Arnold Schwarzenegger
Governor

CERTS MICROGRID LABORATORY TEST BED

Test Plan Section 8.0
Reduced System Tests

APPENDIX K

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CERTS MICROGRID TEST REPORT

SECTION 8.0

"Reduced System Tests"

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1.0 INTRODUCTION

A series of tests were performed on the CERTS Microgrid by American Electric Power at the Walnut test site in Groveport, Ohio with support from Lawrence Berkeley National laboratory, Sandia National Laboratory, TECOGEN, The Switch (originally Youtility), Distributed-Energy (originally Northern Power) and University of Wisconsin. These tests were designed to demonstrate the CERTS Microgrid concepts of control and protection while connected to the utility electrical system and isolated (i.e., referred to as "islanded" from it. This paper describes the tests that were performed in Section 8.0 "Reduced System Tests" of the CERTS Micro-grid Test Plan.

2.0 BACKGROUND

The CERTS Microgrid Concept is an advanced approach for enabling integration of, in principle, an unlimited quantity of DER (e.g., distributed generation (DG), energy storage, etc.) into the electric utility grid. A key feature of a microgrid is its ability to separate and island itself from the utility system, during a utility grid disturbance. This is accomplished via intelligent power electronic interfaces and a single, high-speed, switch which is used for disconnection from the grid and synchronization to the grid. During a disturbance, the DER and corresponding loads can autonomously be separated from the utility's distribution system, isolating the microgrid's load from the disturbance (and thereby maintaining high level of service) without harming the integrity of the utility's electrical system. Thus, when the utility grid returns to normal, the microgrid automatically synchronizes and reconnects itself to the grid, in an equally seamless fashion. Intentional islanding of DER and loads has the potential to provide a higher level of reliability than that provided by the distribution system as a whole.

What is unique about the CERTS Microgrid is that it can provide this technically challenging functionality without extensive (i.e., expensive) custom engineering. In addition, the design of the CERTS Microgrid provides a high level of system reliability and great flexibility in the placement of DER within the microgrid. The CERTS Microgrid offers these functionalities at much lower costs than traditional approaches by incorporating peer-to-peer and plug-and-play concepts for each component within the microgrid.

The original concept was driven by two fundamental principles: 1.) A systems perspective was necessary for customers, utilities, and society to capture the full benefits of integrating DER into an energy system; and 2.) The business case for accelerating adoption of these advanced concepts will be driven, primarily, by lowering the up-front cost and enhancing the value offered by microgrids.

Each innovation was created specifically to lower the cost and improve the reliability of small-scale DG systems (i.e., installed systems with capacities ranging from less than 100kW to 1000kW). The goal was to increase and accelerate realization of the many benefits offered by small-scale DG, such as their ability to supply waste heat at the point of need or to provide a higher level of reliability to some but not all loads within a facility. From an electric utility perspective, the CERTS Microgrid Concept is attractive because it recognizes that the nation's distribution system is extensive, aging, and will change over time which impacts power quality. The CERTS Microgrid Concept enables high penetration of DG systems without requiring re-design or re-engineering of the utility's distribution system.

Prospective applications of the CERTS Microgrid include industrial parks, commercial and institutional campuses, situations that require uninterrupted power supplies and high power quality, CHP systems, Greenfield communities, and remote applications. In short, wherever economic and DG location considerations indicate the need for multiple DG units within a (or among) site, the CERTS Microgrid offers the potential for a much more reliable, flexible, and lower cost solution compared to traditional engineering approaches for integrating DG.

3.0 MICROGRID TESTBED SETUP

The CERTS Microgrid Test Bed is operated at 480/277 volts (i.e., three-phase, four-wire) and consists of three TECOGEN Generators at 480 volts capable of producing 60kW plus 60kVAr (Gen-set A1, Gen-set A2 and Gen-set B1) and four load banks (Load Bank 3, Load Bank 4, Load Bank 5 and Load Bank 6) capable of consuming 100kW plus 20kVAr each, as shown in Figure 2. Each of the generators are connected to a 112kVA isolation transformer and interfaced to the CERTS Microgrid through an inverter, developed by The Switch, where the algorithms for the CERTS Microgrid controls are embedded. . A semiconductor switch made by S&C Electric Company, known as the static switch, connects the CERTS Microgrid to the utility grid. Load Banks 3 – 5 are the local loads in zones located beyond the static switch; and Load Bank 6 is a customer load in Zone 6 located on the utility side of the static switch.

Figure 1 - CERTS Microgrid Aerial Photo

There are 6 zones in the Test Bed with Zones 2 - 6 contained within the CERTS Microgrid design and Zone 1 being the utility interface and referred to as the point-of-common coupling (PCC) to the grid. Each zone is protected by a Schweitzer SEL-351 relay. Faults of varying magnitude can be applied to each zone through an additional breaker which allows fault application and removal.

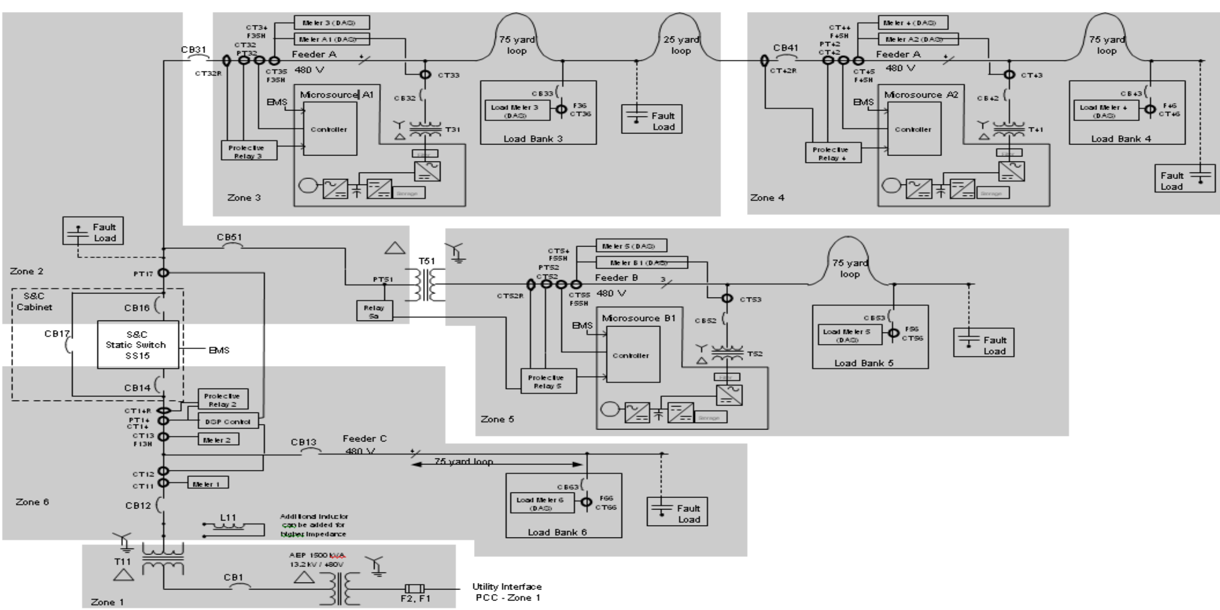

Figure 2 - One Line Diagram of CERTS Microgrid Test Bed

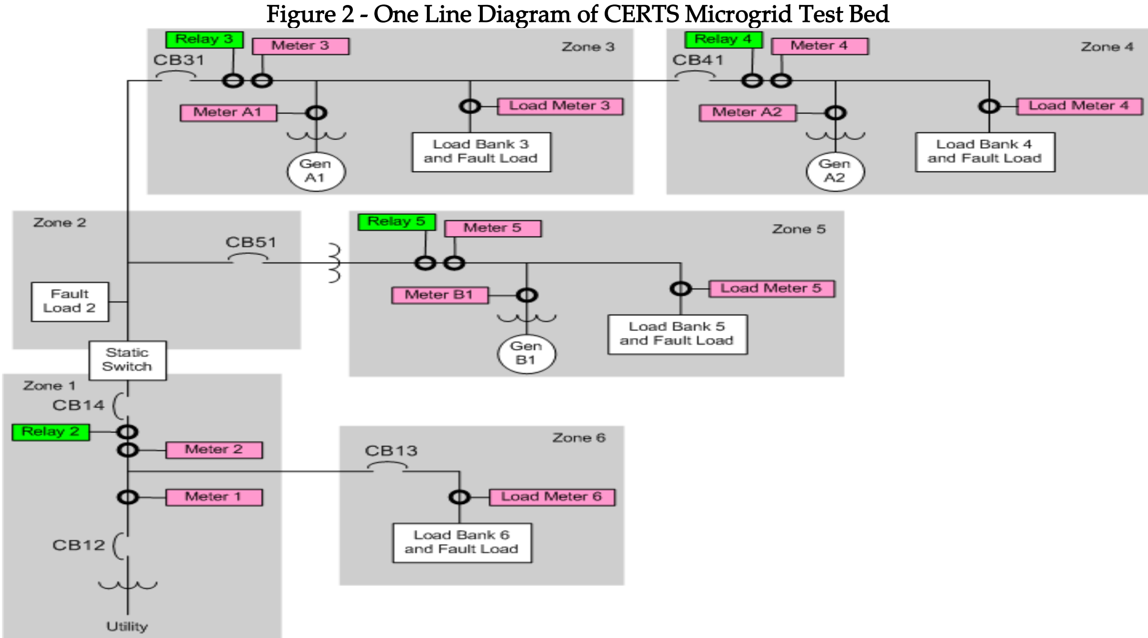

Figure 3 - Simplified diagram of Test Bed showing Meter and Relay locations

There are twelve PML ION 7650 meters placed through out the microgrid and shown in Figure 3, which monitor electrical system conditions, plus acquire phase current and voltage waveforms; and calculate RMS values of voltage, current, active power, reactive power, and frequency.

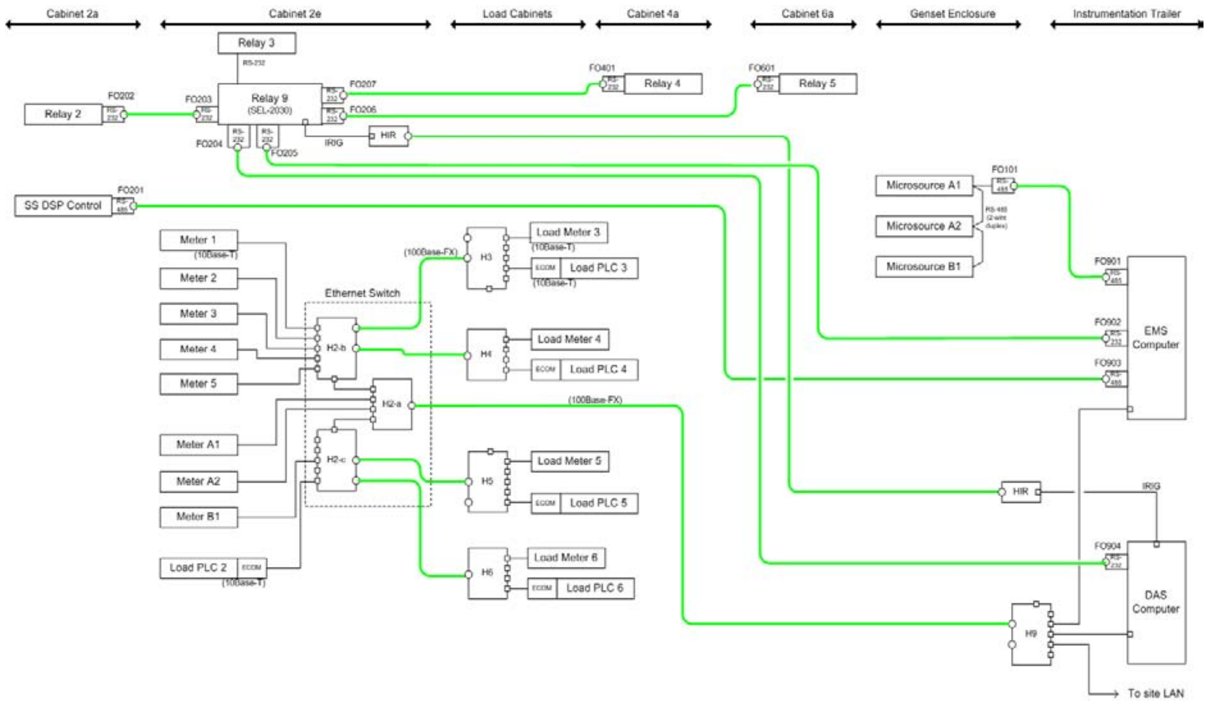

Figure 4 - Diagram of DAS & EMS Data networks

An Ethernet network was provided as shown in Figure 4, for communications between all meters, load control PLCs, and the Data Acquisition System (DAS) computer, using fiber-optic links and switches. The DAS and Energy Management System (EMS) computers were also networked into the local Dolan Local Area Network (LAN) and to a secure Website with user ID and password protection. Additional serial links, using fiber optic converters, connect all relays, static switch Digital Signal Processor (DSP) controller, and TECOGEN Gen-set controls to the EMS computer.

4.0 PROPOSED TEST PLAN

The CERTS Microgrid Test Plan was developed by the CERTS Microgrid Team to demonstrate the unique concepts of control and protection of the CERTS Microgrid. This test plan was reviewed by a Technical Advisory Committee outside the CERTS Microgrid Team and then implemented by American Electric Power. CERTS Microgrid Test Plan consists of 12 sections with 5 of them detailing desired tests, starting at section 6.0, to demonstrate the controls and concepts of the CERTS Microgrid. The other 7 sections pertain to safety procedures, equipment calibration, and documentation. Each section of the test plan is described below.

- Section 1 – "Purpose, References, and Definitions" describes the purpose of the test plan, helpful references for further explanation of how the test bed was created, and definitions used through out the test plan.

- Section 2 – "Responsibilities" informs personnel of their responsibilities while working on or near the CERTS Microgrid test site.

- Section 3 – "Training - Team Members" lists the mandatory training needed by personnel before they can work on or near the CERTS Microgrid test site.

- Section 4 – "Procedure – CERTS Microgrid Test Bed Lockout/Tagout" entails how to safely shut down the equipment and lockout/tagout the closest upstream disconnect to work on or near equipment.

- Section 5 – "Procedure – General" is the daily procedures performed at the CERTS Microgrid Test Site, prior to performing a test from Section 6 through Section 10.

- Section 6 – "Procedure – Microgrid Test Bed System Checkout" was designed to check control and operation of the static switch, basic power and voltage control of the Gen-sets, and a preliminary check of the protection scheme. The goal is to assure that the test bed is operating and ready to perform the tests described in the remaining sections of the test plan document.

- Section 7 – "Validate Protection Settings & Initial Fault Testing" is designed to examine a preliminary set of fault (i.e. overload simulating a fault) condition tests to ensure protection and safety of the Micro-grid test Bed, while performing other planned tests. The goal is to test and adjust protection settings to achieve the most ideal conditions and protection design.

- Section 8 – "Procedure – Reduced System Tests" is a limited set of tests to build confidence that the Gen-set inverter controls are working correctly. This includes unit control, zone control, and mixed power controls, in conjunction with limit controls and synchronized closing of the static switch. These tests are based on the TECOGEN/THE SWITCH factory acceptance testing.

- Section 9 – "Procedure – Demonstration Tests of Control Power Flow" demonstrates the flexibility of the Micro-grid both grid connected and islanded for different loads, power flows and impact on the utility.

- Section 10 – "Procedure – Test Difficult Loads" determines operation limits of the Micro-grid (i.e. power quality, protection and inverter limits) with low pf loads, motor loads, harmonic loads and unbalance loads.

- Section 11 - "Hazards & Mitigation" informs the personnel of hazards that may exist while working on or near the CERTS Micro-grid test site and how to mitigate them.

- Section 12 – "Quality Assurance" ensures quality for the acquiring data results by providing a checklist reminder for personnel.

5.0 TESTS PERFORMED IN SECTION 8.0

Prior to each test day, the person in charge performed a job safety briefing (JSB) with barricades and test setup inspected for safety and compliance. A minimum of two people were on-site during each planned test.

Visual and audible alarms were used to warn persons that energized testing was being performed in the Microgrid Test Bed area. The visual alarm consisted of a portable red flashing light, located between the Control Trailer and Gen-set Enclosure. An audible alarm, consisting of a portable wireless motion detector, was located at the front gate of the Walnut Test Site with the fence gate "Closed", not locked, and audible alarm in the trailer operational during test(s).

Barricades were set up around the Micro-grid Test Bed area (i.e., saw-horse style barricades with a "Red" plastic chain surrounded the test area containing the Gen-set Enclosure, Micro-grid switching cabinets, plus load and fault bank cabinets).

Prior to performing tests, the Test Engineer or Technical Consultant verified that all personnel and visitors were properly protected and in assigned locations. Personnel were in or adjacent to the Control Trailer while tests were being performed. All nonessential personnel either left the main site or were sheltered in the Control Trailer.

For all tests the following waveforms were captured and recorded in the DAS for voltage (V) and current (I). From these waveforms real power (kW), reactive power (kVAr), and frequency (freq) were post calculated by the PQView software. Frequency measurements in this report should be used for steady state information and not used for transient analysis, due to the calculation and filtering methods employed. Below is a list of the meters capturing this data.

- Meters 1, 2, 3, 4 & 5
- Load Meters 3, 4, 5, & 6
- Meters A1, A2 & B1
- Meter 2 also measures the voltage across the static switch on phase A

Schweitzer event reports were also captured for each event, along with breaker and static switch status, such as Open or Close.

To maintain a common understanding of Gen-set control modes during tests described in the following paragraphs, it is important to know the difference between unit power control mode and zone control mode. Unit power control mode involves the amount of power (i.e., kW) injected into the Zone from the Gen-set being controlled. Zone power control mode involves the amount of power (i.e., kW) entering/exiting the Zone which controls the output of the Gen-set in that zone.

Section 8 consists of 13 tests designed to validate the inverter controls tested by TECONGEN/The Switch in a laboratory setting with field demonstration. In each test waveforms were captured and recorded in the DAS, as described below.

Test 8.1 was designed to verify smooth transitions in Gen-set A1 when different step conditions of load are applied in Load Bank 3 with voltage set points ranging from +5% to -5%. The same test was repeated for Gen-set A2 and Load Bank 4 and Gen-set B1 and Load Bank 5.

Test 8.2 was designed to verify smooth transitions of Gen-sets A1 and A2 response to different step conditions which drive Gen-set A1 to a lower limit of zero kW.

Test 8.3 verified smooth transitions of Gen-sets A1 and A2 response to different step conditions which drive Gen-set A2 to an upper limit of 60kW.

Test 8.4 verified smooth transitions of Gen-sets A1 and A2 response to different step conditions with an un-balanced load in Zone 3.

Test 8.5 verified smooth transitions of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode. During a load step change in Load Bank 3, Gen-set A1 was driven to an upper limit of 60kW.

Test 8.6 verified smooth transitions of Gen-sets, A1 in zone operation mode and Gen-set A2 in Unit operation mode. During a load step change in Load Bank 4, Gen-set A1 is driven to its maximum which causes an automatic reset of the zone set points.

Test 8.7 verified smooth transitions of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode, with a change of zone power in Feeder A.

Test 8.8 verified smooth transition of Gen-sets, A1 in zone operation mode and A2 in unit operation mode, with a static switch operation and a change of zone power in Feeder A when islanded.

Test 8.9 verified smooth transition of Gen-sets, A1 in Zone operation mode and A2 in Unit operation mode, with a static switch operation and a change of zone power in Feeder A when islanded. Gen-sets A1 and A2 were driven to their maximum which caused an automatic reset of their set-points.

Test 8.10 verified smooth transitions of Gen-sets, A1 and B1 in Zone operation mode, with a static switch operation and a change of zone power in Feeder A and Feeder B when islanded.

Test 8.11 verified smooth transitions of Gen-sets, A1 and B1 in Zone operation mode, with a static switch operation and a change of zone power in Feeder A and Feeder B when islanded. When islanded, Gen-set A1 and B1 set-points were reset based on the remaining load in the islanded system.

Test 8.12 tested the manual procedure used to black-start the CERTS Micro-grid Test Bed in the event of a lengthy utility outage occurs with the Gen-sets off-line.

Test 8.13 was designed to determine the black-start capacity by increasing the amount of load on the CERTS Microgrid Test Bed from a black-out condition without generation or protection trips.

6.0 ANALYSES OF TEST RESULTS

6.1 SECTION 8 – REDUCED SYSTEM TESTS

6.1.1 Initial Voltage Regulation Test – Single Zone, Islanded

Performance Goal:

Verify smooth transitions of Gen-sets A1 response to different step conditions of load in Load Bank 3 with voltage set point changes ranging from +5% to -5%. Repeat tests with Gen-set A2 and Load Bank 4, then with Gen-set B1 and Load Bank 5.

During all tests in this voltage regulation test section, the static switch was open isolating the microgrid from the utility grid. All data graphs from each voltage regulation test are available in Appendix A. Table 3 provides a brief summary of test results obtained during these twenty-seven voltage step changes in Zone 3, Zone 4 and Zone 5 of the microgrid.

Initially, Gen-set A1 in Zone 3 was running for a few minutes to warm-up with the voltage set-point at 277V, with zero load at Load Bank 3. Load Bank 3 was set at 20kW which was measured as approximately 19kW. Real and reactive power output response to this load increase was approximately 21kW and 4kVAr, respectively. The electrical impedance in the 75 yards of distribution conductors between Gen-set A1 and Load Bank 3 was the primary cause of the power difference. The voltage at Gen-set A1 was steady at approximately 273V and the frequency was approximately 59.99 Hz. Once all the data was recorded and validated, Load Bank 3 was increased from 20kW to 40kW. A smooth transition occurred when the load increased by ~20kW with the resultant load being 36kW, as measured by Load Meter 3. At the time of this load change, Gen-set A1 increased its output power from approximately 21kW and 4kVAr to 38kW and 4.4kVAr. The voltage remained the same at the Gen-set (i.e., 273V) from the previous reading and the frequency dropped to 59.84Hz. Once all the data was recorded and validated, Load Bank 3 was increased by an additional 20kW to a total of 60kW. Power flow at Load Bank 3 was approximately 52.5kW and the Gen-set responded to this load step with a smooth transition producing an output power of 55kW and 4.8kVAr. The voltage at Gen-set A1 measured the same as the previous load change, at 273V. During this load change, frequency was reduced from approximately 59.84Hz to 59.70Hz. The drop in frequency was caused by the CERTS algorithm for Real Power versus Frequency droop control. Gen-set A1 and the microgrid remained stable through all the load step changes of 20kW at 277V. All data was recorded in DAS and the next test was implemented.

The voltage set-point (i.e., MG Voltage) of Gen-set A1 was increased by 5% to 291V and Load Bank3 was reset to 0kW. Then, Load Bank 3 was brought on-line with a 20kW setting. In response to this load step change, output power at Gen-set A1 was 22.5kW and 6.5kVAr. The voltage was measured at approximately 287V, which remained the same at Gen-set A1. The rise in reactive power from the previous test (i.e., load step of 20kW at 277V) was adjusted by the Gen-set to increase its voltage from 273V to 287V. Frequency at Gen-set A1 was 59.98Hz. Once all data was recorded and validated, Load Bank 3 was increased from 20kW to 40kW. Load Meter 3 measured a power flow of approximately 40kW at Load Bank 3 with voltage at Gen-set A1 of 287V. The voltage held constant, allowing for a smooth transition between the load step changes. Gen-set A1 increased its output power from approximately 22.5kW and 6.5kVAr to 41.5kW and 6.8kVAr, supplying power to Load Bank 3 and the frequency within the microgrid decreased from 59.98Hz to 59.82Hz. Once all data was recorded and validated, Load Bank 3 was increased from 40kW to 60kW. The voltage at Gen-set A1 remained the same at 287V, resulting in a smooth transition. Load Meter 3 measured a power flow of approximately 57kW at Load Bank 3 and the resultant output power of Gen-set A1 increased to 59.5kW and 7.7kVAr. The microgrid frequency during this load step change decreased from 59.82Hz to 59.15Hz. All data was recorded in the DAS and the next test was implemented.

The voltage set-point (i.e., MG Voltage) of Gen-set A1 was decreased from 291V to 263V (i.e., minus 5% of nominal 277V) and Load Bank 3 was reset to 0kW. Load Bank 3 was then brought on-line with a 20kW setting and a resultant measurement of approximately 17kW. The voltage was measured at approximately 260V and remained the same at Gen-set A1. In response to the load step change, the output power at Gen-set A1 was 19kW and 2.55kVAr. A decrease in the reactive power from the previous test (i.e., load step of 20 kW at 277V) was adjusted by the Gen-set to decrease its voltage to approximately 260V. Frequency in the microgrid from Gen-set A1 was 60.00Hz. Once all data was recorded and validated, Load Bank 3 was increased from 20kW to 40kW. Load Meter 3 measured a power flow of approximately 32kW with voltage at Load Bank 3 of 260V. The voltage held constant, allowing for a smooth transition between load step changes. Gen-set A1 increased its output power from approximately 19kW and 2.55kVAr to 34.5kW and 2.9kVAr, supplying power to Load Bank 3, and frequency within the microgrid decreased from 60.00Hz to 59.87Hz. Once all data was recorded and validated, Load Bank 3 was increased from 40kW to 60kW. Voltage at Gen-set A1 remained the same from the 40kW load step test at 260V, resulting in a smooth transition. Load Meter 3 measured a power flow of approximately 47.5kW at Load Bank 3 and the output power of Gen-set A1 increased to 50kW and 3.3kVAr. The microgrid frequency during this load step change decreased from 59.87Hz to 59.74Hz. Once all data was recorded and validated, Gen-set A1 was shut down, manually, and all loads and alarms were reset in preparation for the next set of tests.

The above tests were repeated with adding 3 load steps of 20kW and varying the voltage by +5% and -5% of the nominal 277V for Gen-set A2 with Load Bank 4; and repeated again for Gen-set B1 with Load Bank 5. In each test, the Gen-sets transitioned smoothly through each load step change and voltage change.

	Set-point Values		Test Results				
	Gen-set Voltage	Load Bank kW	Load Bank (kW)	Gen-set Output Real Power (kW)	Gen-set Output Reactive Power (kVAr)	Freq. (Hz)	Voltage
Gen A1	277	20	19	21	4	59.99	273
	277	40	36	38	4.4	59.84	273
	277	60	52.5	55	4.8	59.70	273

	291	20	20	22.5	6.5	59.98	287
	291	40	40	41.5	6.8	59.82	287
	291	60	57	59.5	7.7	59.15	287
	263	20	17	19	2.55	60.00	260
	263	40	32	34.5	2.9	59.87	260
	263	60	47.5	50	3.3	59.74	260
	277	20	18.5	21	4.45	58.89	277
	277	40	37	39	5	59.84	277
	277	60	53.5	56	5.4	59.71	277
	291	20	20	23	7.5	59.97	291
Gen A2	291	40	39.5	42.5	8	59.82	291
	291	60	57.5	60.5	8	59.59	291
	263	20	16.5	18.5	2.9	60.02	263
	263	40	33	35	3.2	59.89	263
	263	60	48.5	51	3.6	59.75	263
	277	20	20	22.5	4.9	59.99	277
	277	40	37.5	40	5.2	59.85	277
	277	60	54.5	57	5.5	59.71	277
	291	20	21.5	24	8.2	59.97	291
Gen B1	291	40	40	43.5	8.4	59.82	291
	291	60	57.5	60	7.7	59.68	291
	263	20	16.5	19	3	60.02	263
	263	40	33.5	36	3.3	59.88	263
	263	60	49.5	51.5	3.6	59.75	263

Table 1 – Voltage regulation test results of Gen-set A1, A2 and B1 in Zone 3, 4 and 5, respectively.

6.1.2 Open Static Switch Test, Gen-set A1

Performance Goal:

Verify smooth transitions in Unit power control mode of Gen-sets A1 and A2 response to different step conditions (i.e., static switch “OPEN” / “CLOSE”) when the lower power control limit, 0kW, of Gen-set A1 is reached.

Table 4 shows the values of Gen-sets, loads, power flows and frequency with the static switch closed and the final values after the static switch was opened, islanding the microgrid. The static switch was also allowed to reclose in this test and resultant values were expected to return to the initial values before the static switch was opened. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition, Load Banks 3, 4 and 6 were connected with approximately 18.2kW, 18.1kW and 28.7kW, respectively. Gen-set A1 output power was approximately 5kW and Gen-set A2 output power was approximately 55kW. Power flow through the static switch, before it was open, was approximately -21.5kW. Power flow from the utility grid was approximately 7kW which combined with the power flowing from the microgrid supplying power for Load Bank 6.

As soon as the manual open was asserted to the static switch, Load Bank 6 was no longer powered by the Gen-sets but by the utility grid and was approximately 29.35kW. Load Banks 3 and 4 were picked up by Gen-set A2, because of the CERTS power versus frequency droop control, and Gen-set A1 output power was reduced to 0kW. Gen-set A2 output power was approximately 37kW and Load Banks 3 and 4 were 17.5kW and 17.3kW, respectively. The frequency increased when the microgrid islanded from 60.00Hz to 60.14Hz, because the load demand decreased within the microgrid and because of the CERTS algorithm. Power flow at the static switch was 0kW and approximately 29.5kW at Meter 1 on the utility side of the switch. The islanded microgrid operated this way for a few minutes before the static switch manual open was removed.

After the manual open was removed, the static switch reconnected the microgrid to the utility grid in a smooth transition and Load Bank 6 was supplied power by the microgrid and utility grid. Gen-set A1 increased its output power to approximately 6kW and Gen-set A2 increased output power to approximately 56.5kW. Load Banks 3, 4 and 6 measured approximately 18.2kW, 18.1kW and 28.7kW, respectively. Power flow at the static switch was approximately -22.5kW with 7kW at the utility side. Frequency within the microgrid decreased from 60.15Hz to approximately 60.00Hz. The resultant values, after the static switch reconnected the microgrid to the utility grid, were very similar to the values at the beginning of the test.

Gen-sets A1 and A2 were shut down manually and all loads and alarms were reset and equipment was prepared for the next test.

Test Results							
Event Open SS				Event Results Open SS		Event Results Close SS	
	Mode	Set-point	Expected Result	Start	End	Start	End
A1	Unit	5kW	0.0kW	5kW	0.0kW	0.0kW	6.0kW
A2	Unit	55kW	40kW	56kW	37kW	37.5kW	56.5kW
B1		Off	Off	Off	Off	Off	Off
Freq		~60Hz	~60.12Hz	60Hz	60.14Hz	60.15Hz	60Hz
L3		20kW	20kW	18.2kW	17.5kW	17.5kW	18.2kW
L4		20kW	20kW	18.1kW	17.3kW	17.3kW	18.1kW
L5		0.0kW	0.0kW	0.0kW	0.0kW	0.0kW	0.0kW
L6		30kW	30kW	28.7kW	29.35kW	29.4kW	28.7kW
SS		-20kW	0.0kW	-21.5kW	0.0kW	0.0kW	-22.5kW
Grid		0.0kW	20kW	7kW	29.5kW	30kW	7kW
Let SS re-close Expect the system to return to Start values							

Table 4 – Open Static Switch (SS) Test Results, Gen-set A1

6.1.3 Open Static Switch Test, Gen-set A2

Performance Goal:

Verify smooth transitions in Unit power control mode of Gen-sets A1 and A2 response to different step conditions (i.e., static switch "OPEN" / "CLOSE") when the upper power control limit, 60kW, of Gen-set A2 is reached.

Table 5 shows the values of Gen-sets, loads, power flows and frequency with the static switch closed and the final values after the static switch was opened, islanding the microgrid. The static switch was also allowed to reclose in this test and resultant values were expected to return to the initial values before the static switch opened. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition, Load Banks 3 and 4 were connected with approximately 53.9kW and 35.6kW, respectively. Gen-set A1 output power was approximately 5kW and Gen-set A2 output power was approximately 55kW. Power flow from the utility grid through the static switch was approximately 32kW, indicating that part of the loads within the microgrid were being supported by the utility grid.

As soon as the static switch opened, the utility grid was no longer providing the additional power needed to satisfy loads in the microgrid. Therefore, Gen-set A1 and A2 had to increase their output power, accordingly. Gen-set A1 output power increased from approximately 5kW to 29kW and Gen-set A2 increased from 55kW to 60kW. The frequency decreased when the microgrid islanded from 59.94Hz to 59.80Hz, because load demand increased within the microgrid and because of the CERTS algorithm. Likewise, voltage in the system dropped from approximately 280V to 277V, decreasing load demands in Load Banks 3 and 4 to approximately 51.75kW and 34.2kW, respectively. Power flow from the utility and through the static switch was 0kW. The islanded microgrid operated for a few minutes before the static switch manual open was removed.

The static switch reconnected the microgrid to the utility in a smooth transition with Load Banks 3 and 4 being supplied by the microgrid and utility grid. Gen-set A1 decreased its output power to approximately 2kW and Gen-set A2 had an output power of approximately 53kW. Load Banks 3 and 4 measured approximately 53.7kW and 35.5kW, respectively. The power flow at the static switch was approximately 37kW at the utility side. Voltage within the microgrid increased from approximately 277V to 280V and the frequency increased from 59.80Hz to approximately 60.02Hz. The values after the static switch reconnected the microgrid to the utility grid are very similar to the values at the beginning of the test which was expected.

Gen-sets A1 and A2 were shut down manually and all loads and alarms were reset, and equipment was prepared for the next test.

Test Results							
Event Open SS				Event Results Open SS		Event Results Close SS	
	Mode	Set-point	Expected Results	Start	End	Start	End
A1	Unit	5kW	40kW	5kW	29kW	29kW	2kW
A2	Unit	55kW	60kW	55kW	60kW	60kW	53kW
B1		Off	Off	Off	Off	Off	Off
Fq		~60Hz	~59.72Hz	59.94Hz	59.8Hz	59.80Hz	60.02Hz
L3		60kW	60kW	53.9kW	51.75kW	51.7kW	53.7kW
L4		40kW	40kW	35.6kW	34.2kW	34.25kW	35.5kW
L5		0kW	0kW	0kW	0kW	0kW	0kW
L6		0kW	0kW	0kW	0kW	0kW	0kW
SS		40kW	0kW	32kW	0kW	0kW	37kW
Grid		40kW	0kW	32kW	0kW	0kW	37kW
Let SS re-close Expect the system to return to Start values							

Table 5 – Open Static Switch (SS) Test Results, Gen-set A2

6.1.4 Test Island Operation, Unbalanced Load

Performance Goal:

Verify smooth transitions in Unit power control mode of Gen-sets A1 and A2 response to different step conditions (i.e., static switch "OPEN" / "CLOSE") with an un-balanced load in Zone 3.

Table 6 shows the values of Gen-sets, loads, power flows and frequency before and after the load on A-phase of Load Bank 3 was reduced. During this test, the static switch remained open.

After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition, Load Bank 3 was connected with approximately 54kW. Gen-set A1 output power was approximately 13kW and Gen-set A2 output power was approximately 43kW.

As soon as A-phase load in Load Bank 3 was reduced, as verified by 0A flowing at Load Meter 3 on A-phase, Gen-sets A1 and A2 output power decreased to meet the new load demand. Gen-set A1 output power decreased from approximately 13kW to 4kW and Gen-set A2 decreased from approximately 43kW to 34kW. The frequency increased when the microgrid was islanded from approximately 60.00Hz to 60.09Hz, because load demand decreased within the microgrid and because of the CERTS algorithm. Likewise, voltage in the system increased from approximately 275V to 277V on phases A and B and decreased on C-phase from approximately 275V to 270V. After reducing A-phase load to zero, Load Bank 3 decreased to approximately 35kW. Gen-sets A1 and A2 were shut down manually and all loads and alarms were reset, and equipment was prepared for the next test.

Test Results					
Event Open Phase-A of Load Bank 3				Event Results	
	Mode	Set-point	Expected Results	Start	End
A1	Unit	15kW	~2.5kW	13kW	4kW
A2	Unit	45kW	~37.5kW	43kW	34kW
B1		Off	Off	Off	Off
Freq		~60Hz	~60.09Hz	60Hz	60.09Hz
L3		60kW	40kW	54kW	35kW
L4		0kW	0kW	0kW	0kW
L5		0kW	0kW	0kW	0kW
L6		0kW	0kW	0kW	0kW
SS	Open	0kW	0kW	0kW	0kW

Grid		0kW	0kW	0kW	0kW
Should be no current in Phase A					
Note: SS Open					

Table 6 - Test Results, Island Operation, Unbalanced Load

6.1.5 Mixed Mode Operation Test – Feeder A, Gen-set A1 Upper Limit, 60kW

Performance Goal:

Verify smooth transitions of Gen-set, A1 in Zone power control mode with a 60kW upper limit and Gen-set A2 in Unit power control mode, during a load step change in Load Bank 3.

Table 7 shows the values of Gen-sets, loads, power flows and frequency before load in Zone 3 was expected to increase by 50kW and the final values after load in Zone 3 was increased. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-set A1 was set for zone power control mode and Gen-set A2 was set for unit power control mode. After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition with the static switch closed, Load Banks 3 and 4 were connected and measured approximately 35kW and 33.5kW, respectively. Gen-set A1 output power was approximately 10kW and Gen-set A2 output power was approximately 5.5kW. Power flow through the static switch before additional load was added to Zone 3 was approximately 55kW. Likewise, power flow from the utility grid was approximately 55kW. Frequency in the microgrid before Zone 3 load was increased was approximately 60.005Hz and voltage was approximately 277V.

As soon as load was added in Zone 3 by Load Bank 3, increasing its load from approximately 35kW to 80kW, Gen-set A1 increased its output power from approximately 10kW to 55kW due to its Zone control set-point, which satisfied the increased load demand. Because frequency remained at approximately 60.005Hz no additional power was supplied from Gen-set A2. The resultant voltage in the system dropped from approximately 277V to 276V, decreasing load power demand in Load Bank 4 to approximately 33.25kW. Power flow from the utility through the static switch was 57kW. Although it was desired to put Gen-set A1 at its upper power control limit, differences in actual power delivered by the load banks prevented it from being reached. Gen-set A1 did correctly meet its zone control set point of 54kW; however, it only needed to provide 55kW instead of the anticipated 60kW. The electrical system was allowed to operate for a couple of minutes to see if an event would occur, which did not happen.

Gen-sets A1 and A2 were shut down manually, all loads and alarms were reset, and equipment was prepared for the next test.

Test Results					
Event Load Step in Zone 3				Event Results	
	Mode	Set-point	Expected Results	Start	End
A1	Zone	54kW	54kW	52kW	54kW
A1	Injected P	10kW	60kW	10kW	55kW
A2	Unit	6kW	6kW	5.5kW	5.5kW
B1		Off	Off	Off	Off
Freq		~60Hz	~60Hz	60.005Hz	60.005Hz
L3		35kW	85kW	35kW	80kW
L4		35kW	35kW	33.45kW	33.25kW
L5		0kW	0kW	0kW	0kW
L6		0kW	0kW	0kW	0kW
SS	Closed	54kW	54kW	55kW	57kW
Grid		54kW	54kW	55kW	57kW

Table 7 - Mixed Mode Operation Test Results, Feeder A, Gen-set A1 Upper Limit, 60kW

6.1.6 <u>Mixed Mode Operation Test – Feeder A, Automatic Reset of Zone Level Set-Point</u>

Performance Goal:

Verify smooth transitions of Gen-set A1 in Zone power control mode with an automatic reset of the set-point and Gen-set A2 in Unit power control mode, during a load step change in Load Bank 4.

Table 8 shows the values of Gen-sets, loads, power flows and frequency before load in Zone 4 was increased by 20kW and the resultant values after load in Zone 4 was increased. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-set A1 was set for zone power control mode and Gen-set A2 was set for unit power control mode. After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition with the static switch closed, Load Banks 3 and 4 were connected and measured approximately 68.95kW and 33.5kW, respectively. Gen-set A1 output power was approximately 44kW and Gen-set A2 output power was approximately 6.5kW. Power flow through the static switch before additional load was added to Zone 4 was approximately 55kW. Likewise, power flow from the utility grid was approximately 55kW which means that about half of the load in Load Banks 3 and 4 was supplied power by the utility grid. Frequency in the microgrid, before Zone 4 load was increased, was approximately 59.95Hz and voltage was approximately 277V.

As soon as load was added in Zone 4 by Load Bank 4, increasing its load from approximately 33.5kW to 52.5kW, Gen-set A1 increased its output power from approximately 44kW to 58kW due to its Zone control set-point, which satisfied the increased load demand. No additional power was supplied from Gen-set A2, which remained the same at approximately 6.5kW, and load demand in Load Bank 3 stayed the same at approximately 68.95kW. The resultant voltage in the system dropped from approximately 277V to 276V and frequency increased from approximately59.95Hz to 59.98Hz. Power flow from the utility through the static switch was 61kW. Gen-set A1 did correctly meet its zone control set-point of 55kW; however, differences in actual power delivered by the load banks prevented it from reaching the anticipated 60kW. The electrical system was allowed to operate for a couple of minutes to see if an event would occur, which did not happen.

Gen-sets A1 and A2 were shut down manually, all loads and alarms were reset and equipment was prepared for the next test.

Test Results					
Event Load step in Zone 4				Event Results	
	Mode	Set-point	Expected Results	Start	End
A1	Zone	55kW	65kW	52kW	58kW
A1	Injected P	50kW	60kW at Max	44kW	58kW

A2	Unit	5kW	5kW	6.5kW	6.5kW
B1		Off	Off	Off	Off
Freq		~60Hz	~60Hz	59.95Hz	59.98Hz
L3		75kW	75kW	68.95kW	68.95kW
L4		35kW	55kW	33.5kW	52.5kW
L5		0kW	0kW	0kW	0kW
L6		0kW	0kW	0kW	0kW
SS	Closed	55kW	65kW	55kW	61kW
Grid		55kW	65kW	55kW	61kW
Starting and ending frequency are ~60Hz					

Table 8 – Mixed Mode Operation Test Results, Feeder A, Automatic Reset of Zone Level Set-point.

6.1.7 Mixed Mode Operation Test – Feeder A, Zone Power Change

Performance Goal:

Verify smooth transitions of Gen-set A1 in Zone power control mode and Gen-set A2 in Unit power control mode, with a change of zone power in Feeder A. Table 9 shows the values of Gen-sets, loads, power flows and frequency before the EMS requested Zone 3 power be increased by 56kW and the resultant values after Zone 3 power was increased. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-set A1 was set for zone power control mode and Gen-set A2 was set for unit power control mode. After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition with the static switch closed, Load Banks 3 and 4 were connected and measured approximately 75.7kW and 33.3kW, respectively. Gen-set A1 output power was approximately 50.5kW and Gen-set A2 output power was approximately 5.25kW. Power flow through the static switch was approximately 57kW before the EMS increased power in Zone 3 and was approximately 54kW in Zone 3. Frequency in the microgrid before the EMS changed the power in Zone 3 was approximately 60.008Hz and voltage was approximately 277V.

As soon as the EMS increased the power set-point setting of Gen-set A1 in Zone 3, Gen-set A1 decreased its output power from approximately 50.5kW to 0kW, due to its zone control set-point which increased load demand to Zone 3. Gen-set A2 output power increased slightly from 5.25kW to approximately 5.6kW. The resultant voltage in the system dropped from approximately 277V to 276V and frequency decreased slightly (i.e., from 60.008Hz to 60.003Hz), reducing load at Load Banks 3 and 4 to approximately 75.55kW and 33.24kW, respectively. Power flow at the static switch increased from 57kW to 107.5kW. This 50.5kW increase by the utility grid was required to meet the increased set-point setting in Zone 3, and Gen-set A1 reduced to 0kW. The electrical system was allowed to operate for a couple of minutes to see if an event would occur, which did not happen.

Gen-sets A1 and A2 was shut down manually, all loads and alarms were reset and equipment was prepared for the next test.

Test Results					
Event Increase Zone 3 set-point				Event Results	
	Mode	Set-point	Expected Results	Start	End
A1	Zone	54kW	110kW	54kW	104kW
A1	Injected P	60kW at Max	4kW	50.5kW	0kW
A2	Unit	6kW	6kW	5.25kW	5.6kW
B1		Off	Off	Off	Off
Freq		~60Hz	~60Hz	60.008Hz	60.003Hz
L3		85kW	85kW	75.7kW	75.55kW
L4		35kW	35kW	33.3kW	33.24kW
L5		0kW	0kW	0kW	0kW
L6		0kW	0kW	0kW	0kW
SS	Closed	54kW	110kW	57kW	107.5kW
Grid		54kW	110kW	57kW	107.5kW
Reset Zone Power for Gen-set A1 to ~110kW					

Table 9 - Mixed Mode Operation Test Results, Feeder A Zone Power Change

6.1.8 Mixed Mode Operation Test – Feeder A, Zone Power Change When Islanded

Performance Goal:

Verify smooth transition of Gen-sets, A1 in Zone power control mode and A2 in Unit power control mode, with a static switch operation to island the microgrid and a change of zone power control in Feeder A.

Table 10 shows the values of Gen-sets, loads, power flows and frequency before the static switch was opened and the resultant values after the static switch islanded the microgrid. The static switch was also allowed to reclose in this test to compare values indicated in the table before the static switch was opened. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-set A1 was set for zone power control mode and Gen-set A2 was set for unit power control mode. After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition with the static switch closed, Load Banks 3 and 4 were connected and measured approximately 33.75kW and 33.4kW, respectively. Gen-set A1 output power was approximately 14kW and Gen-set A2 output power was approximately 5kW. Power flow through the static switch, from the utility grid, was approximately 52.5kW with approximately 75% of the loads within the microgrid being supplied by the utility grid.

As soon as the static switch was manually opened, the utility grid was no longer providing power to the microgrid with Gen-sets A1 and A2 adjusting their output power, accordingly. Gen-set A1 output power decreased from approximately 14kW to 9kW because Zone 3 power set-point was decreased from 50kW; and Gen-set A2 output power increased from 5kW to 59kW. Gen-set A1 continued producing power in Zone 3, because Gen-set A2 was at its maximum power limit and could not satisfy load demand from Load Banks 3 and 4. The resultant frequency decreased when the microgrid islanded from 60.02Hz to 59.58Hz, because the load increased within the microgrid and because of the CERTS algorithm. In addition, voltage in the microgrid dropped from approximately 280V to 277V, and decreased load power demands in Load Banks 3 and 4 to approximately 32.8kW and 32.6kW, respectively. Power flow at the static switch decreased from 52.5kWto 0kW. The islanded microgrid operated this way for a few minutes before the static switch manual open was removed.

The static switch reconnected the microgrid to the utility grid in a smooth transition with Load Banks 3 and 4 supplied power by the microgrid and utility grid. Gen-set A1 increased its output power to approximately 14kW and Gen-set A2 decreased its output power to approximately 5kW. Load Banks 3 and 4 were measured at approximately 33.65kW and 33.4kW, respectively. Power flow through the static switch was approximately 52.5kW from the utility. Voltage within the microgrid increased from approximately 277V to 280V and frequency increased from approximately 59.55Hz to 60.00Hz. The resultant values after the static switch reconnected the microgrid to the utility grid were very similar to the values at the beginning of the test.

Gen-sets A1 and A2 were shut down manually, all loads and alarms were reset, and equipment was prepared for the next test.

Test Results							
Test Event Open SS				Event Results Open SS		Event Results Close SS	
	Mode	Start	End	Start	End	Start	End
A1	Zone	50kW	0kW	50kW	0kW	0kW	50kW
A1	Injected P	14kW	~18kW	14kW	9kW	9kW	14kW
A2	Unit	6kW	~52kW	5kW	59kW	59kW	5kW
B1		Off	Off	Off	Off	Off	Off
Freq		~60Hz	~59.6Hz	60.02Hz	59.58Hz	59.55Hz	60Hz
L3		35kW	35kW	33.75kW	32.8kW	32.7kW	33.65kW
L4		35kW	35kW	33.4kW	32.6kW	32.6kW	33.4kW
L5		0kW	0kW	0kW	0kW	0kW	0kW
L6		0kW	0kW	0kW	0kW	0kW	0kW
SS	Closed	50kW	0kW	52.5kW	0kW	0kW	52.5kW
Grid		50kW	0kW	52.5kW	0kW	0kW	52.5kW
Allow SS to re-close Expect the system to return to Start values.							

Table 10 - Mixed Mode Operation Test Results, Feeder A, Zone Power Change When Islanded

6.1.9 Mixed Mode Operation Test – Feeder A, When Islanded Automatic Reset of Zone Level Set-point

Performance Goal:

Verify smooth transitions of Gen-sets A1 in Zone power control mode with automatic reset of set point and Gen-set A2 in Unit power control mode, with a static switch operation and a change of zone power control set-point in Feeder A, when islanded.

Table 11 shows the values of Gen-sets, loads, power flows and frequency before the static switch opened and the resultant values after the static switch islanded the microgrid. The static switch was also allowed to reclose in this test to compare values indicated in the table before the static switch was opened. During this test, the series inductor L11 is connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-set A1 was set for zone power control mode and Gen-set A2 was set for unit power control mode. After Gen-sets A1 and A2 were running for a few minutes and in a steady state condition, Load Banks 3 and 4 were connected and measured approximately 54kW and 54kW, respectively. Gen-set A1 output power was approximately 50kW and Gen-set A2 output power was approximately 10kW. Power flow from the utility through the static switch, before it was opened, was approximately 53kW, indicating that about half of the load within the microgrid was being supplied by the utility grid.

As soon as the static switch was manually opened, the utility grid was no longer providing additional power needed to satisfy the loads in the microgrid; therefore, Gen-set A1 and A2 had to increase or decrease their output powers, accordingly. Gen-set A1 output power decreased from approximately 50kW to 47kW and Gen-set A2 increased from 10kW to 60kW. Gen-set A1 continued producing power because Gen-set A2 was at its maximum power point and could not satisfy load demand from Load Banks 3 and 4. The frequency decreased when the microgrid islanded from 59.965Hz to 59.78Hz, because the load demand increased within the microgrid and because of the CERTS algorithm. The resultant voltage in the system dropped from approximately 280V to 275V, decreasing load power demands in Load Banks 3 and 4 to approximately 52kW and 52.25kW, respectively. Power flow from the utility through the static switch was 0kW. The islanded microgrid operated this way for a few minutes before the static switch manual open was removed.

The static switch reconnected the microgrid to the utility grid in a smooth transition with Load Banks 3 and 4 supplied power from the microgrid and utility grid. Gen-set A1 increased its output power to approximately 49kW and Gen-set A2 decreased its output power to approximately 4kW. Load Banks 3 and 4 measured approximately

53.5kW and 52.8kW, respectively. Power flow at the static switch was approximately 57.5kW from the utility side. Voltage within the microgrid increased from approximately 275V to 280V and frequency increased approximately to 60.02Hz. The values after the static switch reconnected the microgrid to the utility grid were very similar to the values at the beginning of the test, which was expected.

Gen-sets A1 and A2 were shut down manually, all loads and alarms were reset, and equipment was prepared for the next test.

Test Results							
Event Open SS				Event Results Open SS		Event Results Close SS	
	Mode	Set-point	Expected Results	Start	End	Start	End
A1	Zone	54kW	0kW	50kW	0kW	0kW	55kW
A1	Injected P	60kW	60kW at Max	50kW	47kW	45kW	49kW
A2	Unit	6kW	60kW	10kW	60kW	60kW	4kW
B1		Off	Off	Off	Off	Off	Off
Freq		~60Hz	~59.5Hz	59.965Hz	59.54Hz	59.79Hz	60.02Hz
L3		60kW	60kW	54kW	52kW	51.7kW	53.5kW
L4		60kW	60kW	54kW	52.25kW	51.3kW	52.8kW
L5		0kW	0kW	0kW	0kW	0kW	0kW
L6		0kW	0kW	0kW	0kW	0kW	0kW
SS	Closed	54kW	0kW	53kW	0kW	0kW	57.5kW
Grid		54kW	0kW	53kW	0kW	0kW	57.5kW
Allow SS to Re-close Expect the system to return to Start values.							

Table 11 - Mixed Mode Operation Test Results, Feeder A When Islanded Automatic Reset of Zone Level Set-point

6.1.10 Two Sources in Zone Control – Separate Feeders, When Islanded Automatic Reset of Zone Set Points, Zones Sum Equal 0kW

Performance Goal:

Verify smooth transitions of Gen-sets, A1 and B1 in Zone power control mode, with a static switch operation and a change of zone power control settings in Feeder A and Feeder B, when islanded.

Table 12 shows the values of Gen-sets, loads, power flows and frequency before the static switch opened and resultant values after the static switch opened, islanding the microgrid. The static switch was also allowed to reclose in this test to compare values with initial values of the test before the static switch was opened. During this test, the series inductor L11 was connected to the utility grid to simulate weak grid conditions at the PCC to the microgrid.

Gen-sets A1 and B1 are both set for zone power control mode. After Gen-sets A1 and B1 were running for a few minutes and in a steady state condition, Load Banks 3 and 5 were connected, measuring approximately 35.5kW and 46.4kW, respectively. Gen-set A1 output power was approximately 0kW and Gen-set B1 output power was approximately 34kW. Power flow from the utility through the static switch, before it opened, was approximately 50kW, with a little more than half of the load within the microgrid being supplied by the utility grid.

As soon as the static switch was manually opened, the utility grid was no longer providing additional power needed to satisfy the loads in the microgrid; therefore, Gen-set A1 and B1 increased their output power, accordingly. Gen-set A1 output power increased from approximately 0kW to 22kW and Gen-set B1 increased from 34kW to 61kW. Zone 3 received 15kW from Zone 5 to cover the load demand of Load Bank 3. Frequency decreased when the microgrid islanded from 60.03Hz to 59.78Hz, because load demand increased within the microgrid and because of the CERTS algorithm. The resultant voltage in the system dropped from approximately 277V to 272V, decreasing load power demands in Load Banks 3 and 5 to approximately 34.2kW and 45.4kW, respectively. Power flow from the utility through the static switch was 0kW. The islanded microgrid operated this way for a few minutes before the static switch manual open was removed.

The static switch reconnected the microgrid to the utility grid in a smooth transition with Load Banks 3 and 5 being supplied power by the microgrid and utility grid. Gen-set A1 decreased its output power to approximately 0kW and Gen-set B1 decreased its output power to approximately 34kW. Load Banks 3 and 5 measured approximately 35.7kW and 46.3kW, respectively. Power flow at the static switch was approximately

50kW from the utility grid. Voltage within the microgrid increased from approximately 272V to 277V and frequency increased to approximately 60.015Hz. The resultant values after the static switch reconnected the microgrid to the utility grid were very similar to the values at the beginning of the test, which were expected.

Gen-sets A1 and B1 were manually shut down, all loads and alarms were reset, and equipment was prepared for the next test.

Test Results							
Event Open SS				Event Results Open SS		Event Results Close SS	
	Mode	Start	End	Start	End	Start	End
A1	Zone	40kW	10kW	35kW	13kW	13kW	36kW
A1	Injected P	0kW	30kW	0kW	22kW	21.5kW	0kW
A2		Off	Off	Off	Off	Off	Off
B1	Zone	10kW	-10kW	13kW	-15kW	-15.5kW	12kW
B1	Injected P	40kW	60kW	34kW	61kW	61kW	34kW
Fq		~60Hz	~59.76Hz	60.03Hz	59.78Hz	59.87Hz	60.015Hz
L3		40kW	40kW	35.5kW	34.2kW	34.4kW	35.7kW
L4		0kW	0kW	0kW	0kW	0kW	0kW
L5		50kW	50kW	46.4kW	45.4kW	45.3kW	46.3kW
L6		0kW	0kW	0kW	0kW	0kW	0kW
SS	Closed	50kW	0kW	50kW	0kW	0kW	50kW
Grid		50kW	0kW	50kW	0kW	0kW	50kW
Allow SS to re-close Expect the system to return to Start values							

Table 12 - Two Sources in Zone Control Test Results, Separate Feeders When Islanded, Automatic Reset of Zone Set-points, Zone Sums Equal Zero kW

6.1.11 Two Sources in Zone Control – Separate Feeders, When Islanded Automatic Reset of Zone Set Point

Performance Goal:

Verify smooth transitions of Gen-sets A1 and B1 in Zone power control mode, both having automatic reset of set points, with a static switch operation and a change of zone control power in Feeder A and Feeder B, when islanded.

Table 13 shows the values of Gen-sets, loads, power flows and frequency before the static switch opened and resultant final values after the static switch opened, islanding the microgrid. The static switch was also allowed to reclose in this test to compare values indicated in the table with initial values of the test before the static switch opened. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-sets A1 and B1 were both set for zone power control mode. After Gen-sets A1 and B1 were running for a few minutes and in a steady state condition, Load Banks 3, 5 and 6 were connected, measuring approximately 18.1kW, 35.8kW, and 18.15kW respectively. Gen-set A1 output power was approximately 43.6kW and Gen-set B1 output power was approximately 14kW. Power flow through the static switch before it opened was approximately -0.5kW, meaning that power was flowing beyond the static switch. Power flow from the utility grid was approximately 17.7kW which means that Load Bank 6 was being supported mainly by the utility grid. Gen-set A1 was supporting Load Bank 3 and sending approximately 25.1kW to Zone 5 and Load Bank 6.

As soon as the static switch was manually opened, the utility grid was no longer providing additional power needed to satisfy loads in the microgrid, therefore, Gen-set A1 and B1 had to increase and decrease their output powers, accordingly. Because nearly 0kW was being exported from the microgrid very little changed once the static switch opened. The frequency increased from 60.014Hz to 60.024Hz because load demand decreased within the microgrid and because of the CERTS algorithm. The resultant voltage in the system dropped from approximately 280V to 272V decreasing the load power demands in Load Banks 3 and 5 to approximately 17.45kW and 34.2kW, respectively. Power flow at the static switch was 0kW with approximately 18.6kW from the utility feeding Load Bank 6. The islanded microgrid operated this way for a few minutes before the static switch manual open was removed.

The static switch reconnected the microgrid to the utility grid in a smooth transition with Load Banks 3, 5 and 6 now being supplied power by the microgrid and utility grid. Gen-set A1 increased its output power to approximately 45kW and Gen-set B1 increased its output power to approximately 15.25kW. Load Banks 3, 5 and 6 measured approximately 18.15kW, 35.7kW and 18.1kW, respectively. Power flow at the static switch was approximately -3.5kW and 14.75kW from the utility side. Gen-set A1 increased its power output which was distributed to Zone 5 and Load Bank 6. Voltage within the microgrid increased from approximately 272V to 280V and frequency decreased to approximately 60.005Hz. The resultant values after the static switch reconnected the microgrid to the utility grid were very similar to the values at the beginning of the test, which was expected.

Gen-sets A1 and B1 were manually shut down, all loads and alarms were reset, and equipment was prepared for the next test.

Test Results							
Event Open SS				Event Results Open SS		Event Results Close SS	
	Mode	Set-point	Expected Results	Start	End	Start	End
A1	Zone	-30kW	-25kW	-25.1kW	-25.4kW	-25.5kW	-26.75kW
A1	Injected P	50kW	45kW	43.6kW	42.9kW	43kW	45kW
A2		Off	Off	Off	Off	Off	Off
B1	Zone	20kW	25kW	21.7kW	22.7kW	22.5kW	20.5kW
B1	Injected P	20kW	15kW	14kW	12kW	12.25kW	15.25kW
Freq		~60Hz	~60.04Hz	60.014Hz	60.024Hz	60.01Hz	60.005Hz
L3		20kW	20kW	18.1kW	17.45kW	17.55kW	18.15kW
L4		0kW	0kW	0kW	0kW	0kW	0kW
L5		40kW	40kW	35.8kW	34.2kW	34.4kW	35.7kW
L6		20kW	20kW	18.15kW	18.475kW	18.425kW	18.1kW
SS	Closed	-10kW	0kW	-0.5kW	0.1kW	0kW	-3.5kW
Grid		10kW	20kW	17.7kW	18.6kW	18.5kW	14.75kW
Allow SS to re-close Expect the system to return to Start values							

Table 13 - Two Sources in Zone Control Test Results, Separate Feeders When Islanded, Automatic Reset of Zone Set-point

6.1.12 Test Generator Black-Start Procedure

Performance Goal:

Bring up the Micro-grid Test Bed from a black-out condition without generation or protection trips. During this test, the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-set A1, A2 and B1 were set for injection power control, but were left off-line. Breaker CB1 was then opened where the microgrid was isolated from the utility with Load Bank 6 still part of the microgrid loads. A manual open was sent to the static switch to isolate the microgrid, islanding it from the utility grid. Gen-sets A1, A2 and B1 were started and allowed to run for a few minutes until steady state conditions were established. At this time Load Banks 3, 4, and 5 were applied to the microgrid at approximately 22.55kW + j10.35kVAr, 22.3kW + j9.95kVAr and 22.625kW + j10.45kVAr, respectively. Gen-set A1, A2 and B1 output powers were approximately 23kW, 23kW and 24kW, respectively. Frequency on the microgrid was 59.978Hz at a voltage level of approximately 271V. The grid supplied approximately 6kW to Load bank 6 which measured approximately 5.9kW + j10.95kVAr.

The manual “Open” was removed from the static switch and CB1 was closed. The static switch waited 300 seconds before closing into the utility grid, because of IEEE Standard 1547 requirements. A smooth transition occurred when the static switch closed into the utility grid.

The voltage and frequency increased in the microgrid to approximately 277V and 60.006Hz which in turn increased the load demands in Load Banks 3, 4 and 5 to approximately 23.35kW + j10.75kVAr, 23.075kW + j10.34kVAr and 23.275kW + j10.775kVAr, respectively. Load Bank 6 reduced to approximately 5.715kW + j10.61kVAr. Gen-sets A1, A2 and B1 decreased their output power to approximately 18.5kW, 19.5kW and 19.5kW, respectively. The additional power needed to support all loads in the microgrid and Load Bank 6 was supplied by the utility grid, which increased from approximately 6kW to 21kW. Zones 3, 4 and 5 increased to approximately 9kW, 4kW and 3.75kW. The microgrid was operated like this for a couple of minutes to monitor performance and fault events, which did not occur.

Gen-sets A1, A2 and B1 were manually shut down, all loads and alarms were reset, and equipment was prepared for the next test.

Test Results			
Event Close SS			
	Mode	Event Results Start	Event Results End
A1	Unit	23kW	18.5kW
A2	Zone	23kW	19.5kW
B1	Zone	24kW	19.5kW
Freq		59.978Hz	60.006Hz
L3		22.55kW	23.35kW
L4		22.3kW	23.075kW
L5		22.625kW	23.275kW
L6		5.9kW	5.715kW
SS	Open	0kW	15.5kW
Grid		6kW	21kW

Table 14 - Generator Black Start Procedure Test Results

6.1.13 Test/Establish Generator Black-Start Capacity

Performance Goal:

Determine the Black-start capacity of the microgrid by increasing the amount of load on the Micro-grid Test Bed from a black-out condition without generation or protection trips. During this test the series inductor L11 was connected to the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Gen-set A1 was set for unit power control mode, but was left off-line. CB1 was opened isolating the microgrid with Load Bank 6 still part of the microgrid loads. A manual open was sent to the static switch to isolate the microgrid, islanding it from the utility grid. At this time Load Bank 3 was connected to the microgrid at approximately 18kW + j17.5kVAr. Gen-set A1 was started and closed into the load in Load Bank 3. Gen-set A1 output power was approximately 20kW + j20.5kVAr. Zone 3 was approximately -2.3kW + j2.75kVAr supporting transformer T51 and the load of the static switch controls. Frequency on the microgrid was 60.00Hz at a voltage level of approximately 270V. Gen-set A1 was shut down manually after if ran for a few minutes. Load Bank 3 was then increased to approximately 31kW + j17.5kVAr and then Gen-set A1 was restarted.

The process above continued for three more load increases in Load Bank 3 (i.e., 47kW + j17.8kVAr, 50kW + j26.5kVAr and 59kW + j26.5kVAr). The results for all the Black-start load step tests are shown in Tables 15a – 15e. Gen-sets A1 was manually shut down, all loads and alarms were reset, and equipment was prepared for the next test.

		Event Results	
	Mode	Open SS and Gen-set A1 Start	
Load		**LOAD 20kW+j20kVar**	
		Start	End
A1	Unit	20kW	-2.3kW-j2.75kVar
A1	Injected P	0kW	20kW+j20.5kVar
A2		Off	Off
B1		Off	Off
Freq		0Hz	60Hz
L3		0kW	18kW+j17.5kVar
L4		Off	Off
L5		Off	Off
L6		Off	Off
SS		0kW+j0kVar	0kW+j0kVar
Grid		0kW+j0kVar	0kW+j0kVar

Table 15a - Black Start Test Results, 20kW + j20kVAr

		Event Results	
	Mode	Open SS and Gen-set A1 Start	
Load		**LOAD 35kW+j20kVar**	
		Start	End
A1	Unit	0kW	-2.3kW-j2.75kVar
A1	Injected P	0kW	32.5kW+j20kVar

A2		Off	Off
B1		Off	Off
Fq		0Hz	59.9Hz
L3		0kW	31kW+j17.5kVar
L4		Off	Off
L5		Off	Off
L6		Off	Off
SS		0kW+j0kVar	0kW+j0kVar
Grid		0kW+j0kVar	0kW+j0kVar

Table 15b - Black Start Test Results, 35kW + j20kVAr

		Event Results	
	Mode	Open SS and Gen-set A1 Start	
Load		**LOAD 55kW+j20kVar**	
		Start	End
A1	Zone	0kW	-2.35-j2.75kVar
A1	Injected P	0kW	50kW+j20.5kVar
A2		Off	Off
B1		Off	Off
Fq		0Hz	59.9Hz
L3		0kW	47kW+j17.8kVar
L4		Off	Off
L5		Off	Off
L6		Off	Off
SS		0kW+j0kVar	0kW+j0kVar
Grid		0kW+j0kVar	0kW+j0kVar

Table 15c - Black Start Test Results, 55kW + j20kVAr

		Event Results	
	Mode	Open SS and Gen-set A1 Start	

Load		**LOAD 60kW+j30kVar**	
		Start	End
A1	Zone	0kW	-2.25kW-j2.5kVar
A1	Injected P	0kW	52.5kW+j29kVar
A2		Off	Off
B1		Off	Off
Fq		0Hz	59.75Hz
L3		0kW	50kW+j26.5kVar
L4		Off	Off
L5		Off	Off
L6		Off	Off
SS		0kW+j0kVar	0kW+j0kVar
Grid		0kW+j0kVar	0kW+j0kVar

Table 15d - Black Start Test Results, 60kW + j30kVAr

		Event Results	
	Mode	Open SS and Gen-set A1 Start	
Load		**LOAD 70kW+j30kVar**	
		Start	End
A1	Zone	0kW	-2.19kW-j2.35kVar
A1	Injected P	0kW	61kW+j29kVar
A2		Off	Off
B1		Off	Off
Fq		0Hz	59.8Hz
L3		0kW	59kW+j26.5kVar
L4		Off	Off
L5		Off	Off
L6		Off	Off
SS		0kW+j0kVar	0kW+j0kVar

Grid	0kW+j0kVar	0kW+j0kVar

Table 15e - Black Start Test Results, 70kW + j30kVAr

7.0 CONCLUSION

The tests performed in section 8.0 "Reduced System Tests" were successfully performed which provided confidence that the Gen-set inverter controls were working properly and prepared for the power control test in section 9.0.

The tests proved to be more robust than previously predicted in the Black Start Tests in section 6.1.13 when the load was increased to a demand greater than the rating of the Gen-sets and all components remained online.