20 percent above their rated current. As a result, conventional overcurrent protection schemes may be no longer applicable.

The most common technologies applied to microgrid protection, either in grid-connected or in island mode of operation, are as follows.

a) Adaptive protection schemes: This type of protection scheme is mainly based on the use of adaptive relays, which can have their settings, characteristics or logic functions changed online by means of externally generated signals or control actions in a timely manner.

b) Voltage based methodologies: These technologies mainly use voltage measurements to provide an adequate protection scheme.

c) Differential protection: These approaches are based on current differences measured in different parts of the microgrid.

d) Distance protection: The techniques in this category use admittance or impedance measurements in order to detect the fault and trip adequately.

e) Overcurrent protection with symmetrical components: These relays attempt to enhance the performance of traditional overcurrent protections by using measurements and/or calculations with symmetrical components.

3.6 REQUIREMENTS FOR DMS AND MICRO EMS PROTECTION FUNCTIONS TO FACILITATE COORDINATION

3.6.1 Challenges of Distribution System Protection Due to Integration of Microgrids

The conventional distribution system protection scheme faces challenges with the high penetration of active devices such as microgrids and DERs.[15] Although the fault current contribution from each microgrid and DER is limited, [16] a high penetration of microgrids and DERs can contribute a considerable amount of fault current. These sources can change the fault current distribution and magnitude and cause new problems for the operation of existing overcurrent protection schemes.[17] In addition, the microgrids and DERs installed in the distribution system have their own protection relays in place with specific protection schemes, such as anti-islanding [2] and detecting abnormal voltage/frequency and tripping with different time responses according to different voltage/frequency deviations.[4] The coordination of microgrid and DER protection relays with conventional distribution feeder protection devices has yet to be addressed. Moreover, a mechanism for coordinating feeder head relays connected on the same bus and the substation transformer protection relays should be developed to help address some of the emerging protection problems due to large-scale microgrid and DER integration.

These emerging protection issues due to the integration of microgrids and DERs are listed in Table 4.

Table 4 Summary of Main Distribution System Protection Issues Due to Microgrid and DER Integration

Protection Issue	Detailed Description
Increased fault current	High penetration of the microgrids and DERs on a distribution feeder will contribute to a higher magnitude of fault current induced by a fault on the feeder. Also, the aggregate of microgrid and DER fault current contribution will increase the fault current level on the adjacent feeder.
Sympathetic tripping	When a fault occurs on a distribution feeder, the aggregate fault current contribution from the microgrids and DERs on the adjacent feeder may cause sympathetic tripping of the circuit breaker of the adjacent feeder.
Desensitizing the protection devices	When the fault impedance is non-zero, and microgrids and DERs are contributing to the fault current, the fault current contribution from the substation or upstream source may be reduced. The reduction in fault current will desensitize the protection device at the source.
Coordination of microgrid and DER protection relays with existing feeder protection devices	IEEE Standard 1547 [4] mandates that a microgrid and DER protection relay be able to detect voltage/frequency deviations and trip with pre-specified time responses, and isolate itself within two seconds of the formation of an unintentional islanding.[2] Poor coordination between microgrid and DER protection relays' protection schemes and conventional feeder protection devices may lead to nuisance fuse blowing, reclosing out of synchronism, sectionalizer miscount, etc.
Fault ride-through capabilities of microgrid and DER protection devices	During a transmission contingency, the deviated voltage and/or frequency condition experienced throughout the entire grid may cause the microgrids and distribution DERs to trip, which may further reduce the total available generation and thus endanger the bulk power system stability. Similarly, momentary voltage sag caused by a fault on an adjacent feeder may cause microgrids and DER inverters to trip. The IEEE Standard 1547 amendment [4] stipulates that microgrid and DER systems have voltage and frequency ride-through capability in case of a contingency on the transmission line. This provision, however, may pose some challenges to the coordination between the microgrid's and DER's protection relays and the distribution grid protection devices.

Table 4 (Cont.)

Protection Issue	Detailed Description
Tripping of substation transformer protection relay	The high penetration of microgrids and DERs on distribution circuits may create reverse power flow back to the transmission system, causing the substation transformer protection relay to trip.
Circuit reconfiguration	Circuit topology is subject to change due to either post-contingency service restoration or purposeful load balancing. If a circuit can be reconfigured for emergency service or maintenance, each possible reconfiguration variation must be examined to determine whether concerned microgrids and DERs should be permitted to stay connected to ensure proper operation (e.g. voltage, loading, and fault sensing requirements).

3.6.2 DMS and Micro EMS Protection Function Requirements to Facilitate Coordination

In this subsection, we will discuss protection function requirements for the DMS and the micro EMS based on whether the microgrid is grid-connected or islanded.

a) Grid-Connected Operation

In grid-connected operation, current distribution system protection devices suffer from inaccurate settings, because they are derived from short-circuit analysis without accounting for microgrid and DER fault current contributions.[18] Moreover, these settings are manually pre-loaded into relays and therefore cannot be adjusted according to the latest microgrid and DER states to ensure sensitivity and selectivity. To address these challenges, the DMS should deploy a real-time setting update system to perform bi-directional short-circuit analyses with the as-operated circuit connectivity and knowledge of microgrids and DERs in the system. The micro EMS is responsible for communicating its aggregated power output at the POI to the DMS. Frequency of execution is governed by the communication capabilities of the distribution system. If the communication bandwidth and speed allow, an execution cycle of one minute can be assumed in this discussion. The DMS will communicate the dynamic setting update to all the feeder protection devices through SCADA every one minute. If the micro EMS is unable to dispatch the DER outputs due to their intermittent nature, it should notify the DMS with the aggregated forecast power. The DMS protection function can then operate with the best estimate of the microgrid available power, even though it is intermittent.

Due to the lack of protection coordination between microgrid and DER protection devices and distribution feeder protection devices, many potential problems may emerge.[19] Some of the adverse consequences include nuisance fuse blowing, reclosing out of synchronism, sectionalizer miscount, and so on.[20] One potential solution acquires local intelligence at the distribution protection device, such as the recloser, to determine whether the fault is temporary or permanent, and then launches communication-based local coordination to coordinate the sequence of actions for the microgrid and DER protection devices and the feeder protection devices.

Another practical solution does not require communication between distribution protection devices and microgrid and DER protection devices, but rather coordinates their actions by managing the microgrid and DER voltage/frequency deviation based protection function and anti-islanding scheme. In addition, the distribution protection devices such as reclosers may be required to install additional voltage sensing relays to facilitate proper coordination. The microgrids and DER voltage/frequency deviation based protection function obeys the IEEE Standard 1547 amendment: [4]

- If the voltage at the POI falls below 45% of base voltage, the microgrid or DER should cease to energize the distribution grid within 0.16 seconds.

- If the voltage at the POI falls between 45% and 60% of base voltage, the microgrid or DER should cease to energize the distribution grid within 11 seconds.

- If the voltage at the POI falls between 60% and 88% of base voltage, the microgrid or DER should cease to energize the distribution grid within 21 seconds.

- If the voltage at the POI falls between 110% and 120% of base voltage, the microgrid or DER should cease to energize the distribution grid within 13 seconds.

- And if the voltage at the POI falls above 120% of base voltage, the microgrid or DER should cease to energize the distribution grid within 0.16 seconds.

The extended clearing time for the 45V-88V and 110V-120V ranges allows the microgrid or DER to ride through potential transmission line or adjacent feeder faults. In the meantime, the microgrid and DER must isolate itself within two seconds of the formation of an unintentional islanding. Coordination among distribution protection devices and microgrid or DER protection relays are discussed below with the following three scenarios: a distribution feeder permanent fault, a distribution feeder temporary fault, and a transmission line or adjacent feeder fault.

- *Scenario 1*: *A permanent fault on the distribution feeder*. When the fault occurs, the nearest upstream recloser senses the fault and immediately opens up. The voltage/frequency deviation based protection functions and anti-islanding schemes of all the downstream microgrids and DERs are engaged simultaneously to detect whether there is any sustained voltage deviation and whether an island is formed. Since the downstream microgrids and DERs are feeding into the fault, the voltages at the POIs of these microgrids and DERs will most likely fall below 45% of base voltage, such that the voltage deviation based protection scheme will disconnect the microgrids and DERs within 0.16 seconds. When the recloser is ready to reclose, it uses its voltage sensing relay to determine that there is no downstream source online and proceeds to reclose. The recloser then goes through the remainder of the reclosing sequence until lockout. This scenario also applies to a temporary fault that is not cleared by the first tripping of the recloser (e.g., the arcing still exists) and the downstream microgrids and DERs are still feeding the temporary fault.

- *Scenario 2: A temporary fault on the distribution feeder*. When the fault occurs, the nearest upstream recloser senses the fault and immediately opens up. Consequently the arc is extinguished by the tripping of the recloser, and an unintentional island is formed, in which the downstream microgrids and DERs continue to energize a portion of the distribution feeder without the utility source. At the same time, the voltage/frequency deviation based protection functions and anti-islanding schemes of all of the downstream microgrids and DERs are engaged to detect whether there is any sustained voltage deviation and whether an island is formed. If the voltages at the POIs of the downstream microgrids and DERs fall below 45% of the base voltage, they will be disconnected within 0.16 seconds. When the recloser is ready to reclose, it uses its voltage sensing relay to determine that there is no downstream source online, then proceeds to reclose and holds. If the voltages at the POIs of the downstream microgrids and DERs fall within 45%-88% or 110%-120% of the base voltage, the voltage deviation based protection scheme will go through the extended clearing time before disconnection. In the meantime the anti-islanding schemes of the downstream microgrids and DERs should identify that an island has been formed, override the voltage deviation based protection scheme, and disconnect from the distribution grid within two seconds. Coordination scenario with the recloser depends on the programmed reclosing intervals. If the recloser is programmed to reclose within two seconds (before the microgrids and DERs are disconnected from the anti-islanding scheme), its voltage sensing relay should prohibit the reclosing action and will allow reclosing only after the anti-islanding scheme has disconnected the microgrids and DERs. If the recloser is programmed to reclose in more than two seconds (after the anti-islanding scheme has disconnected the microgrids and DERs), its voltage sensing relay should determine that there is no downstream source online and proceed to reclosing and hold.

- *Scenario 3: A fault on the transmission line or adjacent feeder.* The extended clearing time, compared to the original IEEE Standard 1547, ensures the fault ride-through capabilities of microgrids and DERs for contingencies on transmission lines or adjacent feeders. A fault on a transmission line, an adjacent feeder or a local feeder may cause the same level of voltage and frequency deviation from the standpoint of microgrid and DER local protective relays. Following the extended clearing time allows the microgrids and DERs to survive faults on transmission lines and adjacent feeders by preventing them from tripping and further upsetting the bulk power system voltage/frequency through losing a significant amount of generation.[21],[22] In addition, the anti-islanding protection schemes of microgrids and DERs can serve as backup mechanisms to confirm that no unintentional island is formed and ensure that microgrids and DERs ride through faults on transmission lines and adjacent feeders.

Proposed solutions for main distribution system protection issues due to microgrid and DER integration are summarized in Table 5.

Table 5 Solutions to Main Distribution System Protection Issues Due to Microgrid and DER Integration

Protection Issue	Proposed Solution
Increased fault current	The settings of the feeder protection devices must be updated adaptively to accommodate the increased fault current level, including contributions from adjacent feeders.
Sympathetic tripping	Feeder head protection devices should be able to identify the source of fault events, based on the direction of the current flow and voltage level, to determine whether to trip. Feeder head relays interconnected on the same bus need to be coordinated properly to avoid sympathetic tripping.
Desensitizing the protection devices	Bi-directional short-circuit analyses based on as-operated circuit connectivity and knowledge of microgrids and DERs states in the system are necessary to properly configure the relay settings. The relay settings should be sensitive enough to pick up the lowest short circuit current, but also should be able to remain inoperative for a large surge of load current, especially during cold load pick-up, in which all motor loads start although all the disconnected generations are not back online. The upstream protection device should provide backup for downstream protective elements.
Coordination of microgrid and DER protection relays with existing feeder protection devices	In one solution, intelligence at the distribution feeder protection device (e.g. reclosers) will first determine whether the fault is temporary or permanent. Communication-based local coordination will then coordinate the sequence of actions of the microgrid and DER protection relays and feeder protection devices to avoid nuisance fuse blowing, reclosing out of synchronism, sectionalizer miscount, etc. Another practical solution does not require communication between distribution protection devices and microgrid and DER protection devices, but rather coordinates their actions by managing the microgrid and DER voltage/frequency deviation based protection functions and anti-islanding schemes. In addition, distribution protection devices such as reclosers may be required to install additional voltage sensing relays to facilitate proper coordination.
Fault ride-through capabilities of microgrid and DER protection devices	Implement the extended clearing time for certain voltage deviation ranges to ensure the fault ride-through capabilities of microgrids and DERs for contingencies on transmission lines or adjacent feeders. In addition the anti-islanding protection schemes of microgrids and DERs can serve as backup mechanisms to confirm that no unintentional island is formed.
Tripping of substation transformer protection relay	The transformer protection relays need to coordinate with the feeder head protection relays to distinguish reverse power flow from fault events either at the downstream feeder, at the substation transformer itself, or on the upstream transmission lines.
Circuit reconfiguration	Comprehensive bi-directional short-circuit analyses should be carried out to determine and update feeder protection device settings to ensure proper fault sensing and coordination under the new circuit configuration.

b) Island Operation

Two different island operation cases should be considered: intentional island operation and unintentional island operation. Intentional islanded condition is typically scheduled, so the micro EMS can inform the DMS of the planned transition. The DMS dynamic setting update function then conducts short-circuit analyses by removing the fault current contribution from the microgrid to be disconnected and determines the new settings for feeder protection devices before the disconnection. In addition, if the communication-based local coordination scheme is implemented to coordinate the microgrid and DER protection relays with the distribution grid protection relays, the micro EMS should also inform the associated feeder protection relay of the planned transition. This way the concerned microgrid can be removed from the feeder protective relay's local coordination scheme, which orchestrates its own action with those of the microgrid and DER protection devices. On the microgrid side, the micro EMS needs to adjust the protection scheme and settings accordingly, given the absence of large utility fault current contribution, if an internal fault were to occur during the island operation mode.

Unintentional island operation can be triggered by an internal fault inside the microgrid or a grid-side fault outside the microgrid. An unintentional island on certain portions of a distribution feeder forms when a grid-side fault occurs, and the microgrid continues to serve load in the absence of the utility source after the feeder protection relay trips and clears the fault. The anti-islanding protection or the voltage/frequency deviation based protection scheme of the micro EMS, whichever responds first, disconnects the microgrid from the main grid, and the microgrid goes into an unintentional island operation mode. Then the micro EMS needs to adjust the protection scheme and settings accordingly given the loss of large utility fault current contribution if an internal fault were to occur during the island operation mode.

Unintentional island operation could also be caused by an internal fault within a microgrid. In this case, the micro EMS is responsible for detecting the fault and performing the corresponding protective actions, including interrupting the fault current supply to the faulted section, disconnecting the microgrid from the distribution grid, and informing the DMS about the mode transition. On the DMS side, meanwhile, its dynamic setting update function should then conduct short-circuit analyses by removing the fault current contribution from the disconnected microgrid, determine the new settings for feeder protection devices, and implement them. The disconnected microgrid will then be removed from the associated feeder protective relay's local coordination scheme accordingly as well, if the communication-based local coordination scheme is implemented to coordinate the microgrid and DER protection relays with the distribution grid protection relays.

3.7 ANALYSIS OF DMS AND MICRO EMS PROTECTION COORDINATION IN VARIOUS EVENT SCENARIOS

3.7.1 DMS and Micro EMS Protection Coordination for Grid-Side Faults

In this subsection, we will analyze DMS and micro EMS protection coordination for faults occurring on the grid side, including the actors involved, the required sequential action, and the content of information exchanged between micro EMS and DMS protective devices for grid-side faults. The distribution feeder protection devices are the main actors in detecting and interrupting the faults occurring at the grid side.

The sample distribution system integrated with microgrids and DERs shown in Figure 6 will be used to illustrate the various fault scenarios. The distribution system contains two feeders, protected by Circuit Breaker 1 and Circuit Breaker 2, respectively, and interconnected by a normally open tie switch. The first feeder includes three microgrids that are interconnected to the feeder via µG SW1, µG SW2, and µG SW3, respectively.

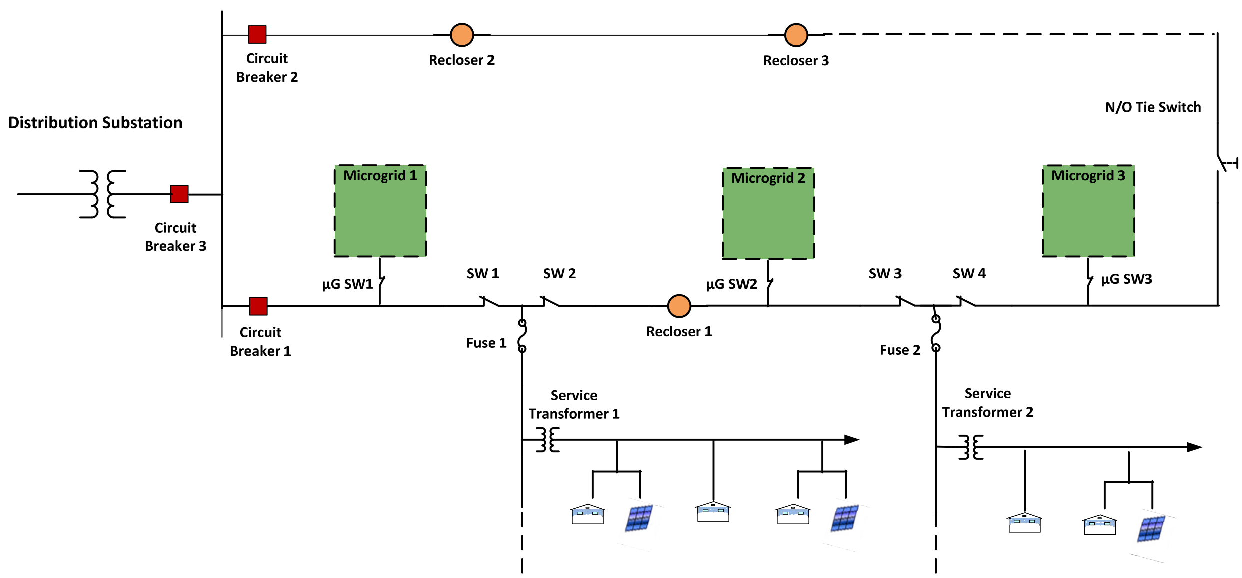

Figure 6 Sample Distribution System Integrated with Microgrids and DERs.

Each micro EMS communicates its aggregated power output schedule or forecast at the POI to the DMS every minute. The DMS also receives other available measurements from line sensors, smart meters, and intelligent electronic devices (IEDs) in a one-minute resolution. Based on the latest state of the system, the DMS then carries out bi-directional short-circuit analyses with the as-operated circuit connectivity and knowledge of microgrid and DER output in the system, and determines the settings of all the feeder protection devices. The DMS will communicate the dynamic settings to all the feeder protection devices through the supervisory control and data acquisition (SCADA) system.

Assume a temporary fault occurs on the main feeder section between Recloser 1 and µG SW 2. Microgrid 1 is upstream of the fault location, and Microgrid 2 and Microgrid 3 are downstream of the fault location. The coordination scenarios among distribution protection devices and microgrid and DER protection relays are laid out below for both communication-based and non-communication-based local coordination schemes.

- **Communication-based local coordination scheme**. When the fault occurs, Recloser 1 senses the downstream fault first and applies the local data analytics on the captured fault waveform to promptly determine the nature of the fault, which is temporary in this case. Recloser 1 then informs the micro EMSs downstream of the fault, which are Microgrid 2 and Microgrid 3 in this case, about the nature of the fault and requests them to disconnect. Recloser 1 will then go through a series of reclosing actions, clear out the temporary fault, and finally stay closed. Upon successfully clearing the temporary fault, Recloser 1 will send out the reconnection command to the downstream micro EMSs. This communication-based local coordination mechanism successfully avoids the reclosing out of synchronism problem. Throughout the process, Microgrid 1 utilizes either the voltage/frequency deviation based protection scheme and/or the anti-islanding scheme to ride through the whole disturbance.

- **Non-communication-based local coordination scheme**. When the fault occurs, Recloser 1 senses the downstream fault first and trips immediately. Consequently the arc is extinguished by the tripping of the recloser, and an unintentional island is formed where Microgrid 2 and Microgrid 3 continue to energize, without the utility source, the portion of the distribution feeder downstream of Recloser 1. At the same time, the voltage/frequency deviation based protection function and anti-islanding scheme of Microgrid 2 and Microgrid 3 are engaged to detect whether there is any sustained voltage deviation and whether an island is formed. If the voltages at the POIs of Microgrid 2 and Microgrid 3 fall below 45% of the base voltage, they are disconnected within 0.16 seconds. When Recloser 1 is ready to reclose, it uses its voltage sensing relay which determines that there is no downstream source online, then proceeds to reclose and holds. If the voltages at the POIs of Microgrid 2 and Microgrid 3 fall within 45%-88% or 110%-120% of the base voltage, the voltage deviation based protection scheme will go through the extended clearing time before disconnection. In the meantime, the anti-islanding scheme of the Microgrid 2 and Microgrid 3 should identify that an island has been formed, override the voltage deviation based protection scheme, and disconnect from the distribution grid within two seconds. The coordination scenario with the recloser depends on the programmed reclosing intervals. If Recloser 1 is programmed to reclose within two seconds (before Microgrid 2 and Microgrid 3 are disconnected from the anti-islanding scheme), its voltage sensing relay should prohibit the reclosing action and will only allow reclosing after the anti-islanding scheme has disconnected Microgrid 2 and Microgrid 3. If Recloser 1 is programmed to reclose in more than two seconds (after the anti-islanding scheme has disconnected Microgrid 2 and Microgrid 3), its voltage sensing relay should determine there is no downstream source online and proceed to reclosing and hold.

3.7.2 DMS and Micro EMS Protection Coordination for Microgrid-Side Faults

In this subsection we will analyze DMS and micro EMS protection coordination for faults occurring on the microgrid side, including the actors involved, the required sequential action, and content of information exchanged between the micro EMS and DMS protective devices for grid-side faults. The microgrid protection devices are the main actors in detecting and interrupting the faults occurring at the microgrid side.

If a permanent fault occurs in Microgrid 1, the nearest upstream protection device within the microgrid senses the fault occurrence and automatically opens up to interrupt the fault current. Then the operated protection relay will notify the micro EMS and DMS of the fault occurrence. Due to the designed fast action of the local microgrid protection relay, the protection devices on the grid side will not operate. The other microgrids connected to the distribution grid, Microgrid 2 and Microgrid 3, determine through either the voltage/frequency deviation based protection scheme or the anti-islanding scheme to ride through the whole disturbance. The DMS will execute its dynamic setting update function by conducting short-circuit analyses, without considering the fault current contribution from Microgrid 1, and determine the new settings for the feeder protection devices and implement them. Microgrid 1 will then be removed from Circuit Breaker 1's local coordination scheme if the communication based local coordination scheme is implemented, to coordinate the microgrids' and DERs' protection relays with the distribution grid protection relays.

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SECTION IV – TOOLS AND TECHNIQUES FOR THE INTEGRATION OF MICROGRIDS IN THE DMS – POWER FLOW AND FAULT ANALYSIS

The distribution grid is becoming highly active with high penetration of microgrids and DERs. Advanced applications in the DMS are facing completely new environments that are very different from the traditional passive networks on which conventional applications are based. This results in a series of challenges to advanced DMS applications. The most important challenge is from the bi-directional power flow in the grid, which may change from time to time, depending on the real-time dynamics of the load and the microgrid output. The second challenge comes from the additional uncertainties associated with the microgrid output, in that most of its generation may be from renewable resources. Advanced DMS applications will need to be sufficiently robust and able to respond quickly to dramatic condition changes. Some key applications may need to be able to look ahead when providing predicted operational schedules and strategies, including VVO, FLISR, etc.

The following subsections of this section will identify several key advanced DMS applications that are significantly affected by the integration of microgrids, analyze the impact on those advanced applications from the integration of microgrids, and define the requirements and effective approaches to developing or modifying the identified advanced applications to support the integration of microgrids.

4.1 MAJOR ADVANCED DMS APPLICATIONS AFFECTED BY INTEGRATION OF MICROGRIDS

The major advanced DMS applications that are significantly affected by the integration of microgrids are on-line power flow (OLPF), short-circuit analysis (SCA), fault location, isolation, and service restoration (FLISR), and volt-VAR optimization (VVO). Their functions, operations and benefits are individually introduced in this section.

4.1.1 On-line Power Flow

On-line power flow determines the steady state solution of the power system for a given operating condition. The function can operate in both real-time and offline modes.

OLPF is a very important application in a DMS. It solves the three-phase balanced or unbalanced power flow of the distribution network, either in a pure radial configuration or a weakly meshed network with a few loops. Power flow results from OLPF are used by many other DMS applications to set initial conditions and validate performance or to show hypothetical impacts such as in VVO, FLISR, and switch order management (SOM). OLPF also provides control center personnel with calculated line section current and power flow quantities and node voltage values, and alerts operators for abnormal operation conditions on the feeders, such as low voltages at feeder extremities and overloaded line sections.[3]

In solving power flow problems, the OLPF uses the distribution system model and load estimate provided by load allocation and estimation functions in its calculations.[3] It may also use the available real-time status of substation and feeder devices and the voltages and phase angles at the substation source buses obtained from the EMS state estimator. More detailed OLPF results include calculated current and voltage magnitudes and phase angles, real and reactive power flows and net bus injections, and technical losses. The detailed results may be presented in various formats, automatically or on request, enabling operators to view power flow summaries for a large area of the distribution system and/or view detailed results for specific points or sections of the distribution system.

4.1.2 Short-Circuit Analysis

SCA is an analysis tool in DMS that operates upon the operator's or a user's request. It calculates the short-circuit current distribution for hypothetical faults and pre-fault operation conditions to evaluate the possible impact of a fault on the distribution grid.[3] SCA results can be used to verify relay protection settings and operation, as well as circuit breaker and fuse ratings, and to propose more accurate relay settings or a better feeder circuit configuration from the viewpoint of circuit protection.

The SCA function enables users to calculate the faulted three-phase voltages and currents on the distribution system that could occur as a result of postulated fault conditions and pre-fault loading conditions.[3] It can calculate and compare fault currents against the switchgear's interrupting capabilities and devices' fault-current limits. It may also be used to help users identify the fault location based on the measured fault magnitude, pre-fault loading, and other information available at the time of the fault.

4.1.3 Fault Location, Isolation, and Service Restoration

As one of the key DMS functions, FLISR is designed to mitigate the impact of permanent faults on distribution systems and ensure a high level of overall system reliability. The FLISR can analyze all available real-time information acquired from field devices, including fault detector outputs, fault magnitude at various locations on the feeder, feeder segment or even the customer meter energization status, and protective relay reports, to detect faults and other abnormal circuit conditions for which service restoration actions are needed.[3] The FLISR then determines the approximate location of the fault, i.e., the faulted section of the feeder that is bounded by two or more feeder switches. It can also automatically isolate the faulted section, and then close the normally open tie switch to transfer the downstream loads to the adjacent feeders to restore service to as many customers as possible. If a single alternative source lacks sufficient capacity to pick up all the loads in the healthy downstream feeder sections, multiple alternative sources may be utilized to share the load, depending upon their available capacities.

FLISR executes control actions by issuing supervisory controls to the corresponding switches, including feeder header circuit breakers at the substations and various feeder switching devices (e.g. reclosers, load breakers, and sectionalizers equipped with supervisory control capabilities).

The FLISR function is normally responsible only for dealing with permanent faults occurring on the main three-phase portion of the feeder circuits and those substation faults that cause the sustained loss of one or more feeders at the substation. Temporary faults that are cleared by automatic reclosing schemes without sustained loss of service are not included in FLISR logic. The FLISR function may not be responsible for restoring service loss that occurs because of fuses blown on feeder laterals, emergency load shedding activities, and manual feeder tripping.[3]

The FLISR generally considers all possible ways to restore as much load as possible without creating undesirable conditions.[3] The optimal service restoration strategy should not cause new undesirable electrical conditions on any distribution feeder, and should restore electrical service to the maximum number of customers with the minimum number of switching operations.

The key benefits of FLISR include reduced outage duration and improved system average interruption duration index (SAIDI). Since some customers will be restored to service in less time than the threshold for permanent outages (usually five minutes), FLISR may also improve the system average interruption frequency index (SAIFI).

4.1.4 Volt-VAR Optimization

VVO adjusts the feeder voltage profile and VAR flow during normal operations. VVO traditionally refers to the integrated control of switched capacitor banks in the substation and along the feeders, substation transformer on-load tap changers (OLTC), and voltage regulators on feeder sections.

The VVO function can operate either in closed-loop or advisory (open-loop) mode. In advisory mode, VVO provides advisory control actions that can be reviewed and then either approved for execution or rejected by the dispatcher.[3] In closed-loop mode, VVO automatically executes the optimal control actions without operator intervention. The VVO function can be executed periodically at a user-specified interval (usually 15 minutes) and terminated upon occurrence of specific events, such as a significant load transfer to an adjacent feeder, a network topology change, or a user request.

In every control cycle, the VVO function retrieves the as-operated distribution system model from the DMS. It also receives real-time data from the IEDs or remote terminal units (RTUs) and line sensors installed in the substation and the field through SCADA or other proprietary communication channels. These data sets typically include voltages, currents, and real and reactive power measurements. VVO also obtains the feeder load forecast for look-ahead optimization. In addition, VVO may use near-real-time voltage measurements from selected advanced metering infrastructure (AMI) meters if available. These voltage measurements can be continuously monitored by the VVO function to verify that ANSI voltage limits are not violated at these locations. In some advanced algorithms, AMI customer voltage data can be used as input to VVO optimization to determine optimal control decisions, which helps maximize the voltage control capability.

VVO solves an optimization problem to determine the optimal control settings for on/off status of capacitor banks and tap positions for OLTC and voltage regulators. These control commands are sent to the local controllers of the field devices, through SCADA, to maintain the corresponding status for the entire control cycle. The optimization process takes into account device operation constraints, including the maximum number of tap changes within a given time period, maximum number of capacitor switching operations allowed each day, and minimum time interval required between capacitor switching actions. VVO is also subject to voltage operational limits and power factor constraints.

VVO can be assigned to achieve any of the following objectives or a weighted combination of all of them:

- Minimize distribution losses by maintaining a desired power factor.
- Ensure a desired voltage profile along the feeder circuit during normal conditions.
- Reduce peak loads through conservation voltage reduction (CVR).

4.2 ANALYSIS OF THE IMPACT ON INDIVIDUAL ADVANCED APPLICATIONS FROM INTEGRATION OF MICROGRIDS

4.2.1 On-line Power Flow

Traditionally, distribution grids are largely passive networks in which each feeder circuit is supplied by a distribution substation as its sole energy source. It is generally assumed that no other energy resources or devices are connected to the feeder circuit except passive shunt devices, like capacitor banks, and the loads of the individual end users.

Typically, the load flow and unbalanced load flow (LF/UBLF) functions available in the DMS are configured to run in offline mode. Traditionally, power flow functions utilize network parameters and power injections at different nodes that do not change very often. Power flow functions may be triggered by an event (fault, switching), operator request, or change of analog and/or status value in some specific measurements. Thus its operation is typically off-line. However, due to the integration of microgrids, power injections may change more frequently, and the OLPF function should incorporate such changes. The conventional off-line operation will no longer be appropriate for real-time control in systems with microgrids. The LF/UBLF function needs to be reconfigured for online operation.

Another challenge to the OLPF is bi-directional power flow due to the presence of microgrids and DERs, which in turn may have an impact on network parameters, essentially driving the OLPF function. For example, a frequent tap setting change may be caused by power flow reversing, and the OLPF function should have a provision to account for this.

Some of the microgrids may not manage all of their internal DERs directly, and therefore their outputs may be stochastic in nature. When a microgrid controller is responsible for managing the intermittency of its internal DERs, it can provide the power injection information at the POI to the OLPF function. Hence a deterministic OLPF function can determine the operating state of the distribution network at the POI with the provided power injections at the POIs. The variability of power due to DERs within the microgrid requires a local stochastic power flow engine to regulate flow at the POIs. The problem is of a hierarchical nature and requires a two-stage OLPF solution: one deterministic stage at the DMS level and the other stochastic stage within each microgrid (micro EMS).

4.2.2 Short-Circuit Analysis

Microgrids can also contribute fault currents, leading to multiple fault current contribution sources — a situation that is quite different from what conventional passive networks face. The variability of microgrid output causes random changes to the system operating conditions. Thus when microgrids are connected, short-circuit analysis should be performed for many hypothetical operating conditions. One approach to incorporating multiple operating scenarios is Monte Carlo simulation with various forecasts and/or schedules of microgrid outputs at the POIs.

The impact of microgrid integration on the algorithmic design of short-circuit analysis can be analyzed for different short-circuit analysis approaches. One approach is based on sequence domain analysis with symmetrical components. Since symmetrical components need balanced system networks to exploit the advantages of the sequence analysis, they cannot be directly used in distribution systems that are modeled with multi-phase unbalanced conductors. Adding dummy nodes and lines to create an equivalent three-phase system is one method that has been developed for dealing with unbalanced multi-phase distribution feeder lines. By this method, the traditional bus impedance matrix based short-circuit analysis for sequence networks can be leveraged for short-circuit analysis, and the fault current contribution of microgrids can be integrated conveniently.

Another approach to short-circuit calculation is based directly on phase domain analysis using phase coordinates. It uses an analytical method to calculate the voltages and currents of the system by modifying the nodal admittance matrix according to the fault parameters. The microgrid outputs can be modeled as net current injections at the respective nodes. The constraints of a fault are used to reduce the order of the nodal admittance matrix.

4.2.3 Fault Location, Isolation, and Service Restoration

The interconnection of microgrid may have significant impacts on the logic of fault location and the strategy of service restoration in FLISR. This is because the fault current will take multiple paths from all connected energy sources, rather than a single path as in the conventional passive network. After the faulted segment is located and isolated, the task of service restoration will not be as simple as it is for the passive feeders. It has to account for the presence of the associated microgrids in the feeder sections in addition to de-energized loads, reliability requirements, service priorities, and other constraints applied to FLISR. In general, the connection of microgrids may require more advanced algorithms for effectively locating and isolating the faulted feeder section and providing the best effective restoration plan.[3]

In grid-connected operation, if the micro EMS is unable to mitigate its internal intermittent DER output power, or if the microgrid is dominated by non-dispatchable DERs, it should notify the FLISR function with the aggregated forecast power. When the micro EMS is able to dispatch its internal DERs, it should also notify the FLISR with the available aggregated power capacity. These will enable the FLISR function to operate with the best estimate of the available microgrid power. Specifically, the fault location mechanism should consider the fault current contributions from microgrids in order to accurately locate the fault. In service restoration, a transition in which loads are be restored first, and then microgrids, may occur because microgrids may have been disconnected during de-energization and will not reconnect immediately when the feeder is energized again.

For the island operation, two different cases should be considered: intentional island operation and unintentional island operation. Intentional island operation is typically scheduled, so the FLISR function can be prepared for the power variation induced by disconnecting the microgrid. The fault location algorithm should remove the fault current contribution from the disconnected microgrid. Instead of the disconnected microgrid alternative power sources should be selected by the FLISR function to pick up load after isolating the fault.

In unintentional island operation condition, possibly triggered by an internal fault within the microgrid, the micro EMS is responsible for detecting the fault inside the microgrid and disconnecting the microgrid from the distribution system. The DMS should treat the disconnection as a sudden power change, and the FLISR function should be notified so that it can update the fault location algorithm by removing the fault current contribution from the microgrid, and update the service restoration scheme so as to not account for the disconnected microgrid.

4.2.4 Volt-VAR Optimization

Volt-VAR control and management in VVO will face a few challenges from the microgrid connections. The voltage profiles of a feeder circuit are determined not only by the transformer tap positions, voltage regulators, and capacitor bank status, but also by the real and reactive power outputs from microgrids at different locations along the feeder circuits.

The conventional VVO is generally designed to control capacitor banks, substation transformer taps, and feeder voltage regulators, which are all binary or discrete control variables. The VAR outputs of microgrids can change continuously, unlike the VAR outputs from capacitor banks that are integers — either “on” or “off” with an approximately fixed amount of VAR. The inclusion of the VAR resources from microgrids in the overall VVO formulation will result in a complicated mixed-integer programming problem. In other words, the VVO algorithms will need to handle mixed control variables, some in discrete and others in continuous quantities.

Another important factor to be considered is that conventional voltage regulating devices are used to control slowly evolving load changes, usually at the minutes level. Microgrid controllers are used to control fast evolving load and DER output, normally at the sub-second level. Therefore the enhanced VVO algorithms must be able to hierarchically integrate the control effects of different controllers across different time scales simultaneously. The real algorithm will be more complicated when combined with other objectives and constraints, such as the multi-interval look-ahead optimization, and the operation limits of the capacitors and voltage regulators.

A micro EMS can provide the aggregated schedule of its active power and offer its reactive power capacity to the DMS for the overall VVO of the distribution grid. The VVO formulation can treat the power factor of each microgrid as a decision variable in addition to the conventional decision variables. The DMS can send out the power factor or reactive power set point for each microgrid to maintain at the individual POI by controlling its internal DERs.

4.3 REQUIREMENTS OF AND EFFECTIVE APPROACHES TO MODIFYING ADVANCED APPLICATIONS TO SUPPORT INTEGRATION OF MICROGRIDS

Modifying the identified advanced applications to support the integration of micro EMSs will require approaches that are:

- Modular and non-vendor-specific to accommodate new functions and remove redundant functions in the system without involving the vendors.

- Flexible enough for network reconfiguration, including the addition and removal of microgrids, DERs and loads.

- Robust against corrupt data and communication failures.

The specific requirements and approaches to modifying each of the identified advanced applications to support the integration of microgrids are discussed in detail in the following sub-sections.

To facilitate effective microgrid integration, we recommend a hierarchical architecture wherein the DMS treats each microgrid as an entity with an aggregated generation and load. The micro EMS is responsible for managing its own DERs and loads. The micro EMS is also responsible for providing the DMS with its real power forecast/schedule and reactive power capacity. The DMS will regard each microgrid as an equivalent power injection node which can be added or deleted in the software design.

4.3.1 On-line Power Flow

In order to make the current power flow function in the DMS work with the microgrid's integrated distribution systems, the following are required:

1. The LF/UBLF function should have a provision to run in real time in order to accommodate the variability of microgrids.

2. In addition to the existing algorithms, a new algorithm needs to be integrated to implement and manage stochastic operation and momentary violation of the operational constraints, as well as computing real-time dynamic constraints based on the system's operational state.

3. The new algorithm should also address the issue of two-way power flow and network configuration changes.

4. The LF/UBLF function should be able to incorporate the forecast results of the microgrids, DERs and loads.

5. It should be able to handle a high volume of data with fast communication and should be robust against latency and data losses.

6. It should have a provision for data pre-processing, so that bad data can be eliminated from the measurement sets.

7. It should have the provision to add and delete a microgrid node.

A hierarchical architecture is a potential approach to enabling effective microgrid integration. In this architecture, responsibility for managing DER intermittency is assigned to the micro EMS for most part. The DMS treats each microgrid as an entity with an aggregated generation and load. With this architecture, the DMS can still use a deterministic OLPL to determine the operating state of the distribution system at the POI. Within the boundary of each microgrid, a stochastic power flow engine can be deployed to regulate the flow at the POI and handle the variability of power due to DERs.

The advantage of this architecture is that the impact of the failure of an individual micro EMS is localized or isolation-capable without affecting the broader distribution system operations, as long as the rules for interconnection are obeyed. Another benefit of this hierarchical structure is that the computational burden for the OLPF is significantly alleviated. Also, this architecture is scalable — a new microgrid can be easily added to or deleted from the distribution network model.

4.3.2 Short-Circuit Analysis

Adapting the DMS's current short-circuit analysis to support microgrid integration into the distribution system requires the following:

1. The SCA function must have a provision for incorporating the variability of microgrid output.

2. The short-circuit analysis algorithms should be modified to include the fault current contribution from microgrids.

4.3.3 Fault Location, Isolation, and Service Restoration

Adapting the DMS's current FLISR to support microgrid integration with the distribution system requires the following:

1. The fault detection and location mechanism should consider the fault current contributions from all grid-connected microgrids in order to accurately detect and locate the fault.

2. The service restoration scheme should adapt to pick up both loads and microgrids following a sequential order, i.e. loads are restored first and then microgrids.

3. The FLISR function should have access to the aggregated forecast or scheduled power from each microgrid.

4. The FLISR function should be notified of an intentional or unintentional islanding condition so that it can remove the fault current contribution from the microgrids for the proper future fault detection and location and update the service restoration scheme to not account for the disconnected microgrids.

Before starting a downstream service restoration action, the FLISR should confirm that the alternative source is energized and available to pick up the additional load to be switched. Service restoration actions performed or recommended by the FLISR should not cause any new undesirable condition, such as voltage violations or overloading conditions on any of the associated feeders. The FLISR should analyze the pre-fault loading on the faulted feeder and the available capacity on the alternative source feeders to determine whether any undesirable electrical condition would occur on the backup feeder with the proposed switching actions. If any portion of the interrupted load cannot be restored by the FLISR due to any limitation, it should notify the operator with an alarm or event message.

4.3.4 Volt-VAR Optimization

Adapting the DMS's current VVO function to accommodate microgrid integration requires the following:

1. The VVO function must be able to handle mixed control variables, some in discrete and others in continuous quantities.

2. The VVO algorithm should adopt a hierarchical control architecture that can coordinate the centralized optimization of conventional regulating devices as well as microgrid controllers. The unified optimization formula must be able to integrate control effects from different controllers across different time scales simultaneously.

3. The VVO formulation should be scalable and flexible, so that it can handle any number of microgrids.

4. The VVO should be able to access the microgrid, DER, and load forecasting for multiple time intervals.

5. The VVO must be able to interface with other DMS modules to receive a high volume of meter and sensor data with fast communication and must be sufficiently robust against communication latency and data loss.

6. The VVO should have a provision for bad-data detection to identify bad measurements to ensure the performance of the VVO function.

The VVO function should have a "fail-safe" design. That is, no control action that would produce any unacceptable voltage or loading conditions should be requested by the DMS as a result of the failure of any DMS component or any other reason. IEDs used on feeder devices should possess a "heartbeat" function to detect loss of communication with the master station within a given time period, such as 10 minutes. This time period should be flexibly configurable. The VVO function should periodically check that the feeder IEDs are under VVO monitoring using the "heartbeat" functionality of the controller. If the local controller fails to communicate with the VVO central processor for a specified time period, the controller should revert to local (standalone) control. When a VVO component is out of service for any reason (controller failure, loss of communication, controller manually bypassed, or blown capacitor fuse), the DMS should continue to operate in these abnormal situations, if possible, without producing unacceptable voltage and loading conditions, using the remaining DMS components.[3]

SUMMARY AND CONCLUSION

This report provides a comprehensive impact analysis for interactive operation of microgrids and the distribution system based on a multi-scale modeling framework. The findings from this report serve as a general guideline for integrating micro EMS and DMS and a corresponding interconnection and operational analysis.

We started by covering the aspects of microgrid operation modes and strategies on connection and disconnection with the distribution system, and we analyzed the interactions and operation impacts in both microgrids and the distribution system for both connected and disconnected operation modes. The communication requirements, such as the data quality and latency issues between DMS and the integrated micro EMS under various operation scenarios, were discussed as well.

We defined the micro EMS functions, responsibilities, control and operation logic by means of which microgrids are integrated with the DMS through standard interface strategies. Specifically, the report identifies twenty-one use cases for microgrid operations to facilitate the analysis, including normal operation, emergency, and faulted conditions. Each use case provides the operation rules and control strategies of microgrids and micro EMS, the operation rules and control strategies for distribution system and DMS, and the interactions and operation impacts on both microgrids and distribution systems.

Online monitoring of microgrid operation conditions, and the corresponding strategies for power quality monitoring, are also analyzed in this report. Specific analyses conducted include the identification of microgrid operation quantities for online monitoring of power quality, the identification of online monitoring strategies for microgrid power quality, and the evaluation of the effectiveness and efficiency of the online monitoring strategies.

One of the potential benefits of a microgrid is that it can reduce additional costs associated with utility-supplied electricity, so this report also discussed power dispatch for multiple microgrids integrated with the distribution utility and markets. We identified the microgrid pools, including multiple microgrids participating in the joint power dispatch, defined the dispatch and operation rules applied to microgrid pools by the distribution utility and markets, and analyze the interaction of the power dispatch for microgrid pools with the distribution utility and markets.

A critical enabler for large-scale integration of microgrids with the distribution system is the proper protection coordination between DMS and micro EMS. This report analyzed several aspects of this protection coordination, including identifying protection schemes of DMS in active distribution networks and the protection schemes of microgrids, defining the requirements of micro EMS and DMS protection functions for coordination with each other, and analyzing the protection coordination between DMS and micro EMS in various event scenarios.

As the distribution grid integrates more microgrids and DERs, advanced applications in the DMS are facing a series of new challenges. Developing new applications or modifying the key advanced applications in the DMS to support the integration of micro EMS is an immediate necessity. This report recommends the following steps to tackle these challenges. First, identify all the major advanced DMS applications that are significantly affected by the integration of micro EMSs. Next, analyze the impacts of the integration on the identified individual advanced DMS applications, and finally, define the requirements and the effective approaches to developing or modifying the identified advanced applications to adapt to the integration of the micro EMS.

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APPENDIX

In either grid-connected or disconnected (island) operation mode, a microgrid should meet specific operation requirements, such as maintaining an acceptable voltage profile, grid frequency, synchronization, and load following. In grid-connected mode, a microgrid can exchange energy with the local utility of the distribution grid, following a predefined schedule between the DMS and the microgrid in normal operation, and can provide mutual support in abnormal conditions. In the disconnected mode, the microgrid should be able to balance its internal load demand by its own energy resources and maintain the same level of voltage quality and grid frequency. It should also be able to reconnect to the distribution grid when requested, which involves resynchronizing with the grid.

Operation strategies of microgrids should include the following requirements:

A.1 RESPONSE TO NORMAL CONDITIONS

A microgrid should be able to perform proper operation functions under normal operating conditions. The following subsections introduce some basic requirements based on the IEEE 1547 standard.

A.1.1 Voltage Regulation

A microgrid should be able to regulate the voltage within a certain range at the active POI as requested by the DMS, and should not cause a voltage violation at the POI or any other point in the distribution grid, as defined in the American National Standard Institute's C84.1-1995, Range A standard.

A.1.2 Coordinated Grounding with the Distribution Grid

A microgrid must have a proper grounding scheme that should be well coordinated with the distribution grid to avoid the occurrence of any possible overvoltage or safety issues in the microgrid or the distribution grid. The grounding scheme in the microgrid may also coordinate with the protection scheme in the distribution grid to avoid any possible interference with the existing ground fault protection logic.

A.1.3 Synchronization

When a microgrid is to connect to the distribution grid, it should go through a synchronization process (which may be automatically checked by the synchronization relay) to ensure that its voltage level, frequency, and phase angle across the connection switch meet the synchronization criteria before closing the connection switch. No voltage or power disturbances to the distribution grid may be tolerated during the synchronization process; the synchronization process should be aborted if any severe disturbance occurs during the process. Upon the completion of the synchronization process, the energy exchange may be ramped to the committed target at a predefined ramping rate.

In the grid-connected mode, a microgrid may operate in parallel with the distribution grid through a single active POI or multiple POIs. For synchronization between the microgrid and the distribution grid at each POI, the voltage fluctuations should be within ±5% of the prevailing voltage level and the requirements for limiting voltage flicker should also be fulfilled.

When multiple active POIs co-exist, wheeling paths among the POI may be formed that are likely to remain unnoticed by the distribution grid operators. Such a situation should be eliminated. Voltage fluctuation imposed by circulating power among POIs should also be avoided.

A.1.4 Inadvertent Energization of the Distribution Grid

The microgrid must cease to energize the distribution grid at any POI when the grid is de-energized.

A.1.5 Monitoring Provisions

If the capacity of the interfacing device at each POI is more than 250 kVA, monitoring of its connection status may be performed, including the monitoring of real power output, reactive power output, and voltage at the POI.

A.1.6 Isolation Device

When required by the distribution grid, isolation devices may be equipped with circuit breakers at each POI of the microgrid.

A.1.7 Interconnect Integrity

The microgrid should be able to withstand electromagnetic interference (EMI) environments in accordance with the IEEE C37.90.2-1995 standard.

It should also be able to withstand voltage and current surges as defined in the IEEE C62.41.2-2002 or IEEE C37.90.1-2002 standards.

A.2 RESPONSE TO ABNORMAL CONDITIONS

The microgrid should operate properly during abnormal conditions, as shown in the subsections below. This guidance also follows the requirements presented in the IEEE 1547 standard.

A.2.1 Distribution Grid Faults

In the case of a distribution grid fault, the microgrid should cease to energize the faulted and de-energized grid at any POI. Meanwhile, power balancing inside the microgrid should be performed.

A.2.2 Distribution Grid Reclosing Coordination

When a microgrid operates in island mode, it may be energizing a portion of the isolated distribution grid through a POI. The microgrid should cease to energize the isolated portions of the distribution grid at any POI prior to reclosing. Power balancing inside the microgrid should be achieved prior to reclosing, and zero power exchange should be maintained after reclosing until it is ready to start transaction schedules.

A.2.3 Voltage Requirements

Voltage at the POI of the microgrid should be monitored in case a fault occurs. If the voltage at the POI is within a range shown in Table 6, the microgrid should cease to energize the distribution grid at the POI. The clearing times for each of the different fault voltages are also shown in Table 6.[2] [4] At a POI with a capacity greater than 30 kW, the voltage set point should be field adjustable, and the clearing time shown in Table 6 is the default value. If the microgrid is disconnected from the distribution grid, the power balance inside the microgrid should be maintained.

Table 6 Interconnection System Response to Abnormal Voltages

Default Settings		Range of Adjustability
Voltage Range (% of Base Voltage)	Clearing Time (s)	Clearing time: adjustable up to and including (s)
V < 45	0.16	0.16
45≤ V <60	1	11.00
60 < V< 88	2	21.00
110 < V< 120	1	13.00
V≥ 120	0.16	0.16

A.2.4 Frequency Requirements

When the system frequency falls within a range listed in Table 7, the microgrid should cease to energize the distribution grid at the POI. The clearing time for different faulted frequencies is shown in Table 7.[2] [4] If the microgrid is disconnected from the distribution grid, the power balance inside the microgrid must be maintained.

Table 7 Interconnection System Response to Abnormal Frequencies

	Default Settings		Ranges of Adjustability	
Function	Frequency (Hz)	Clearing Time (s)	Frequency (Hz)	Clearing time (s) adjustable up to and including
Under Frequency (UF) 1	< 57	0.16	56 – 60	10
Under Frequency (UF) 2	< 59.5	2	56 – 60	300
Over Frequency (OF) 1	> 60.5	2	60 – 64	300
Over Frequency (OF) 2	> 62	0.16	60 – 64	10

A.2.5 Reconnection to Distribution Grid

Reconnection of the microgrid can take place when the voltage is within the range of 88% to 110% of the base voltage and the frequency is within the range of 59.3 Hz to 60.5 Hz.

Reconnection at the POI should include an adjustable or a fixed delay (e.g., five minutes). Power balance inside the microgrid should be guaranteed after reconnection during this time period. Potential wheeling paths when multiple POI are reconnected may be allowable

A.3 VOLTAGE/VAR, FREQUENCY, AND LOAD FOLLOWING

A microgrid is generally not powerful enough to influence the frequency of the distribution grid significantly; however, it should maintain synchronization at the POI with constant power exchange by following the committed transaction schedules with minimum deviation and minimum accumulated inadvertent energy exchange. The DMS should closely monitor the voltage profiles and power fluctuations at the POI in real-time operation. The microgrid should be able to respond quickly to its internal load and generation changes or disturbances so there will be minimum impacts on the distribution grid at the POI. In case of significant generation shortage or surplus, a new power exchange between the distribution grid and the microgrid should be scheduled, or the action of load or generation shedding may be launched in order to maintain the load balancing.

A microgrid should have sufficient capability to maintain the standard voltage profile and frequency range, which requires that the microgrid has sufficient energy resources for both real and reactive power generation to balance its load demands in normal operation, especially for the disconnected operation mode, in which it has only its own resources.

The DMS of the distribution grid should maintain healthy voltage profiles for the feeder circuits where one or more microgrids may be connected. In addition, a microgrid is responsible for assisting the DMS in maintaining the desirable voltage at the POI. The microgrids may offer their additional reactive capacities and resources to the DMS for the overall voltage/VAR optimization of the distribution grid. The DMS can also provide or recommend the optimal voltage or VAR settings for the individual POI of each microgrid. The conventional VVO algorithms in the DMS are designed for controlling the on/off states of the capacitor banks at the feeder circuits and distribution substations, the substation transformer tap positions, and the voltage regulator taps at the feeder circuits, all in binary or discrete 50 quantities. With the microgrid and DER connections, the reactive power and voltage controls may be continuously adjustable quantities within certain ranges. This arrangement will introduce new challenges to the VVC algorithms because they have to handle mixed control variables, some in binary and others in continuous (adjustable) quantities.

A.4 CONNECTION TO AND DISCONNECTION FROM THE DISTRIBUTION GRID

A microgrid should be capable of connecting to and disconnecting from the distribution grid and should disconnect from the distribution grid when encountering faults in the distribution grid that are not cleared in a timely manner. Power balance inside the microgrids should be ensured after the disconnection. If there are multiple POIs, the microgrid should disconnect from the distribution grid at all POIs when the distribution grid is in a severe fault condition, so that the microgrid can completely cease to energize the faulted distribution grid. If a fault occurs inside the microgrid and the local protection mechanism fails to clear the fault within the allowable time, the microgrid should also disconnect from the distribution grid at the POI to avoid further impact on the distribution grid. When the fault is clear, the microgrid can reconnect to the distribution grid. Sufficient delay time is required to ensure the normal status of the grid. This delay time can be either adjustable or fixed (e.g., five minutes).

A.5 INTERNAL PROTECTION

A micro EMS should be capable of detecting any internal fault occurring anywhere in its internal grid. When an internal fault is detected, the faulted circuit or the POI should be tripped to ensure that the fault will not cause an operation problem in the distribution grid, and the faulted circuit section should be isolated to enable the microgrid to restore service to the healthy sections of the faulted circuit. Power balancing within the microgrid should be done after isolating the faulted section or disconnecting from the distribution grid.

Microgrid connections will result in two-way power flows on the distribution grid. The protection scheme in the distribution grid should be adjusted accordingly to cover the multisource contributions of short-circuit currents from different directions to the point of faulting. At a minimum, the distribution grid must implement a directional over-current protection scheme that can support different short-circuit current settings for different fault directions. It is important to note that the protection scheme must be defined in the planning stage. With increasing DER penetration, operators must also modify the protection scheme to ensure the successful integration of the micro EMS and the DERMS into DMS. The distribution grid will generally be an active network with the connections of DERs and microgrids. These local generation resources will introduce significant dynamic changes, conventional static protection schemes, and settings that may not cover all possible scenarios. For this reason, modifications should be made during operations to mitigate the impact of DERs. For example, some of the DERs may be on and off occasionally, and the rest of the DERs in connection may or may not be significant short-circuit current sources, depending upon their energy conversion types (inverter-based DERs may not be significant fault current contributors). The operation topology of the distribution grid may also be dynamically adjusted or reconfigured owing to changes in dynamic operation conditions. Protection schemes and settings should be adjusted so as to adapt closely to operation condition changes. These settings will not only require more reliable remote relay-setting mechanisms but also higher cybersecurity requirements for the protection schemes. In addition, it may also be necessary to strengthen the original protection mechanisms at the POI to isolate the faults occurring in the internal circuit of a microgrid and keep them from having severe impacts on the distribution grid. Another modification of the existing protection scheme is synchronization at the POI. A microgrid should implement a synchronization scheme at the POI for connecting to the distribution grid, in addition to the protection schemes isolating the faults occurring on the grid side or in the internal circuit. The synchronization logic should automatically control the corresponding energy resources to adjust the microgrid frequency and voltage to levels that match the distribution grid at the POI. The synchronization relay can lead to reconnection to the grid by automatically checking the differences in voltage, frequency, and phase angle across the connection switch at the POI.

A.6 MICROGRID CONTROL WHILE INTEGRATED WITH DMS

A microgrid’s local energy resources and load management should have sufficient monitoring and control capabilities to do the following: (1) maintain synchronization with the distribution grid, (2) maintain the desirable voltage profile at the POI and its internal grid, and (3) quickly respond to changes in internal load and generation as well as disturbances from the distribution grid or the internal grid. Operation conditions at the POI should be monitored or visible to the DMS of the distribution grid. The connection switch at the POI may also be controllable by the DMS for emergency disconnection.

A.7 MICROGRID BLACK START

Microgrid black start is the restoration process after a blackout. It involves a set of rules to be followed for system restoration. The following sequence of actions should be carried out in order to restore the low voltage distribution grid after a general blackout [5]:

- Disconnect all loads.
- Run the microgrid in multiple standalone islanded systems, supplying the local loads.
- Synchronize the islands together according to synchronization criteria.
- Connect the controllable loads depending on available capacity of storage and total generation.
- Connect the non-controllable energy sources (i.e. PV and wind) without battery storage capability.
- Increase the loads.
- Synchronize the microgrid with the main grid.

A.8 ENERGY TRANSACTIONS AND WHEELING BETWEEN THE DISTRIBUTION GRID AND MICROGRID

Power exchanges or energy transactions between the distribution grid and a microgrid should be fully monitored by both the DMS and the microgrid and be directly controlled by the microgrid to follow the committed transaction schedule. Energy transactions between the distribution grid and a microgrid are counted as net quantities from any active POI of the microgrid. When more than one active POI is involved, energy wheeling will be more likely to occur. An example of energy wheeling is when one party delivers a certain amount of power to another through one POI and receives some amount of power from another POI. Operators may need to avoid such wheeling in normal operation, although it may be needed in emergency support and therefore must be well coordinated between the two parties. A wheeling path through a microgrid will form a looped operation condition for both the distribution grid and the microgrid, which may result in operation difficulties, including impacts on the protection mechanism, voltage and VAR control, and load flow distribution, if the grids are configured to operate in radial configuration. However, under emergency conditions, such wheeling can be useful in providing alternative paths to deliver power to consumers and helpful in maintaining voltage profiles for the grid. When microgrids are owned by the utility that owns/operates the distribution grid, the microgrid control systems may be embedded into the DMS as sub-functions or applications. This structure permits the scheduling of energy exchanges to be optimized in the same domain as the entire distribution grid. In this case, there may be no need for independent optimization of individual microgrids.

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