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Facility Microgrids

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General Electric Global Research Center
Niskayuna, New York

Subcontract Report
NREL/SR-560-38019
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Executive Summary

Over the past several decades, the North American power grid has evolved into four large interconnected networks that are continuously regulated by sophisticated power-flow control equipment. These grids are robust to most perturbations, but their vulnerability is evident in incidents such as the Aug. 14, 2003, blackout. To avoid such problems, actions must be taken to reduce stress and congestion on this overtaxed transmission and distribution system. Incremental changes to grid infrastructure will not achieve the reliability needed in a digital society; new infrastructures and operational concepts must be explored.

In the Department of Energy's vision of the electric power infrastructure, "Grid 2030" [1], microgrids (also called minigrids) are one of three technical cornerstones. Microgrids are envisioned as local power networks that use distributed energy resources and manage local energy supply and demand. Although they would typically operate connected with a national bulk power transmission and distribution system, they would have the ability to pull themselves off the grid and function in island mode when necessary to increase reliability for the local load.

Microgrids are receiving a considerable interest from the power industry, partly because their business and technical structure shows promise as a means of taking full advantage of distributed generation. Concepts for microgrids fall into two categories:

1. Systems that are intended to always be operated in isolation from a large utility grid
2. Systems that are normally connected with a larger grid.

Conceptually, the isolated microgrid is like a scaled-down version of a large-scale utility grid. Many of the technical requirements are the same. However, there are distinguishing features because of the nonconventional generation contemplated for microgrid applications. These types of generation include power electronic interfaces and are sometimes intermittent in nature (for example, wind and solar power). To supply reliable, quality power, the microgrid must have mechanisms to regulate voltage and frequency in response to changes in customer loads and system disturbances. The penetration of distributed generation in an isolated microgrid is, by definition, 100%. All power comes from the distributed generation within the microgrid.

The grid-connected microgrid is integrated with the bulk grid. The penetration of distributed generation on a grid-connected microgrid could approach or even exceed 100%. The microgrid is designed and operated such that it appears to be a single predictable and orderly load or generator to the bulk grid at the point of interconnection. This arrangement provides several advantages:

- DG owners may be able to rate and operate their generation more economically by exporting power to (and importing it from) the microgrid.
- Local customers may be able to have continued service (although possibly at a reduced level) when connection with the host utility is lost.
- The microgrid can be controlled to be an active asset to bulk system reliability (for example, by providing spinning reserve or black-start services).

- The host utility may be able to depend on the microgrid to serve local customers so substation and bulk power infrastructure do not need be rated (or expanded) to meet the entire load.

The business and regulatory environments presently do not favor (or allow) multiparty microgrids (those in which power and services are exchanged with third parties over regulated power distribution infrastructures). In fact, in many jurisdictions, the interchange of power between adjacent properties, even if it does not involve public utility infrastructure, is illegal as a violation of the monopoly franchise granted to the utility.

The result is that individual entities, such as industrial and institutional facilities, represent the first generation of microgrids. The entities that turn to distributed generation for their power needs are the "first adopters" from which industry understanding and best practice can evolve. The explorations of microgrids in this report are focused on these single-business-entity microgrids. For clarity, these are called "facility microgrids."

This report investigates three key issues associated with facility microgrids:

- Multiple-distributed generation facility microgrids' unintentional islanding protection
- Facility microgrids' response to bulk grid disturbances
- Facility microgrids' intentional islanding.

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1 Introduction

1.1 Background

1.1.1 The Definition of Microgrids

Forming a definition for microgrids has been a difficult and elusive endeavor. Most agree that important elements include co-located power generation sources, energy storage elements, and end-use loads. However, opinions differ about the aggregated generation capacity that should be contained within the power system and whether there should be a single point of common coupling with the main grid or multiple coupling points.

In this report, microgrids are power systems in which generation elements are co-located with loads, regardless of the aggregated generation capacity or the grid interconnection. This definition covers a large application space that ranges from remote rural electrification and residential/community power networks to commercial, industrial, municipal, hospital, campus, and military base power grids. The applications also vary. Some are focused on cost of electricity (e.g., peak shaving), some are focused on local resource use (e.g., wind, solar, biomass systems), and some are focused on energy reliability and security (therefore, sophisticated generation and load controls are required).

1.1.2 Technical Issues

1.1.2.1 Interconnectivity

The complexity of the interconnection between a microgrid and the main grid is affected by the types of power generation on the microgrid, the number and location of points of interconnection with the main grid, and the penetration level of microgrid systems with the main grid.

1.1.2.1.1 Power Generation Types

For a microgrid that uses conventional generation, such as natural gas or diesel reciprocating engines, system design and engineering is relatively well-understood. However, for many emerging microgrids that use alternative energy sources—such as fuel cells, photovoltaics, and microturbines—system design and integration with the main grid are a challenging task because of a lack of experience with nonconventional generation types.

1.1.2.1.2 Points of Interconnection

Most grid-connected microgrids have a single point of interconnection with the bulk grid. The interconnection requirements are relatively well-defined for the single interconnection point. However, large-scale microgrids and microgrids that seek grid-connected reliability through redundancy may require multiple interconnection points. The coordination of control and protection becomes more complicated as the number of interconnection points increases.

The location of the point of interconnection can also have an effect on the design and performance of a microgrid. If the microgrid is in a remote area, as is the case with some village and industrial plants, the grid can be weak because voltage and frequency regulation are not tight. In these situations, transient dynamics in the grid can have a significant effect on system voltage regulation and stability. Additional difficulties can arise when microgrids are connected with a secondary grid network or a spot network. In these situations, the control and protection algorithms are more complicated than those used when connecting with a radial distribution system.

1.1.2.1.3 Penetration Level

System events such as lightning strikes, equipment failures, and downed power lines are commonplace in the bulk grid. Microgrids are typically expected to respond to these events by tripping offline to protect themselves until the grid recovers. However, if the bulk grid is populated with a multitude of microgrids and several of these entities are net power exporters to the bulk grid, response behavior could be detrimental. Ideally, the bulk grid would expect the microgrids to cope with, and help recover from, system events.

One aspect of this challenging requirement is referred to as low-voltage ride-through capability. This capability would not only maintain high availability for the microgrids but also demonstrate "good citizenship" with the bulk grid by enhancing resiliency.

1.1.2.2 Intentional Islanding

Although grid-connected microgrids can be designed with the capability of isolated operation, the transition between grid-parallel and standalone operation can be challenging. In some cases, the microgrids will be expected to shut down once the main grid is lost and then start back up to continue to supply local loads. The power outage to the local loads could last between seconds and minutes, depending on the black-start time of the generation assets within the microgrids. In many cases, however, a disruption or transient effect to the loads within the microgrids will not be acceptable. For these systems, a seamless transition control is needed. This transition process is called intentional islanding.

To prevent the large voltage and frequency transients that follow the loss of the main grid, the intentional islanding control must be capable of maintaining voltage and frequency regulation while exhibiting fast transient disturbance rejection qualities. The distributed generation (DG) must be able to support transient and temporary currents far in excess of the connected load demand because of magnetizing inrush and motor dynamics. Intentional islanding will be one of the most significant challenges for making grid-connected microgrids an attractive solution for high-reliability customers.

1.2 Scope and Objectives

In most applications, multiple DG units are used in a facility microgrid. Similar to a single DG unit, the facility microgrid is required to detect unintentional islanding and isolate itself from the host utility at the point of common coupling. However, most anti-islanding protection and control schemes are developed and tested for a single DG unit isolated from other DG.

The interactions and effects on the overall detection at the point of common coupling are not fully investigated when multiple DG units operate in parallel. One example is the impedance detection scheme. This scheme requires a current signal injection, a terminal voltage measurement, and then a calculation of the impedance. The islanding can be detected by monitoring the impedance changes. When multiple DG units with the same scheme operate in parallel, the measured voltage may be diluted and result in no impedance change under islanding condition. To avoid this, all DG should be synchronized with their injection signals. However, synchronizing the injection signals may be impractical for two reasons:

1. It discourages a plug-and-play autonomous operation approach because of the synchronization link.
2. Unless the DG units are from the same vendor, the injection signals for will be different at particular frequencies or magnitudes, which makes the dilution effect more unpredictable.

Active anti-islanding control is another approach commonly used for DG. The interaction among multiple DG units with active anti-islanding control is not fully explored. The first objective of this report is to investigate the interaction and effectiveness of anti-islanding protection for multiple DG units with proposed General Electric active anti-islanding controls. Cases with multiple inverter-based DG units and multiple machine-based DG units are investigated, and recommendations for applying the General Electric schemes to multiple DG units are made.

A facility microgrid is normally connected with the host utility macrogrid, or area electric power system (Area EPS). Depending on the design, operation philosophy, and contractual arrangement with the host utility, the facility microgrid is most likely to rely on the host grid for a portion of its power, with the balance being generated by the DG imbedded in the microgrid. One issue is that facility microgrids are subject to host utility disturbances. The response of the facility microgrid will, in turn, affect the host utility dynamics. The second objective of this report is to explore these dynamics.

One of the most attractive aspects of facility microgrids is their potential to separate, or island, from the grid. In the simplest sense, this provides a higher level of reliability for the facility than can be obtained from the grid alone. This extra reliability is often the primary motivation for considering individual applications of DG, and it easily expands to the microgrid. To realize these benefits, the DG in the microgrid must have, at the least, additional controls. The third objective of this report is to investigate the facility microgrid system intentional islanding behaviors and control strategies.

1.3 Report Outline

The report is organized by the following sections:

- Facility microgrid unintentional islanding protection with multiple DG units
- Facility microgrid dynamic response under fault events
- Facility microgrid intentional islanding dynamics.

2 Facility Microgrid Unintentional Islanding Protection

Typically, a facility microgrid has multiple distributed generators. The unintentional islanding protection developed for a single DG unit may not work for multiple DG units operating in parallel. This section investigates the effectiveness of the active anti-islanding control developed for a single DG unit when it is applied to multiple DG units. The combinations of multiple DG units include multiple inverter-based DG units, multiple machine-based DG units, and multiple inverter- and machine-based DG units.

2.1 Multiple Inverter-Based Distributed Generation

Two typical schemes are used for inverter-based DG [2]: the active voltage scheme, shown in Figure 1, and the active frequency scheme, shown in Figure 2. These schemes were proposed by General Electric. Detailed discussion can be found in an earlier report [2].

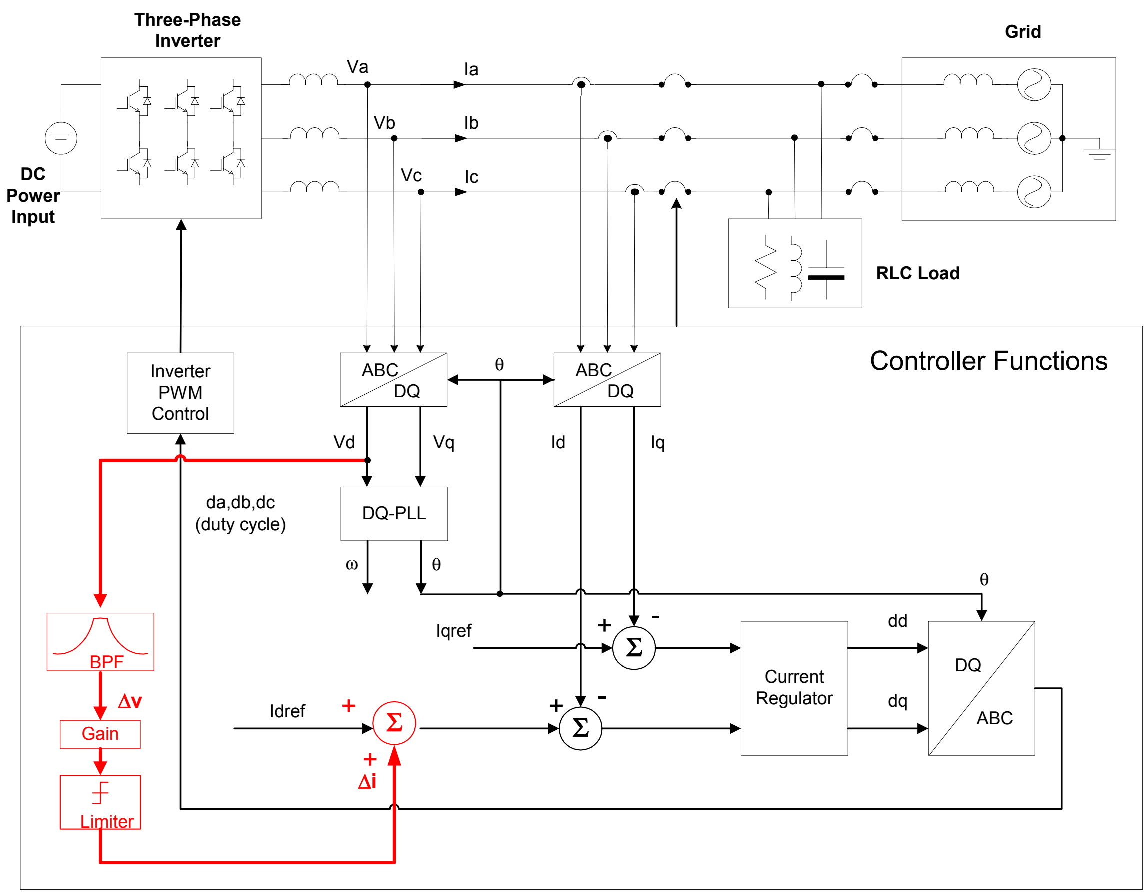


Figure 1. Active voltage scheme for inverter-based distributed generation

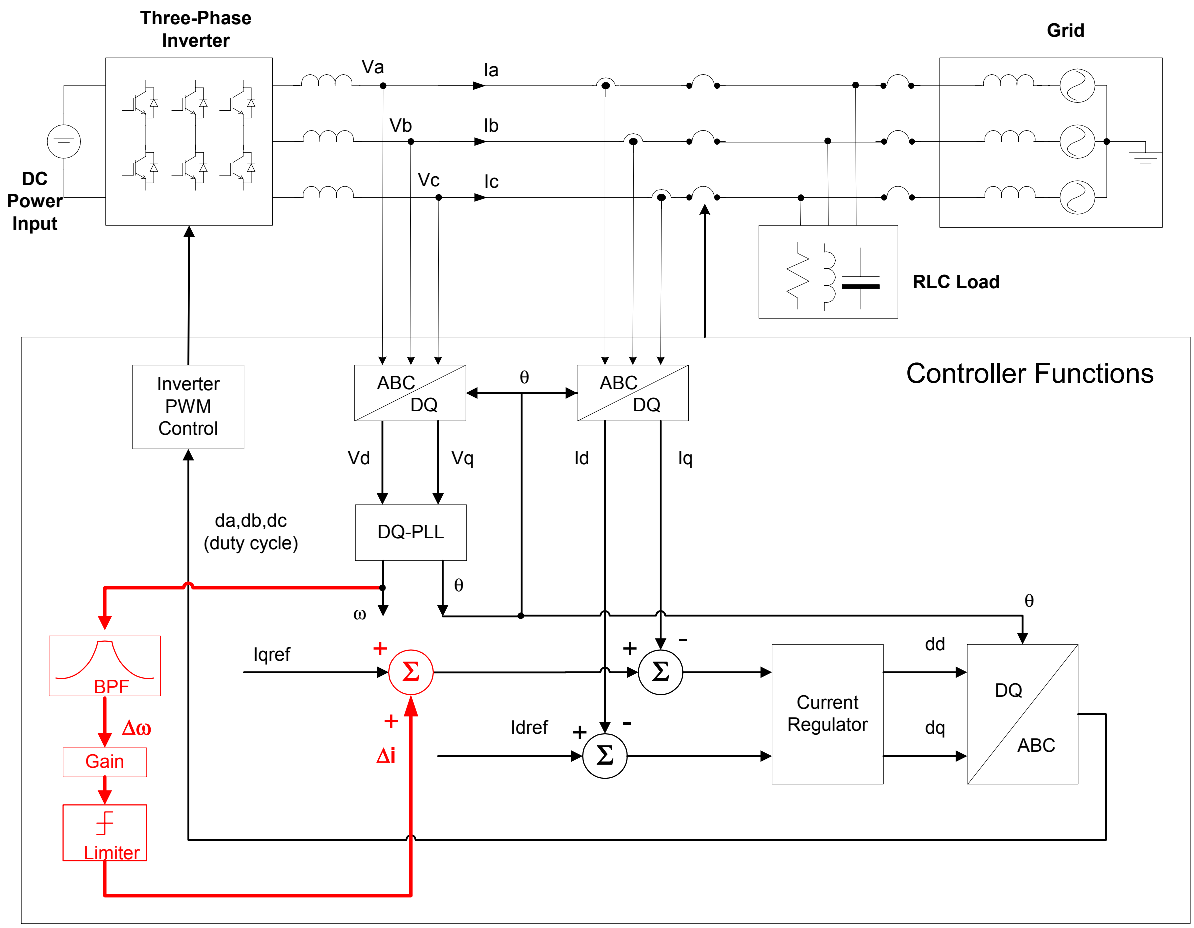


Figure 2. Active frequency scheme for inverter-based distributed generation

For demonstration and simplification, two inverter-based DG units with the same rating were used to illustrate the effect of multiple DG-unit parallel operation. The conclusion drawn from the study can be extended to more than two DG units and to units with different ratings. The studies were carried out in PSCAD. The overall system includes two inverters with impedance in between, RLC load, and a grid with impedance.

Prior to the islanding, the inverters' total output is well balanced by the load (i.e., zero power exchange with the utility). This constitutes the worst case for islanding detection, although in most practical cases, islanding occurs after faults. Seven cases, as defined in Table 1, were simulated.

- Case 1 is the base case. In it, both inverters have no active anti-islanding control enabled. Figure 3 shows that the voltage and frequency stay within nominal ranges after islanding.
- In Case 2, only one DG unit has active anti-islanding control. Figure 3 shows that the voltage and frequency are within nominal ranges after islanding. That means the overall system, including the DG with anti-islanding control, will fail the unintentional islanding detection within the required time.

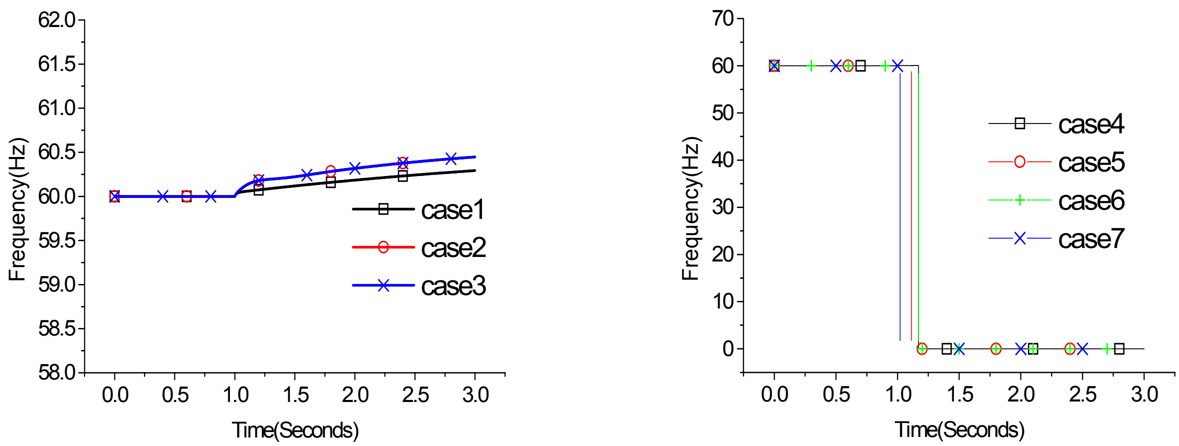
- In Case 3, one DG has only the voltage scheme, and the other has only the frequency scheme. The detection failed.
- In Case 4, both DG units have the same voltage scheme, and the unintentional islanding can be successfully detected.
- In Case 5, both DG units have the same frequency scheme, and the unintentional islanding can be successfully detected.
- Cases 6 and 7 are similar to cases 4 and 5, respectively, except there is an impedance between the two DG units' point of common coupling. For cases 1–5, the two DG units are directly connected at their terminals without any impedance in between.

Table 1. Case Studies for Inverter-Based Distributed Generators

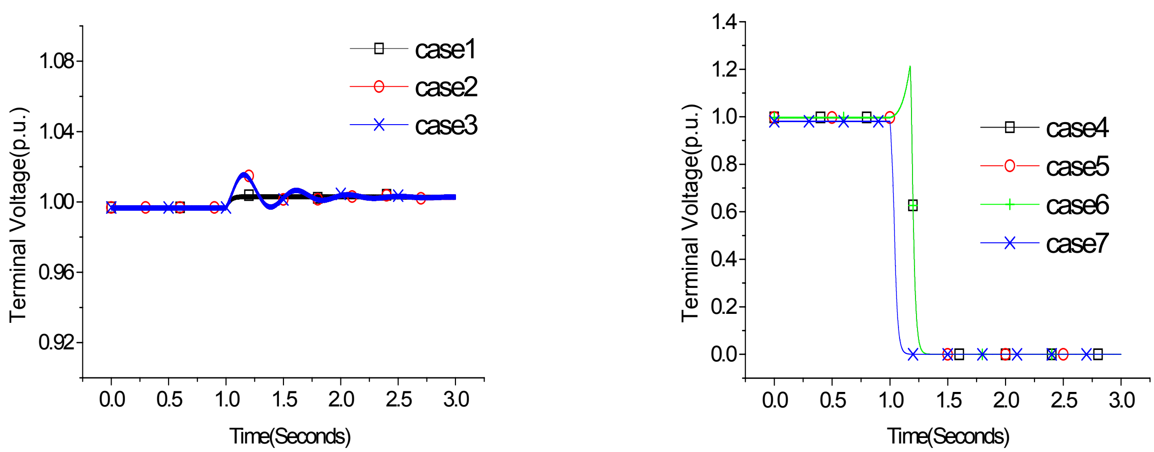
	DG1		DG2		Line Impedance Between DG	
	Voltage Scheme	Frequency Scheme	Voltage Scheme	Frequency Scheme	Resistance (pu)	Inductance (pu)
Case 1					0.0	0.0
Case 2	Enabled	Enabled			0.0	0.0
Case 3	Enabled			Enabled	0.0	0.0
Case 4	Enabled		Enabled		0.0	0.0
Case 5		Enabled		Enabled	0.0	0.0
Case 6	Enabled		Enabled		0.0	0.2
Case 7		Enabled		Enabled	0.0	0.2

The results from the simulations are:

- When both DG units are equipped with the same anti-islanding control, the unintentional islanding can be detected successfully.
- When multiple DG units with active anti-islanding control operate in parallel, the impedance (up to 0.2 pu simulated) between the DG terminals has little effect on the schemes. This indicates the geographical separation of the DG units within a microgrid is insignificant as far as the active anti-islanding protection is concerned.
- Even though each scheme works for a single DG unit, the unintentional islanding detection may fail when some DG units have no active anti-islanding control or use different schemes. This phenomenon can be analyzed and explained with the Middlebrook extra element theorem [3]. Detailed analysis is not presented in this report. However, the concept is that one DG unit's active anti-islanding control loop gain can be reduced by another DG unit that has no active anti-islanding control. If the loop gain is reduced significantly, the anti-islanding control becomes ineffective and the overall parallel DG units are not able to detect the islanding.



(a) Frequency (Hz) in response to the islanding at t = 1s



(b) Terminal voltage (pu) in response to the islanding at t = 1s

Figure 3. Simulation results in PSCAD for a two inverter-based distributed generation system

2.2 Multiple Machine-Based Distributed Generation

Figure 4 shows the anti-islanding controls for synchronous machine-based DG. Two schemes can be implemented for machine-based DG [4]: an active power scheme, programmed as part of the governor control, and a reactive power scheme, programmed as part of the excitation control. These schemes were proposed by General Electric in an earlier report [4].

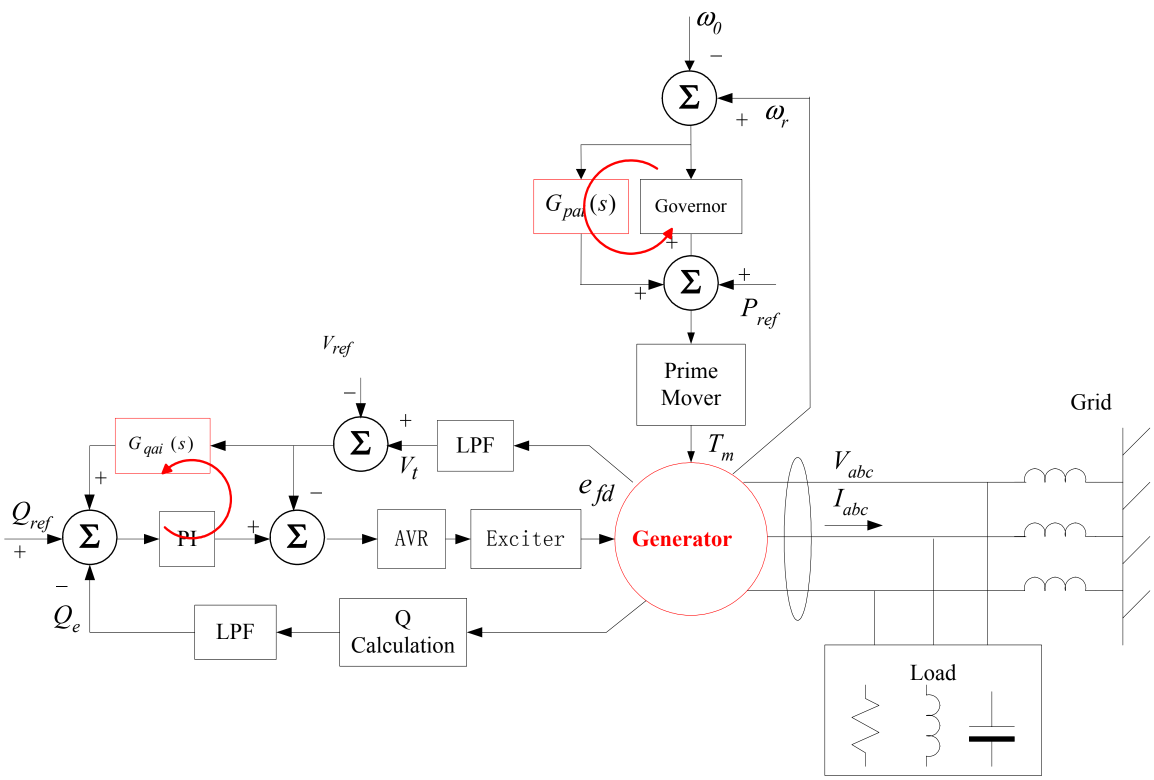
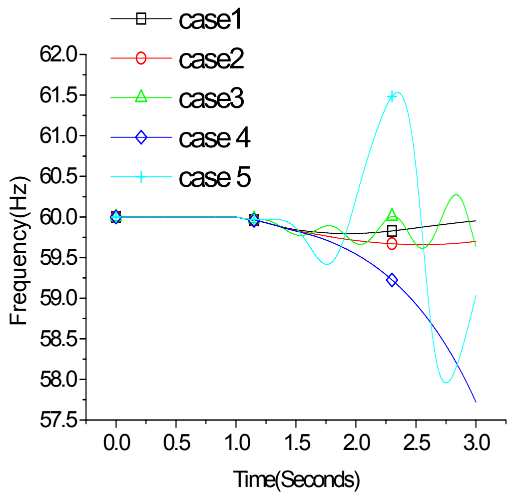


Figure 4. Schematic of the machine with the anti-islanding compensators

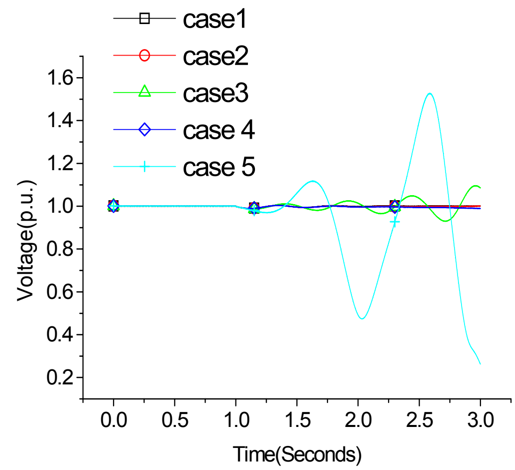
Two machine-based DG units were used to illustrate the effect of multiple-machine DG in parallel operation. The simulations were carried out in PSCAD. Table 2 shows the simulation cases. Figure 5 shows the simulation results.

Table 2. Case Studies for Machine-Based Distributed Generation

	DG1		DG2	
	Active Power Scheme	**Reactive Power Scheme**	**Active Power Scheme**	**Reactive Power Scheme**
Case1				
Case2	Enabled			
Case3		Enabled		
Case 4	Enabled		Enabled	
Case 5		Enabled		Enabled



(a) Frequency in response to the islanding



(b) Terminal voltage in response to the islanding

Figure 5. Simulation results in PSCAD for the interconnection of two machine-based distributed generation systems

The results from the simulations are:

- Similar to the case of inverter-based DG, when both machine-based DG units are equipped with the same anti-islanding control, the unintentional islanding can be detected successfully (as in cases 4 and 5).
- Even though each scheme works for a single DG unit, the unintentional islanding detection may fail when some DG does not have the same active anti-islanding control (as in cases 2 and 3).

2.3 Multiple Inverter-Based and Machine-Based Distributed Generation

The mixture of inverter-based DG and machine-based DG presents a design challenge for any anti-islanding scheme. With the penetration of distributed resources continuously increasing, this situation will become common, and the performance of the anti-islanding protection must be tested in this context.

This mixture condition has not yet been explored extensively. First, the interactions between inverter-based DG and machine-based DG in the island are unknown. Second, existing active anti-islanding schemes have been developed with the assumption of either machine-based DG or inverter-based DG. The schemes for machine-based DG and inverter-based DG are not necessarily compatible because of their different mechanisms.

The distinct feature of active schemes is a positive feedback that breaks down the active or reactive power balance to cause voltage or frequency trips. This mechanism must be preserved and unaffected when multiple DG units of different types and power ratings operate in parallel. Based on this principle, the most effective combination is to have the inverter apply the frequency scheme and the machine apply the reactive power scheme. This combination will lead to effective islanding detection.

The other combinations are not as effective, as indicated by simulation studies. Figure 6 shows the simulation results with the inverter equipped with the frequency scheme and the machine equipped with the reactive power scheme. Once islanded, the frequency and voltage of the inverter-machine-load system drift away quickly so the under/over frequency/voltage relay will detect the islanding.

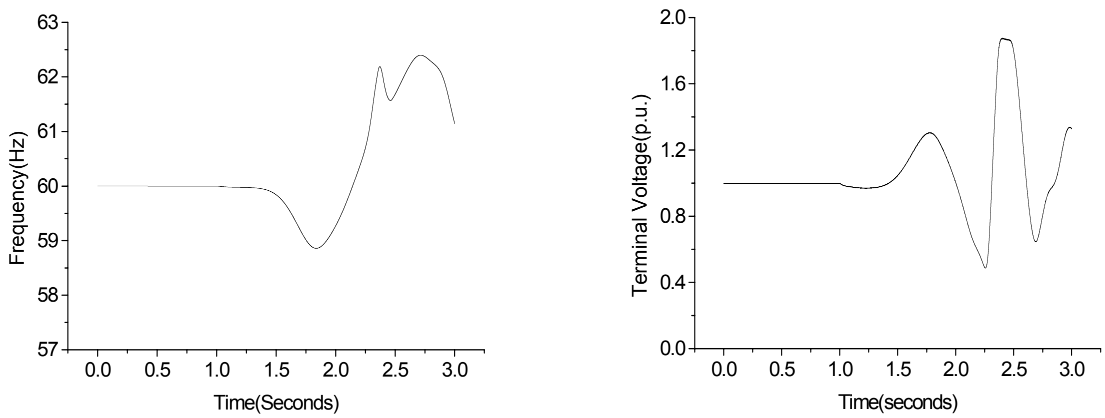


Figure 6. Islanded system frequency and voltage with mixed inverter and machine distributed generation

2.4 Summary

This chapter investigated the performance of active anti-islanding schemes when applied to multiple DG units. Three combinations of the DG have been studied: multiple inverter-based DG, multiple machine-based DG, and a mixture of inverter- and machine-based DG.

Effective strategies to ensure islanding detection have been identified. These strategies are:

- If a facility microgrid is composed of only inverter-based DG, the anti-islanding scheme applied to each DG should be the same (either the active voltage anti-islanding scheme or the active frequency anti-islanding scheme). They therefore can be designed and operated independently. No communication link is needed.
- If only machine-based DG is present in an island, each DG unit should be designed with the same anti-islanding scheme (either the active power anti-islanding scheme or the reactive power anti-islanding scheme). This way, they can be designed and operated independently.

- If the inverter-based DG is mixed with machine-based DG, each inverter-based DG unit should be equipped with the active frequency anti-islanding scheme, and each machine-based DG unit should be equipped with the reactive power anti-islanding scheme. With this combination, the DG units can be designed and operated independently.

Beyond the context of planned microgrid applications, these results raise concerns about the DG anti-islanding performance and qualification testing standards specified in Institute of Electrical and Electronics Engineers standard 1547 (IEEE 1547) and Underwriters Laboratories standard 1741 (UL 1741) when multiple DG units are installed on an Area EPS circuit. Both standards provide for testing of anti-islanding performance on a single-unit basis. The results imply that, unless the anti-islanding protections of the separate DG units are compatible and coordinated, the standards do not protect the grid and its customers from potentially damaging and dangerous islanding situations.

3 Facility Microgrid Fault Event Case Studies

The facility microgrid is normally connected with a host utility (macrogrid, or Area EPS). Although it depends on the design, operation philosophy, and contractual arrangement with the host utility, the facility microgrid is likely to rely on the host grid for a portion of its power, with the balance being generated by the DG in the microgrid. One immediate concern is the potential for microgrids to alter the local dynamics of a specific subsystem or distribution feeder. This becomes a concern when there is a significant penetration of microgrids relative to the total load power on a feeder.

3.1 Facility Microgrid System Description

A relatively simple facility with a variety of loads and DG was used to investigate facility microgrid dynamic behaviors. A one-line diagram of the system that shows the loads, DG, and power flow for the base condition is shown in Figure 7. It includes most basic distribution system components expected to be important for investigation of fundamental frequency performance issues.

The facility has a main 13.8-kV service bus with multiple laterals that serve individual blocks of load. The loads are a variety of motors with different dynamic characteristics. The facility connects with a host utility at a point of common coupling at 115 kV. The 115-kV system is greatly simplified, with two equivalent lines leading to an equivalent hub node. Two 6 MVA DG units are connected with the main facility bus through individual transformers. The model, although simple, is suitable for investigating the performance of microgrid applications.

The line and transformer impedances for the system are shown in Figure 8. In the figure, reactances appear below the line and are given on a 100-MVA base. Each bus is labeled with a name, node number, the initial voltage in per unit, and the initial voltage in kilovolts. Circles with “m” are motors.

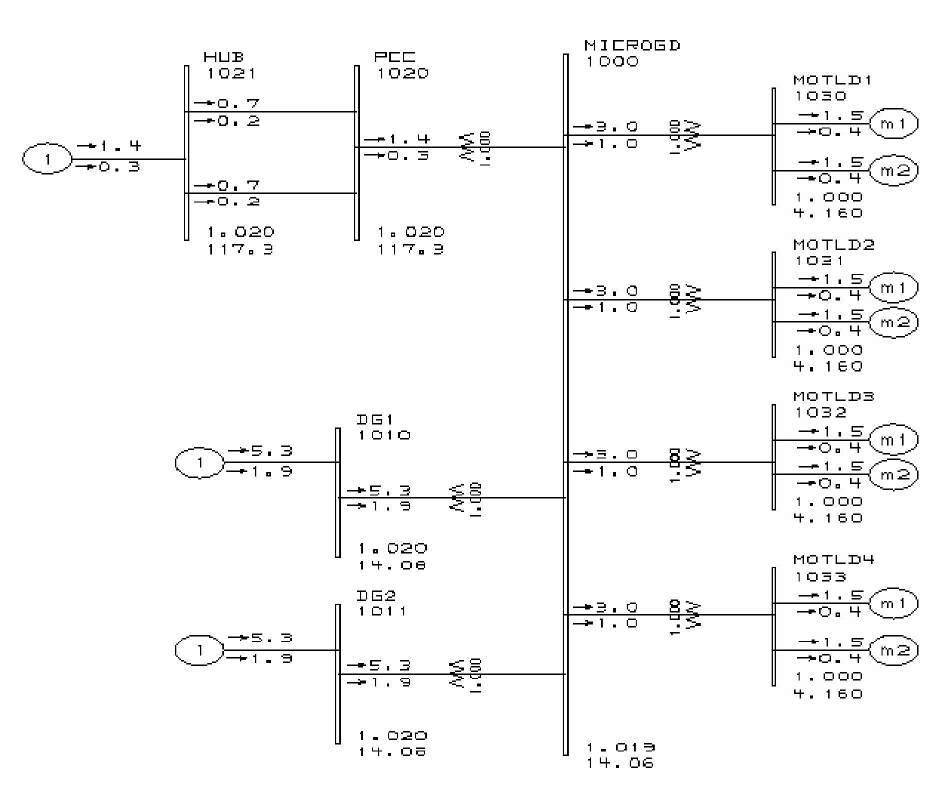


Figure 7. One-line diagram of the facility microgrid – active and reactive power flows

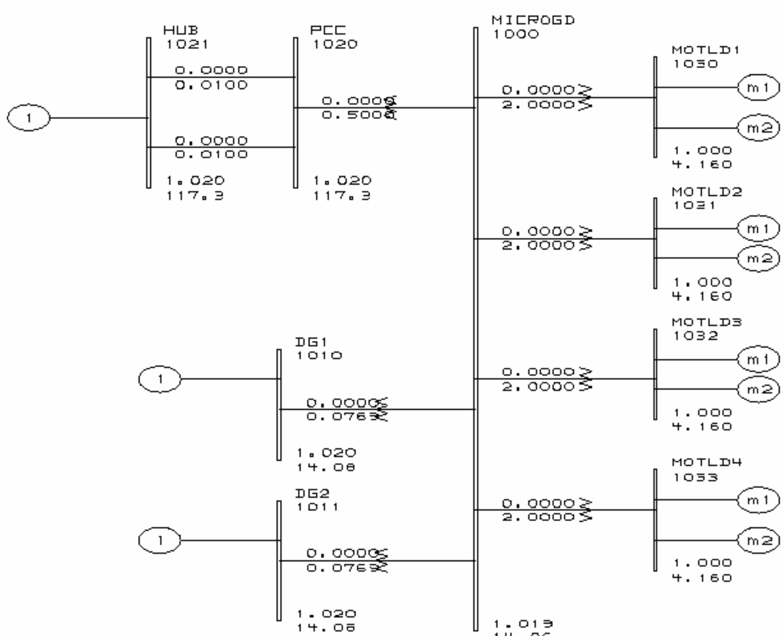


Figure 8. One-line diagram of the facility microgrid – network impedance

3.2 Case Studies

The initial condition for disturbances studied is with some power imported, as shown in Figure 7. In this case, about 10% (1.4 MW) of the facility power is imported.

Figures 9–12 show the response of the facility microgrid to a fault on the host system. The event simulated is a fault at the midpoint of one of the two 115-kV lines from the point of interconnection to the system equivalent hub. The fault is cleared by removal of the faulted line, which leaves the connection of the microgrid with the host system weakened. Each of the four figures shows a different system variable for this event. In each figure, five traces show different DG technologies and controls. In this chapter and the next chapter, the active anti-islanding controls discussed in the previous chapter are not used for the DG.

For each figure, the five traces correspond to:

- Dark blue: No DG, only loads are presented in the facility
- Pink: Inverter-based DG with full controls (voltage and frequency regulation with droop)
- Red: Machine-based DG with full controls (conventional voltage regulator/excitation and frequency regulation/governor, both with droop)
- Light blue: Inverter-based DG with power dispatch (passive) mode (no voltage and frequency regulation)
- Purple: Machine-based DG with power dispatch (passive) mode (no voltage and frequency regulation).

Figure 9 shows the voltage at the motor loads within the facility, Figure 10 shows the active power exchange between the facility microgrid and the host macrogrid, and Figure 11 shows the speed of some of the motors in the facility. Figure 12 shows the current drawn by the loads.

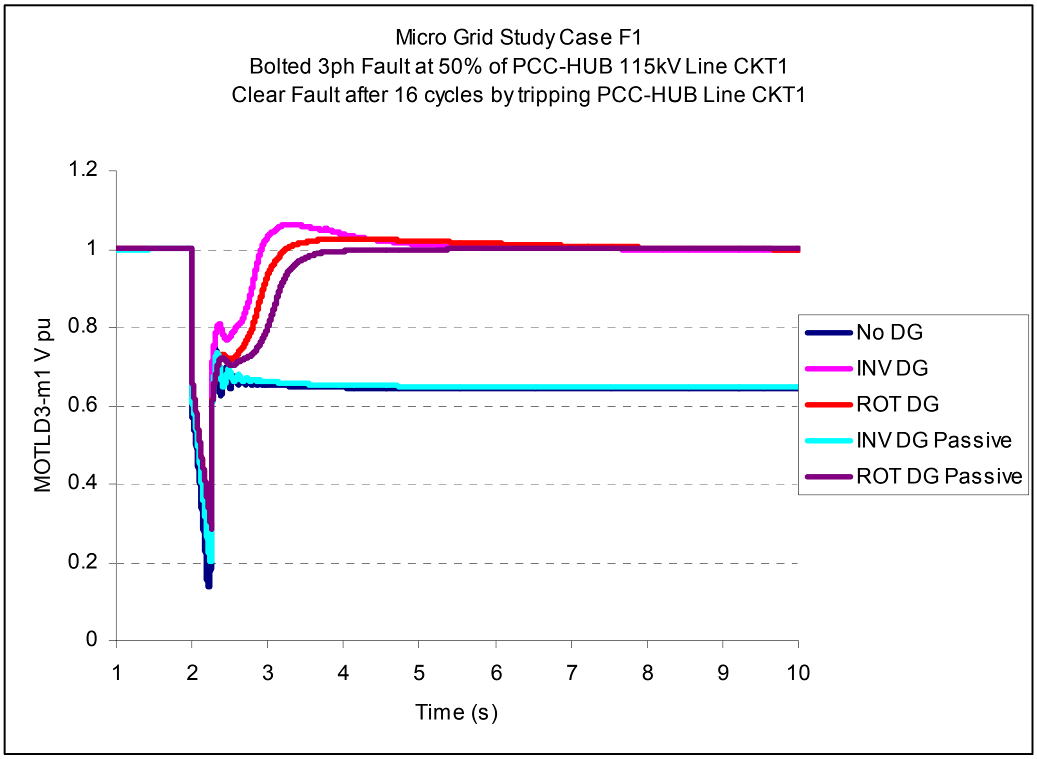


Figure 9. Microgrid load bus voltage following non-islanding grid disturbance

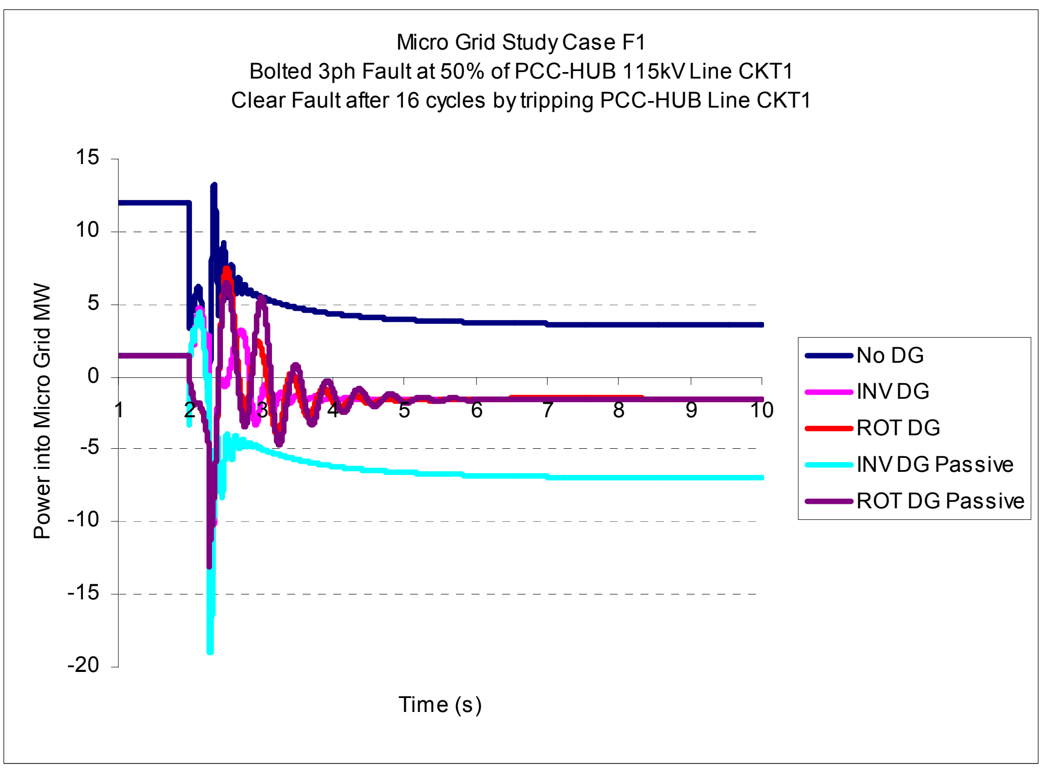


Figure 10. Active power into microgrid following non-islanding grid disturbance

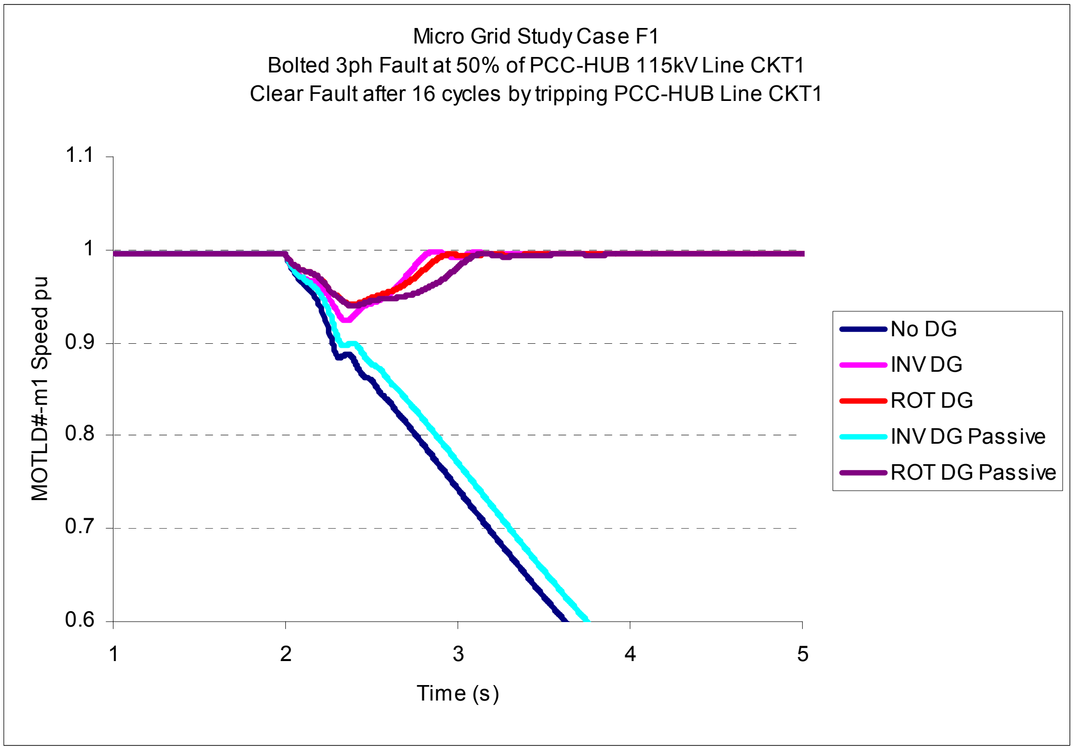


Figure 11. Microgrid load motor speed following non-islanding grid disturbance

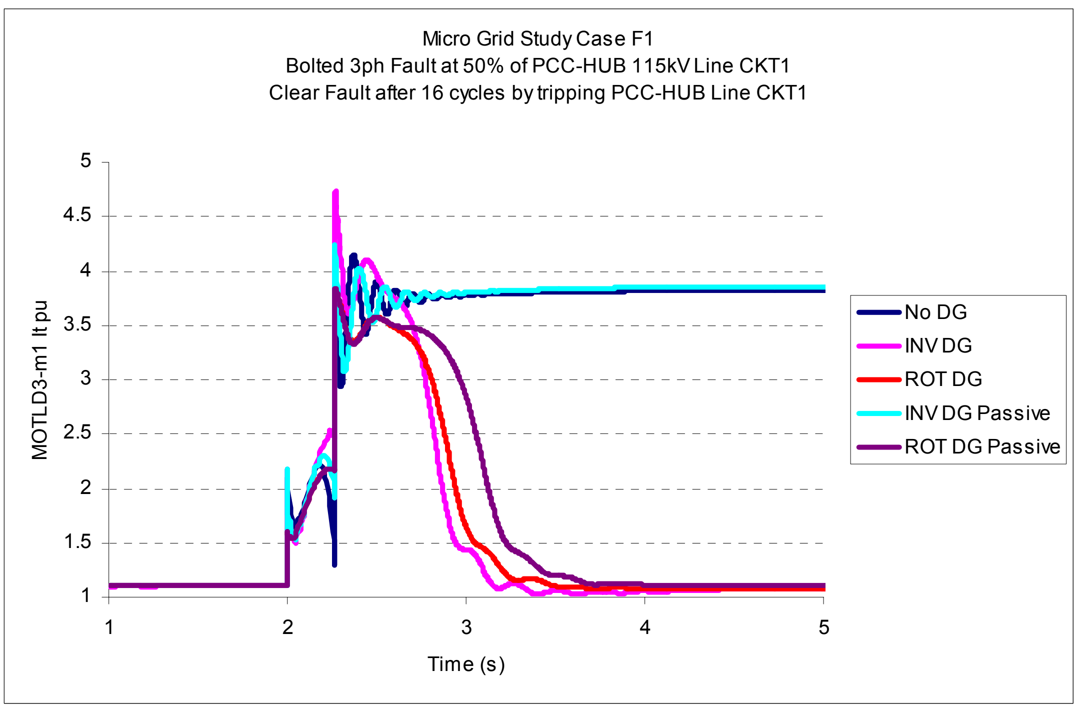


Figure 12. Microgrid load current following non-islanding grid disturbance

3.3 Observations

A number of observations were made from these cases:

- The behavior of the system is significantly different for each set of assumptions. The cases with no DG and with the power dispatch (passive) mode inverter-based DG fail to recover from the fault (i.e., the load in the facility is disrupted, and the facility would likely trip some or all of its load and DG). The collapse of the motor speed is evidence of the failed recovery; the motors have stalled and, in the process, collapsed the voltage. As a result of the collapsed voltage, the motors cannot restart and the voltage cannot recover.
- Failed recovery is disruptive not only to the microgrid load but also to the host grid. This is evident in the high currents drawn after the load stalls. This could cause false trips of protective relaying and possibly result in outage of other customers on the host grid. The addition of controls (voltage and frequency droop regulation mode) for both types of DG allows a successful recovery, and all parties benefit.
- The presence of DG in the microgrid with appropriate controls can be beneficial to both the microgrid (DG owner) and grid. (The no-DG case failed.)
- The machine-based DG with dispatch mode was more benign than the inverter-based DG with dispatch mode. This may be because of the inherent mechanical (and magnetic) inertia of the machine, which may make recovery naturally easier. Conversely, the best performance results were from the inverter-based DG with full control (voltage and frequency regulation). (Here, "best performance" is based on fastest recovery to normal voltage and speed.) This is not surprising. Inverter-based technologies are more controllable and more dependent on good control—different faces of the same nature of the equipment.

4 Facility Microgrid Intentional Islanding Case Studies

4.1 Intentional Islanding Needs

One of the most attractive aspects of a facility microgrid is its potential to separate, or island, from the grid. Although the microgrid can be designed with the capability of isolated operation, the transition between grid-parallel and standalone operation can be challenging. In most applications, the microgrid will be expected to shut down when the main grid is lost and then start back up to supply local loads. The power outage to the local loads could last between seconds and minutes, depending on the black-start time of the generation assets within the microgrid. In some cases, however, a disruption or transient effect to the loads within the microgrid is not acceptable. For these systems, a seamless transition control is needed.

This transition process is called intentional islanding. Although islanding allows the microgrid to recover, the microgrid will be exposed to voltage deviations caused by grid faults before islanding can be accomplished. Therefore, a grid-connected microgrid cannot be viewed as a means of disturbance-free performance, but a microgrid can improve power supply availability for critical loads. Loads subject to transient voltage disturbances (e.g., data centers) will still need an uninterruptible power supply device to ride grid disturbances, but the amount of energy storage in the uninterruptible power supply can be reduced if the load is supplied by a microgrid.

Intentional islanding can be preplanned or unplanned. Unplanned intentional islanding imposes greater challenges than preplanned intentional islanding. First, the loss of the main grid must be detected. Second, to prevent the large voltage and frequency transients that follow the loss of the main grid, the intentional islanding must maintain voltage and frequency regulation while exhibiting fast transient disturbance rejection qualities. The islanded system will then impose very large transient currents on its generation because of magnetic inrush when the microgrid is isolated from the faulted grid. (These highly distorted currents are not simulated in the power frequency simulations discussed here but need to be addressed when an actual microgrid is designed.)

Different levels of power balance (power import/export from the bulk grid) impose different challenges for unplanned intentional islanding. The case of closer power balance (minimal power import/export) is a worse case for loss of grid detection but a better case for smooth transition from grid-connected to island mode. The case of large power imbalance (large power import/export at the point of common coupling) is a better case for loss of grid detection but a worse case for transition because of large transient.

The ability of a microgrid to survive loss of connection with the host utility depends on a number of factors. The microgrid must have sufficient dynamic regulating capability to tolerate the changes in active and reactive power flow that will result from loss of the utility tie. This means at least some of the DG must have both voltage and frequency regulation functions. If the microgrid imports power from the main grid, once it is islanded, not all of the load within the facility can be supplied. In this case, non-essential load (which can be predefined) must be disconnected to allow for secure operation of the critical load. The ability to differentiate between critical and noncritical load is a major reliability consideration and potential advantage for a facility microgrid.

4.2 Case Studies

This section examines facility microgrid behavior under islanding events. The events are unplanned and followed by system faults that cause loss of the main grid. The facility microgrid system is as presented in Chapter 3.

Figures 13, 14, 15, 16, and 17 show the response of the facility microgrid to faults at the point of common coupling that result in a trip of the microgrid from the host system. The events simulated are faults at the terminal 115-kV point of common coupling cleared by removal of the microgrid main transformer. In one pair of cases, the fault is bolted (i.e., has no fault impedance) and more severe than the other pair of cases, in which some fault impedance is assumed.

Each of the following five figures shows a different system variable for this pair of events. In each figure, there are four traces. These traces correspond to:

- Dark blue: Inverter DG for bolted three-phase fault
- Pink: Rotating DG for bolted three-phase fault
- Red: Inverter DG for impedance fault
- Light blue: Rotating DG for impedance fault.

Voltage and frequency regulation are a prerequisite for islanded operation. The cases with power dispatch mode are not studied in this chapter. Thus, only cases with full control are considered. The two fault events are intended to illustrate that having these controls is a necessary condition; it may not be sufficient to ensure successful islanding. The dynamics of tripping from grid connection to islanded operation can be very important.

Figure 13 shows the voltage at the motor loads within the facility, and Figure 14 shows the main bus voltages with the facility microgrid. Figure 15 shows the reactive power output of one of the DG units in the facility, and Figure 16 shows the active power output. Figure 17 shows the currents delivered by one of the DG units in the facility.

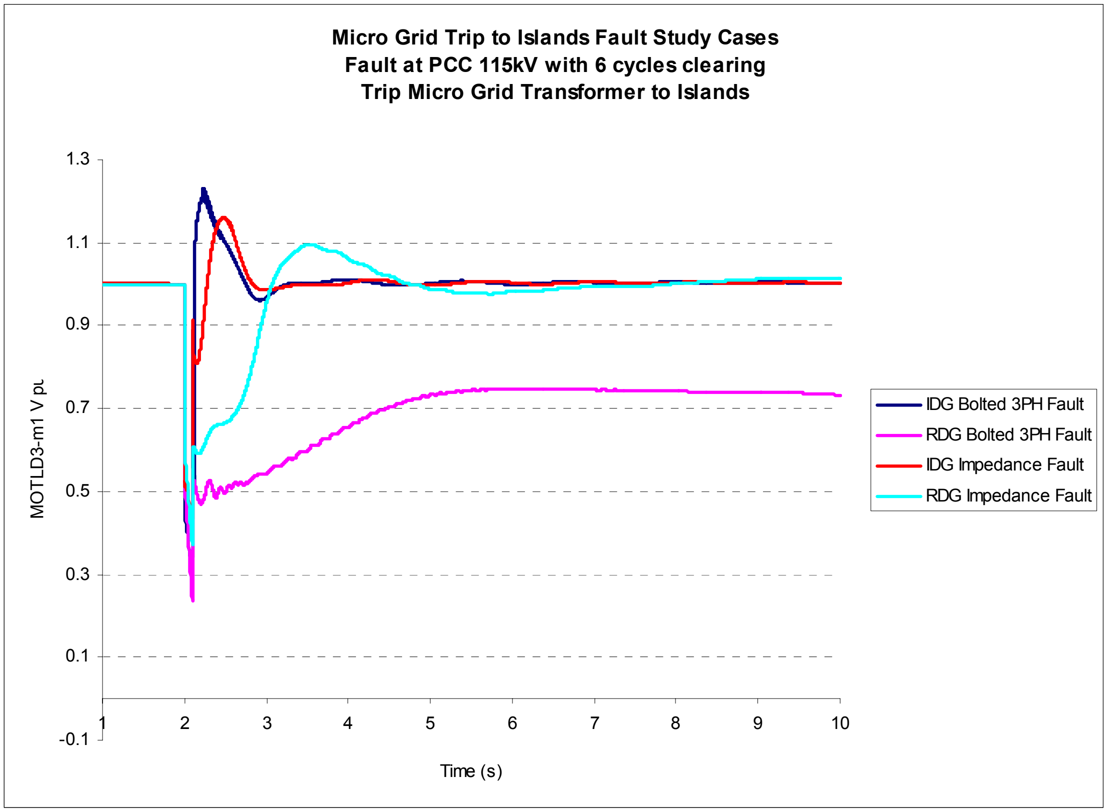


Figure 13. Microgrid load voltage following grid disturbance and trip to island

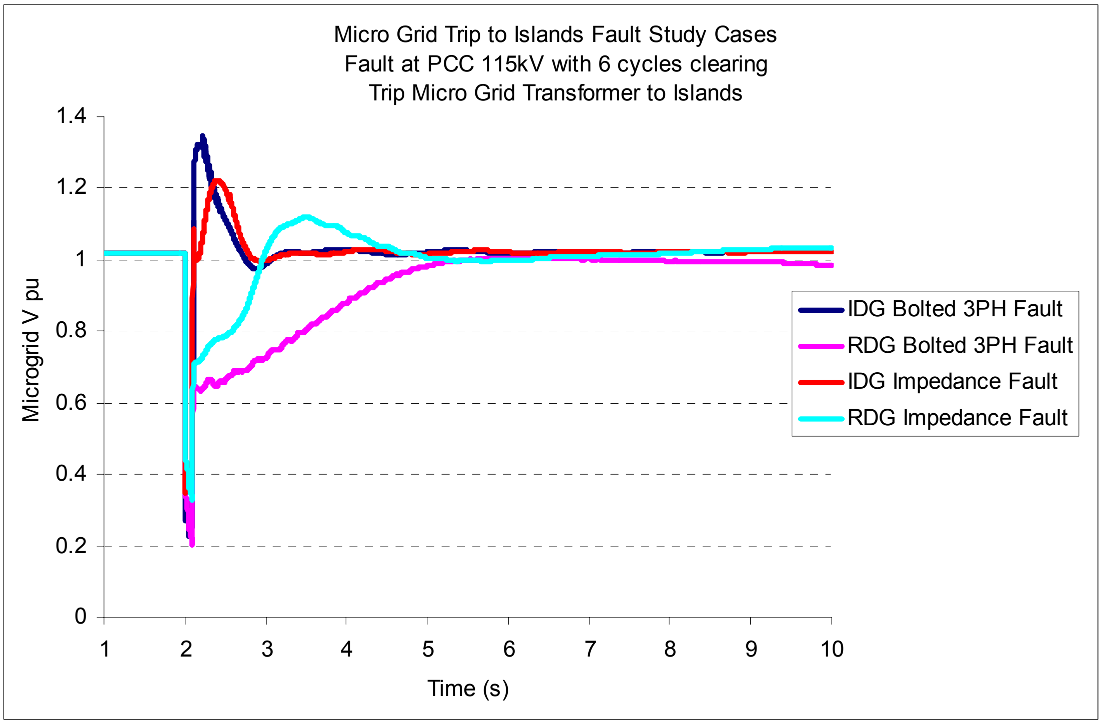


Figure 14. Microgrid main bus voltage following grid disturbance and trip to island

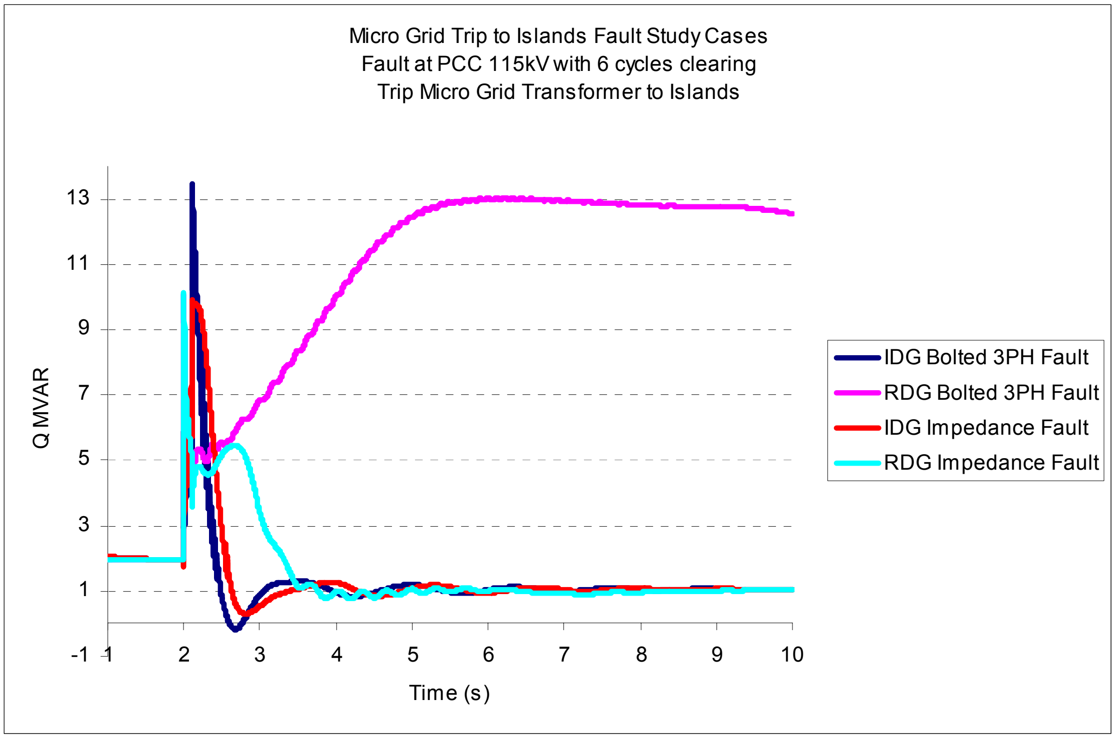


Figure 15. Microgrid distributed generation reactive power output following grid disturbance and trip to island

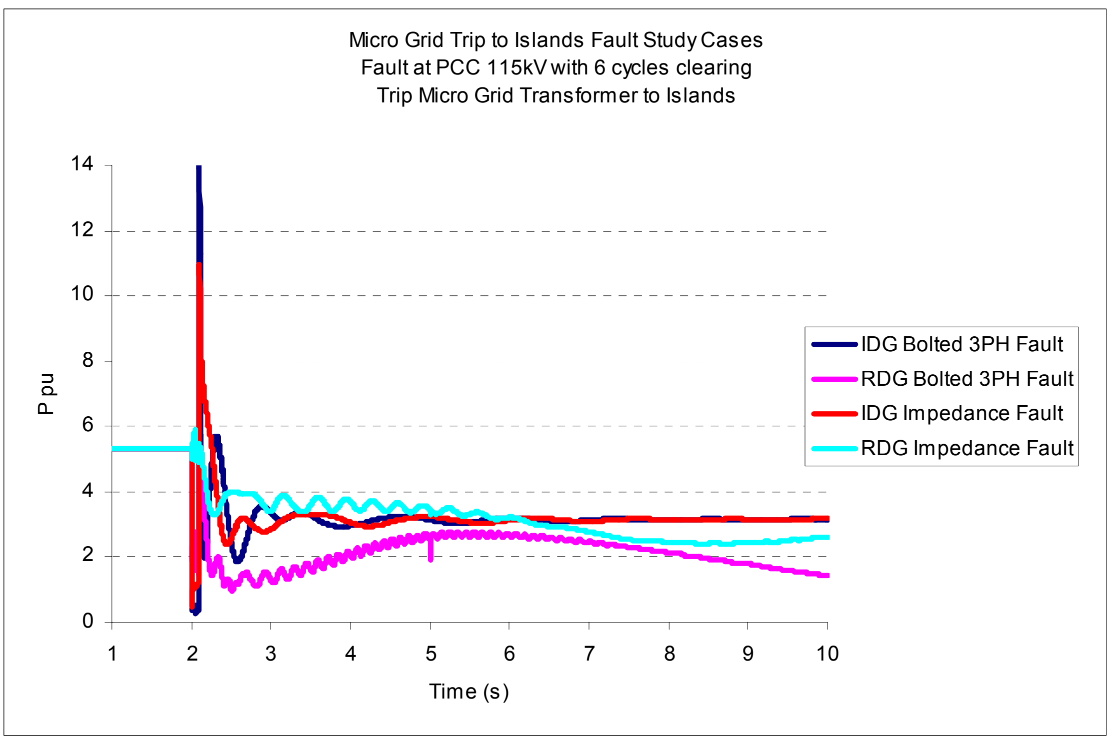


Figure 16. Microgrid distributed generation active power output following grid disturbance and trip to island

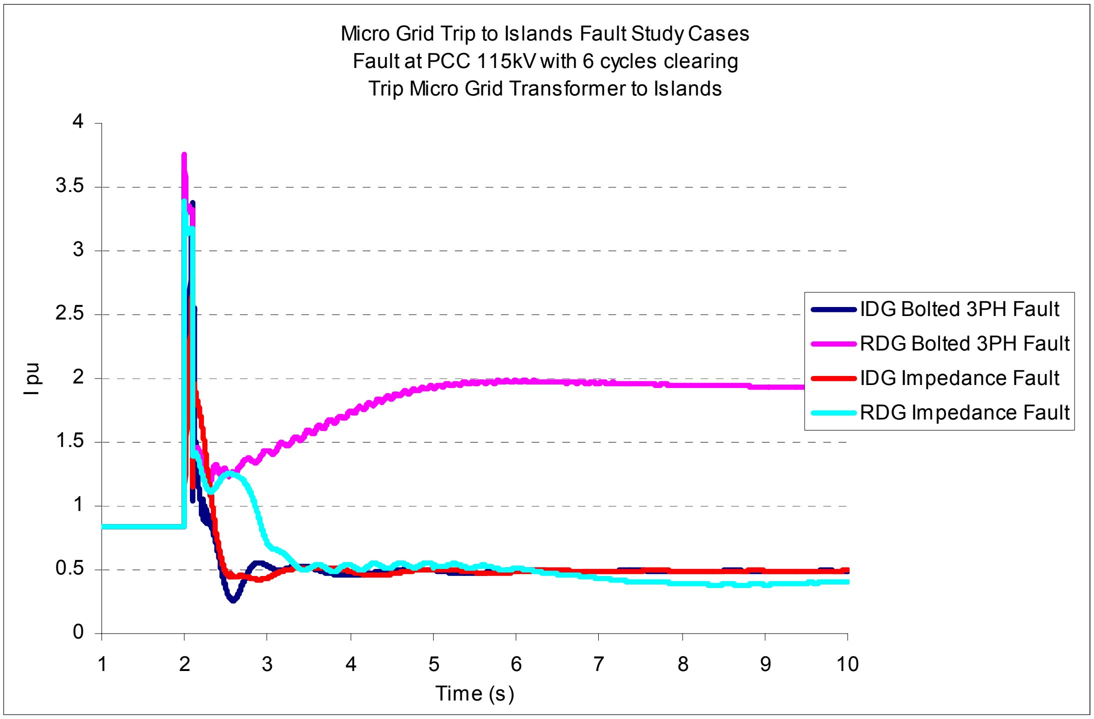


Figure 17. Microgrid distributed generation current following grid disturbance and trip to island

4.3 Observations

A number of observations were made from these cases. First, and most important, for this particular microgrid, not all of the load within the facility can be served when the microgrid trips to islanded operation. In all cases, roughly half of the load in the facility is tripped. Nonessential load is disconnected to allow secure operation of the critical load. The ability to differentiate between critical and noncritical load is a major reliability consideration and a potential advantage for a facility microgrid. In these cases, facility microgrid control disconnects the non-essential load after the transformer circuit breaker opens and creates the island. The transient swings of the system variables reflect the dynamics of the loads responding to the fault and their interaction with the DG controls.

Second, the microgrid fails to tolerate the dynamics associated with the trip to an island in one case: the very severe fault and the machine-based DG. In this case, the motor recovery fails in a fashion similar to the failed recovery cases discussed in the previous chapter. In these cases, the faster response of the inverter-based DG with aggressive controls allows a better recovery. However, this simulation was somewhat idealized; an inverter-based DG might not be able to sustain the temporary overcurrents seen in this case unless it is specially rated for this duty. This particular comparison illustrates that different responses will have an effect on the success (and therefore viability) of the island.

One might be tempted to conclude from this example that inverter-based DG is superior for islanded operation. However, other experience shows that inverter-based DG is generally more sensitive to voltage dips that result from faults and is more likely to trip in response to such stimulus. Inverters, unless over-designed, have limited overcurrent capability. The thermal time-constants of solid-state power electronic devices are short compared with the copper windings of a rotating generator. Unless these devices are selected so that they normally operate well below their maximum allowable temperatures, overcurrents must necessarily be limited by either tripping or limitation of output current via control action. Limitation of current output by DG in a recovering system, where loads demand more current than DG can supply, will result in voltage collapse.

For DG to support microgrid islanding:

- The DG must not trip in response to the initiating disturbance.
- The load in the island must not exceed the capability of the DG in the islanded microgrid. If exceeded, noncritical load-shedding schemes should be incorporated so that the islanded microgrid can support critical load.
- Having enough capability is not sufficient alone. The DG must have the necessary dynamic response to survive the disturbances that cause the trip to island and the dynamic behavior of the loads following islanding, including inrush currents drawn by transformers and motors (which may be highly distorted) and reacceleration of motors and their mechanical loads.

5 Summary

5.1 Findings

This report investigated three key issues:

- Facility microgrid with multiple DG units unintentional islanding protection
- Facility microgrid response to bulk grid disturbances
- Facility microgrid intentional islanding.

One recent advancement in unintentional islanding protection is active anti-islanding controls. The active schemes were developed for single DG units, inverter- or machine-based. Previously, their performance when applied to multiple DG units was not well understood. The first part of the report attempted to gain an in-depth understanding of these new anti-islanding schemes. The recommendations are:

- For a facility microgrid with only inverter-based DG, all DG units should be equipped with the same anti-islanding control, either active voltage scheme or active frequency scheme, or both schemes should be enabled.
- For a facility microgrid with only machine-based DG, all DG units should be equipped with the same anti-islanding control, either active power scheme or reactive power scheme, or both schemes should be enabled.
- For a facility microgrid with mixed inverter- and machine-based DG, all inverter-based DG units should be equipped with active frequency scheme, and all machine-based DG units should be equipped with reactive power scheme.

If the recommendations are not followed, the facility microgrid may risk unintentional islanding unless other means or design changes are provided. These results are also relevant to the performance of multiple DG units not in a planned microgrid but connected to an Area EPS. Despite meeting performance requirements, based on the performance of individual DG units in isolation, desired anti-islanding performance may not be realized. This poses a potential risk to safety and exposes utility and customer equipment to possibly damaging conditions.

Obviously, the DG with active anti-islanding control will not allow seamless transition from grid-paralleled to islanded operation. In this case, the microgrid has to shut down, disconnect from main grid, and then start up as needed to supply local load. For microgrid applications that require seamless transition, other means for loss of main grid detection must be explored.

The report also studied facility microgrid dynamics in response to bulk grid disturbances. The major observations are:

- The dynamic behaviors of the facility microgrid are significantly different for different cases. The cases with no DG and with the dispatch mode inverter-based DG fail to recover from the fault—i.e., the load in the facility is disrupted, and the facility would likely trip some or all of its load and DG.

- Failed recovery is disruptive not only to the microgrid load but also to the host grid. This is evident in the high currents drawn after the load stalls. This could cause false trips of protective relaying and possibly result in outage of other customers on the host grid. The addition of controls (voltage and frequency droop regulation mode) for both types of DG allows a successful recovery, and all parties benefit.
- The presence of DG in the microgrid with appropriate controls can be beneficial to both the microgrid (DG owner) and the grid. (The no-DG case failed.)
- The machine-based DG with dispatch mode was more benign than the inverter-based DG with dispatch mode. This may be because the inherent mechanical (and magnetic) inertia of the machine may make recovery naturally friendlier. Conversely, the best performance results were from the inverter-based DG with full control (voltage and frequency regulation).

Finally, the report studied facility microgrid intentional islanding behaviors. The major observations are:

- Not all of the load within the facility can be served when the microgrid trips to islanded operation. In all cases, roughly half of the load in the facility tripped. Non-essential load can be disconnected to allow for secure operation of critical load. The ability to differentiate between critical and noncritical load is a major reliability consideration and potential advantage for a facility microgrid
- The microgrid fails to tolerate the dynamics associated with the trip to an island for one case: the very severe fault and the machine-based DG. The faster response of the inverter-based DG with very aggressive controls and with sufficient overcurrent capability allows for a better recovery.

5.2 Future Work

Generally, facility microgrids are more technically and economically viable than other microgrid applications. One key issue of making facility microgrids more practical and attractive is autonomous operation. To have autonomous operation, a facility microgrid should be designed to be adaptive to both grid-connected and islanded conditions with minimum load interruption. This requires a system-level design optimization that includes system-level controls (autonomous or self-reconfigurable), energy storage deployment/optimization to deal with transients and the slow response of prime movers, and intelligent load-shedding strategies.

Another issue of critical importance is the problem of incompatible active anti-islanding controls, which may not work together to provide necessary performance. This issue extends beyond the narrow context of microgrids to include DG applications in general. Current industry standards appear to be inadequate to provide critical system protection in the future as DG penetration increases and multiple DG units on a feeder become a routine situation. There is an urgent need to further study and define this issue and recommend changes to standards to achieve the required protection.

6 References

[1] *Grid 2030: A National Vision for Electricity's Second 100 Years*. Department of Energy Office of Electric Transmission and Distribution. July 2003. (http://www.climatevision.gov/sectors/electricpower/pdfs/electric_vision.pdf)

[2] Ye, Z.; Walling, R.; Garces, L.; Zhou, R.; Li, L.; Wang, T. *Study and Development of Anti-Islanding Control for Grid-Connected Inverters*. NREL/SR-560-36243. Golden, CO: National Renewable Energy Laboratory. May 2004. (http://www.nrel.gov/docs/fy04osti/36243.pdf).

[3] Middlebrook, R.D.; Vorperian, V.; Lindal, J. "The N Extra Element Theorem." *IEEE Transactions on Circuits and Systems – I: Fundamental Theory and Applications*; Vol. 45, No. 9, September 1998; pp. 919–935.

[4] Ye, Z.; Walling, R.; Miller, N.; Du, P.; Nelson, K. *Study and Development of Anti-Islanding Control for Synchronous Machine-Based Distributed Generators*. NREL/SR-560-38018. Golden, CO: National Renewable Energy Laboratory.

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Microgrids are receiving a considerable interest from the power industry, partly because their business and technical structure shows promise as a means of taking full advantage of distributed generation. This report investigates three key issues associated with facility microgrids:

- Multiple-distributed generation facility microgrids' unintentional islanding protection
- Facility microgrids' response to bulk grid disturbances
- Facility microgrids' intentional islanding.

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