Arnold Schwarzenegger
Governor

CERTS MICROGRID LABORATORY TEST BED

Test Plan Section 9.0
Power Flow Control Tests

APPENDIX L

Prepared For:
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CERTS MICROGRID TEST REPORT

SECTION 9.0

"Power Flow Control 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 9.0 "Power Flow Control 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.

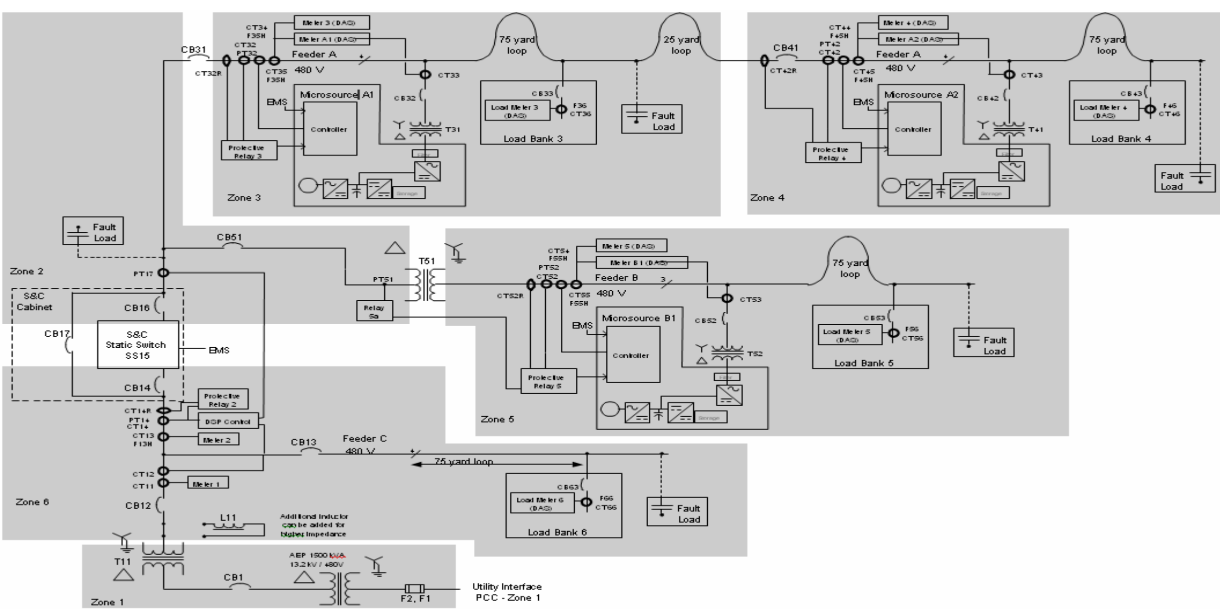

Figure 2 - One Line Diagram of CERTS Microgrid Test Bed

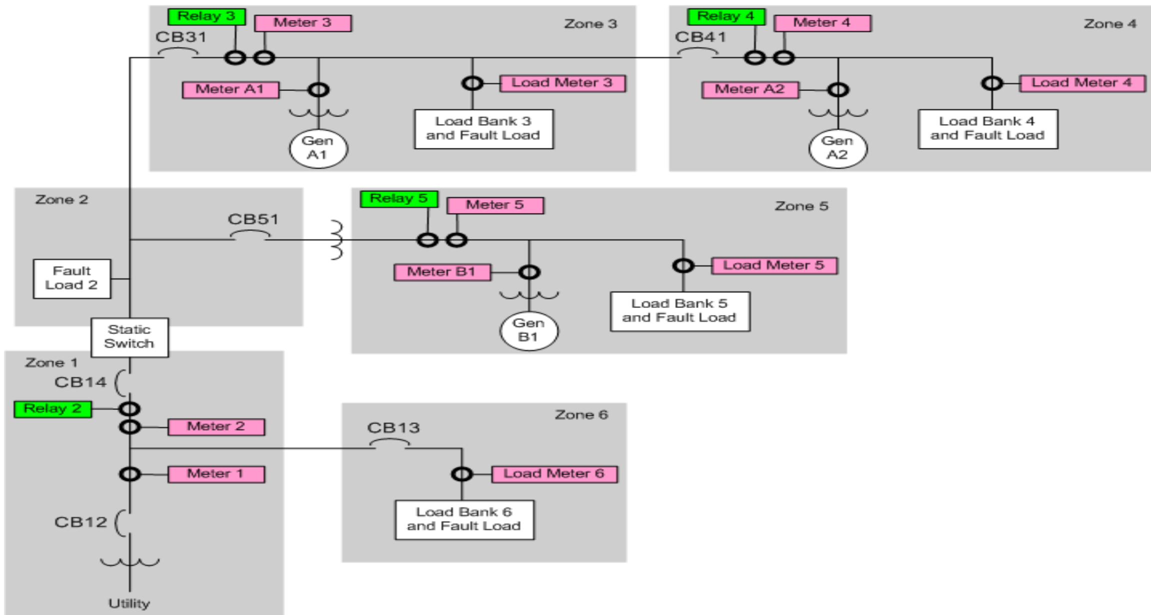

Figure 3 - Simplified diagram of Test Bed showing Meter and Relay locations

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.

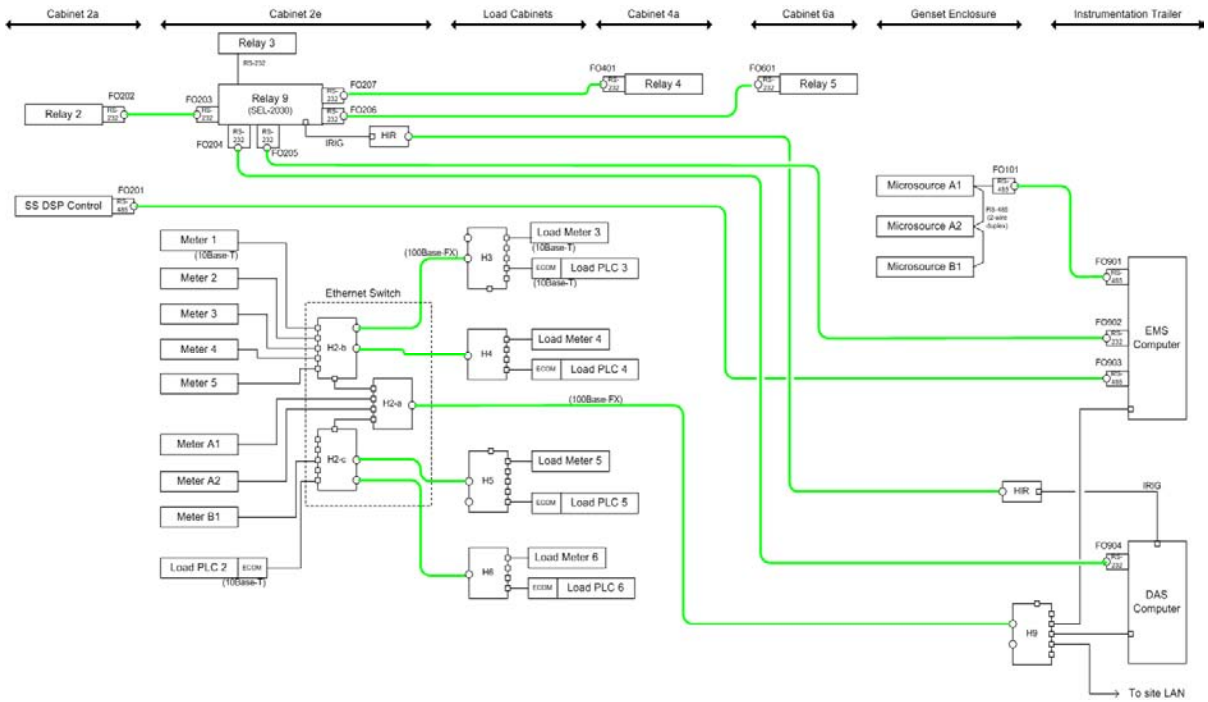

Figure 4 - Diagram of DAS & EMS Data networks

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 9.0

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.

Section 9 tests were designed to demonstrate the flexibility of the CERTS Microgrid connected to the utility grid and islanded. Various loads are applied to the microgrid while in unit control and zone control mode along with different power settings of the Gen-sets.

Tests performed in this section included inductor L11 in the circuit, reflecting weak utility grid conditions. Load on Feeder A and Feeder B were less than 170kW and Feeder C was such that there was no power going into the utility grid. All the loads included an approximate 0.9 power factor (pf) when possible and the motor load was connected and included as part of Zone 3.

Weak grid conditions were tested in the beginning of the test plan to minimize any damage to equipment. Time constraints forced a decision by the Team to postpone strong grid testing to a later date with concentration on weak grid testing. Therefore, strong grid tests were postponed from Tests 9.1, 9.2, 9.3 and 9.4. Tests 9.1 – 9.3 were required to verify and document power flow and Microgrid frequency changes when transitioning from utility connected to an islanded mode of operation. In each test, 9.1 – 9.3, a series of tests were performed that vary in the amount of load that is applied to the microgrid in a weak grid scenario along with the power settings of each Gen-set. The difference between each test is the type of control mode that the Gen-sets are in. In Test 9.1, all the Gen-sets are set for unit control mode and then the next test, 9.2, all the Gen-sets are set for zone control mode. Test 9.3 mixes the unit and zone control modes of the Gen-sets during each test.

6.0 <u>ANALYSES OF TEST RESULTS</u>

6.1 <u>SECTION 9 – POWER FLOW CONTROL TESTS</u>

6.1.1 <u>Unit Control Mode, Weak Grid</u>

Performance Goal:

Verify and document power flow and micro-grid frequency changes when transitioning from utility connected mode to an islanded mode of operation.

Four tests were completed in this section with each test event and settings listed in Table 16a. During each test Gen-sets A1, A2, and B1 were set for unit power control mode of operation. Each of the four tests varied the output power command set-point in each Gen-set, along with varying the load settings in load banks LB3, LB4, LB5 and LB6. During each test, inductor L11 was in series with the utility grid to simulate a weak grid condition at the PCC to the microgrid.

Test Event	Gen-set A1	Gen –set A2	Gen -set B1	Meter 2	Meter 3	Meter 4	Meter 5	LB 3	LB 4	LB 5	LB 6
9.1.7	Unit, 30 kW	Unit, 30 kW	Unit, 30 kW	+30 kW	+20 kW	+10 kW	+10 kW	40 kW 20 kVAr	40 kW 20 kVAr	40 kW 20 kVAr	20 kW 10 kVAr
9.1.8	Unit, 40 kW	Unit, 30 kW	Unit, 25 kW	+15 kW	-10 kW	-15 kW	+25 kW	20 kW 10 kVAr	40 kW 20 kVAr	50 kW 20 kVAr	20 kW 10 kVAr
9.1.9	Unit, 40 kW	Unit, 30 kW	Unit, 30 kW	-10 kW	-30 kW	+10 kW	+20 kW	25 kW 10 kVAr	15 kW 10 kVAr	50 kW 20 kVAr	30 kW 10 kVAr
9.1.10	Unit, 30 kW	Unit, 20 kW	Unit, 45 kW	+20 kW	+40 kW	20 kW	-20 kW	50 kW 20 kVAr	40 kW 20 kVAr	25 kW 10 kVAr	30 kW 10 kVAr

Table 16a - Unit Control Mode, Weak Grid Settings for Load Banks and Gen-sets

The procedure for each test event began with setting the kW and kVAr load (i.e., balanced load) conditions, as indicated in Table 16a, using the EMS at each Load Bank to achieve an approximate 0.9 power factor. Before loads were brought on-line, Gen-sets A1, A2 and B1 were started to allow them to warm up. After the Gen-sets ran for a few minutes and steady-state conditions established, the loads were brought on-line, the static switch was allowed to close, and measurements were taken from Meters 2, 3, 4 and

5. The measurements were then compared with the expected values in Table 16a. When the measured values coincided with the expected values from the table, then a manual open of the static switch was initiated to isolate/island the microgrid from the utility grid. Gen-sets were observed at this time to make sure they increased or decreased their output power as planned to satisfy the loads at load banks (i.e., LB3, LB4, LB5 and LB6) and that a smooth transition occurred. When all the measurements were verified and recorded in the DAS Database, the manual open signal to the static switch was released, allowing it to synchronize and close back into the utility grid. As soon as the static switch synchronized and re-closed, all data (i.e., from the manual open event and the reconnection event) was verified and recorded in the DAS Database. Loads and Unit Power Control set-points were then changed to the settings for the next test. Test results are explained in the following paragraphs.

For Test 9.1.7 the measured values, after the Gen-sets were warmed up and load banks brought on-line, were approximately 40kW at Meter 1, 22kW at Meter 2, 12.5 kW at Meter 3, 3.5kW at Meter 4, 7kW at Meter 5, shown in Table 16b. From the microgrid, 26.5kW was produced by Gen-set A1, 31.5 kW produced by Gen-set A2, and 28kW produced by Gen-set B1. The load banks were slightly less than planned with 35.5kW at LB3, 34.7kW at LB4, 34.8kW at LB5, and 18.32kW at LB6. These measurements were relatively close to the expected values in Table 16a, but not exact due to temperature, phase voltages and electrical losses in conductors. In addition, the 40kW setting for LB3, LB4 and LB5; and 20kW setting for LB6 were also below the selected set values. The deviation of selected values versus actual values was consistent for the other three tests in this section. At the time of these measurements, the voltage and frequency was 276V and 59.99Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 276V and 59.99Hz at Meter 3. The power factor at each load was approximately 0.87 which is a 3% difference from the desired 0.9 power factor.

9.1.7												
	GENSET A1	**GENSET A2**	**GENSET B1**	**METER 1**	**METER 2**	**METER 3**	**METER 4**	**METER 5**	**LB 3**	**LB 4**	**LB 5**	**LB 6**
INITIAL SETUP	UNIT +30kW	UNIT +30kW	UNIT +30kW		+30kW	+20kW		+10kW	40kW	40kW	40kW	20kW
GRID-TO-ISLAND												
Start												
Voltage (V)					276	276						
Current (A)	32	40	39	80	56	41	15	11				
Real Power (kW)	26.5	31.5	28	40	22	12.5	3.5	7	35.15	34.7	34.8	18.32

Reactive Power (kVAr)	0	8	14.5	51	41	31.5	11	5	19.7	19.7	19.7	10.675
Power Factor (pf)	1.00	0.97	0.89						0.87	0.87	0.87	0.86
Frequency (Hz)					59.99	59.99						
End												
Voltage (V)					281	268						
Current (A)	42	54	52.5	26	0	5	6.5	9				
Real Power (kW)	32	37	33.6	19	0	-2.5	-4	-0.25	33.3	32.85	33.3	19
Reactive Power (kVAr)	13	21	25	12	0	3	-3	-6	18.7	18.7	18.9	11.25
Power Factor (pf)	0.93	0.87	0.80						0.87	0.87	0.87	0.86
Frequency (Hz)					59.988	59.944						
ISLAND-TO-GRID												
Start												
Voltage (V)					280	268						
Current (A)	42	52	52	26	0	5	6	8				
Real Power (kW)	32	36.5	33.5	19	0	-2	-4	-0.25	33.35	32.7	33.1	18.75
Reactive Power (kVAr)	13	22	25	12	0	4	-3	-6	18.7	18.75	18.95	11.24
Power Factor (pf)	0.93	0.86	0.80						0.87	0.87	0.87	0.86
Frequency (Hz)					60.009	59.942						
End												
Voltage (V)					276	272						
Current (I)	30	30	35	85	60	45	16	13				
Real Power (kW)	23.5	28.5	25	47	30	17	6	9.5	35.1	34.45	34.55	17.9
Reactive Power (kVAr)	0	9	15.5	50	39	31	10	4	19.7	19.75	19.75	10.7
Power Factor (pf)	1.00	0.95	0.85						0.87	0.87	0.87	0.86
Frequency (Hz)					60.01	60.01						

Table 16b – Test 9.1.7 results with dark squares in the table meaning that measurements were not needed.

According to the measurements in Table 16b when connected to the utility grid, each Gen-set in the microgrid was set at 30kW which was not enough to satisfy the loads in LB3, LB4 and LB5 and needed approximately 22kW from the utility grid, as measured by Meter 2. Total power from the utility grid was measured at approximately 40kW from Meter 1, because it was meeting the demands of not only the microgrid loads, but the load at LB6. Once all data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually open.

When the static switch opened, Meter 1 decreased to approximately 19kW satisfying the load demand in LB6 which was approximately 19kW and not supplying any power beyond the static switch to the microgrid loads. 0kW was recorded at Meter 2, showing that power was not flowing through the static switch. LB3, LB4 and LB5 loads reduced slightly to 33.3kW, 32.85kW and 33.3kW, respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 29a, from approximately 276V (i.e., 276V on A-phase and 273V on B- & C-phases) when connected to the utility grid to 268V at Meter 3 (i.e., on A-, B-, and C-phases) when islanded.

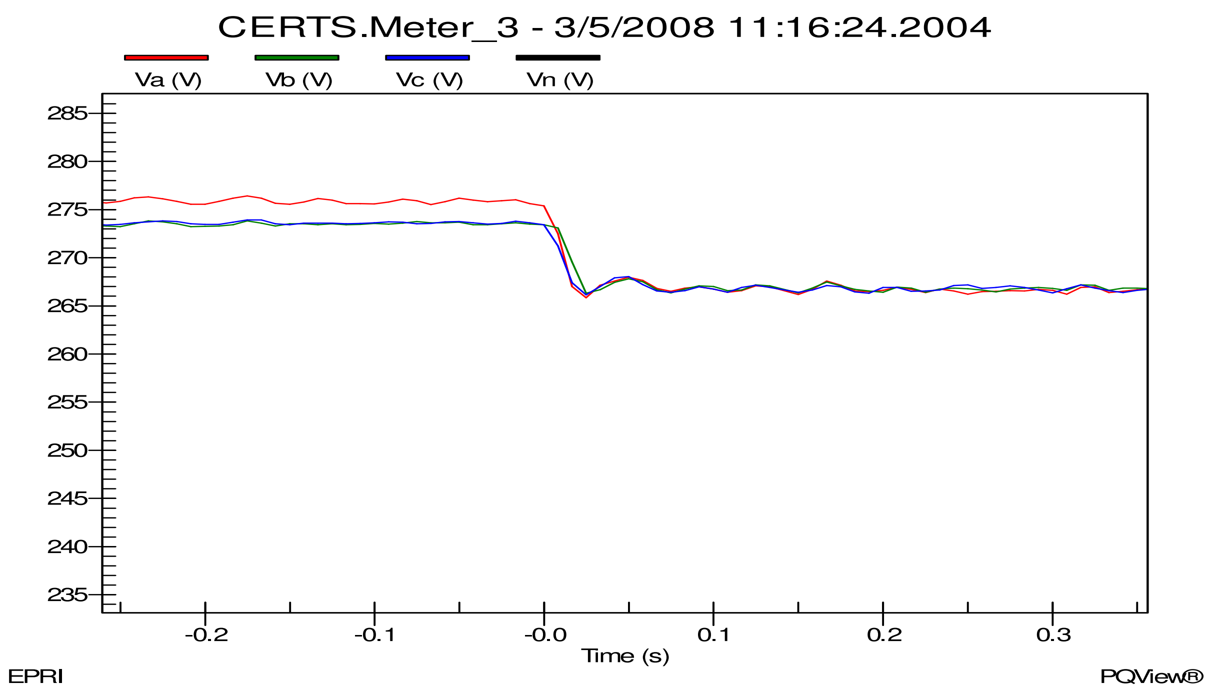

Figure 29a - Meter 3 voltage before/after the static switch opened, islanding the microgrid from the utility grid

Frequency change in the microgrid, shown in Figure 29b, dropped from 59.99Hz when connected to the utility grid to approximately 59.94 Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed the Gen-sets to increase their output power to satisfy the load demands. Gen-set A1, A2, and B1 increased their output power to approximately 32kW, 37kW and 33.6kW, respectively. Meters 3, 4 and

5 were negative values (-2.5kW, -4kW and -0.25kW, respectively), indicating the Gen-sets were satisfying the loads in the microgrid and the power losses in the line. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the manual open signal was released and allowed the static switch to synchronize to the utility grid.

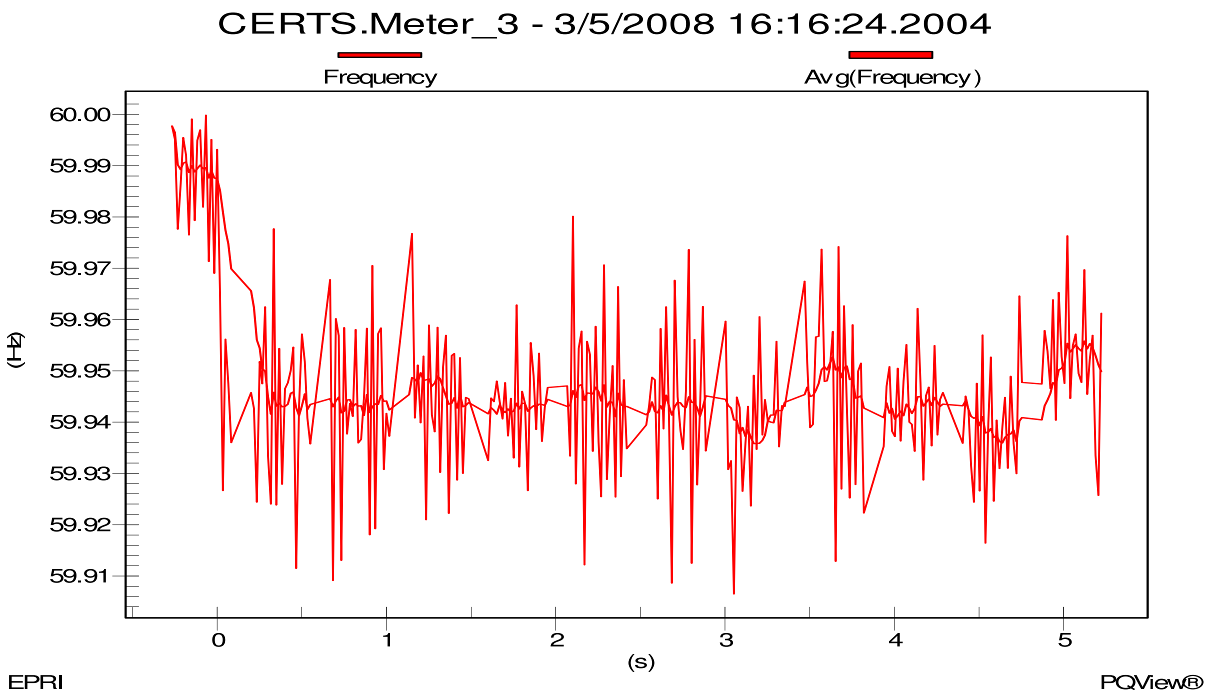

Figure 29b – Meter 3 frequency before/after the static switch opened, islanding the microgrid from the utility grid.

As soon as the static switch closed and steady-state conditions established, the measurements at the Gen-sets, Meters and Load Banks were compared to the initial conditions at the beginning of the test. The measured values when synchronized to the utility grid were very similar to the initial conditions. Voltage and frequency in the microgrid increased from 268V to 276V and 59.944Hz to 60.01Hz. The power factor of approximately 0.87 remained the same throughout the test. After all the data was verified and recorded into the DAS Database the Gen-sets and Load Banks set-points were changed according to the next test (9.1.8) in Table 16a.

For Test 9.1.8 the measured values, after the Gen-sets were warmed up and load banks brought on-line, were approximately 35kW at Meter 1, 17kW at Meter 2, -10 kW at Meter 3, 6kW at Meter 4, and 24kW at Meter 5, shown in Table 16c. From the microgrid, 33.75kW was produced by Gen-set A1, 29 kW produced by Gen-set A2, and 20.5kW produced by Gen-set B1. The load banks were slightly less than planned with 18.05kW at LB3, 34.6kW at LB4, 44.5 kW at LB5, and 18.1kW at LB6. These measurements were relatively close to the expected values in Table 16a but not exact, due to temperature, phase voltages and electrical losses in the conductors. In addition, the desired kW settings for LB3, LB4, LB5 and LB6 were also below the set values. This deviation of set values verses actual values was consistent for the other tests in this section. At the time of these measurements, the voltage and frequency when connected to the utility grid was 277V and 60.008Hz at the static switch (i.e., Meter 2); and 277V and 60.008Hz at Meter 3. The power factor at LB3, LB4 and LB6 was approximately 0.87 and 0.91 at LB5 which is close to the desired 0.9 power factor.

9.1.8												
	GENSET A1	**GENSET A2**	**GENSET B1**	**METER 1**	**METER 2**	**METER 3**	**METER 4**	**METER 5**	**LB 3**	**LB 4**	**LB 5**	**LB 6**
INITIAL SETUP	UNIT +40kW	UNIT +30kW	UNIT +25kW		+15kW	-10kW		+25kW	20kW	40kW	50kW	20kW
GRID-TO-ISLAND												
Start												
Voltage (V)					277	277						
Current (A)	41	37	30	71	50	35	18	30				
Real Power (kW)	33.75	29	20.5	35	17	-10	6	24	18.05	34.6	44.5	18.1
Reactive Power (kVAr)	-3	6	15	47	37	28	0	4.8	10.65	19.95	19.8	10.8
Power Factor (pf)	1.00	0.98	0.81						0.86	0.87	0.91	0.86
Frequency (Hz)					60.008	60.008						
End												
Voltage (V)					280	269						
Current (A)	47	46	44	26	0	26	3	24				
Real Power (kW)	37.5	33.25	25	19	0	-21	0	18	17.15	33	42.8	18.85
Reactive Power (kVAr)	9	18	24.5	12	0	2	1.5	-5.5	10.1	19	19	11.3
Power Factor (pf)	0.97	0.88	0.71						0.86	0.87	0.91	0.86
Frequency (Hz)					60.008	59.974						
ISLAND-TO-GRID												
Start												
Voltage (V)					281	269						

Current (A)	47	46	44	26	0	26	3	24				
Real Power (kW)	38	33.5	25	19	0	-21	0	18	17.25	33.1	42.9	18.9
Reactive Power (kVAr)	9	18	24.5	12	0	2.5	1	-6	10.1	19	19.05	11.35
Power Factor (pf)	0.97	0.88	0.71						0.86	0.87	0.91	0.86
Frequency (Hz)					59.985	59.975						
End												
Voltage (V)					276	276						
Current (I)	42	39	32	70	50	38	19	28				
Real Power (kW)	35.5	31	22.5	30	13	-12.5	4.5	22.5	18.2	34.9	44.7	18.1
Reactive Power (kVAr)	-4	5	14	50	39	29.5	15	5	10.7	20	19.8	10.8
Power Factor (pf)	0.99	0.99	0.85						0.86	0.87	0.91	0.86
Frequency (Hz)					59.995	59.995						

Table 16c – Test 9.1.8 results with dark squares in the table meaning that measurements were not needed.

According to the measurements in Figure 16c when connected to the utility grid, each Gen-set in the microgrid was set at 40kW for Gen-set A1, 30kW for Gen-set A2 and 25kW for Gen-set B1, which was not enough to satisfy the loads in LB4 and LB5, and needed approximately 17kW from the utility grid, measured by Meter 2. Total power from the utility grid was measured at approximately 35kW in Meter 1, because it was meeting the demands of not only the microgrid loads, but the load at LB6. In addition, Meter 3 recorded approximately -10kW, meaning Gen-set A1 was supplying power for all of LB3, 6kW to LB4, measured by Meter 4, and approximately 10kW to LB5. Once all data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually open.

When the static switch opened, Meter 1 decreased to approximately 19kW satisfying the load demand in LB6 which was approximately 18.85kW and not supplying any power beyond the static switch to the microgrid loads. 0kW was measured at Meter 2, showing that power was not flowing through the static switch. LB3, LB4 and LB5 loads reduced slightly to17.15kW, 33kW and 42.8kW, respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 29c, from approximately 277V (i.e., 277V on A-phase, 275V on B- and C-phases) when connected to the utility grid to 269V on all three phases when islanded.

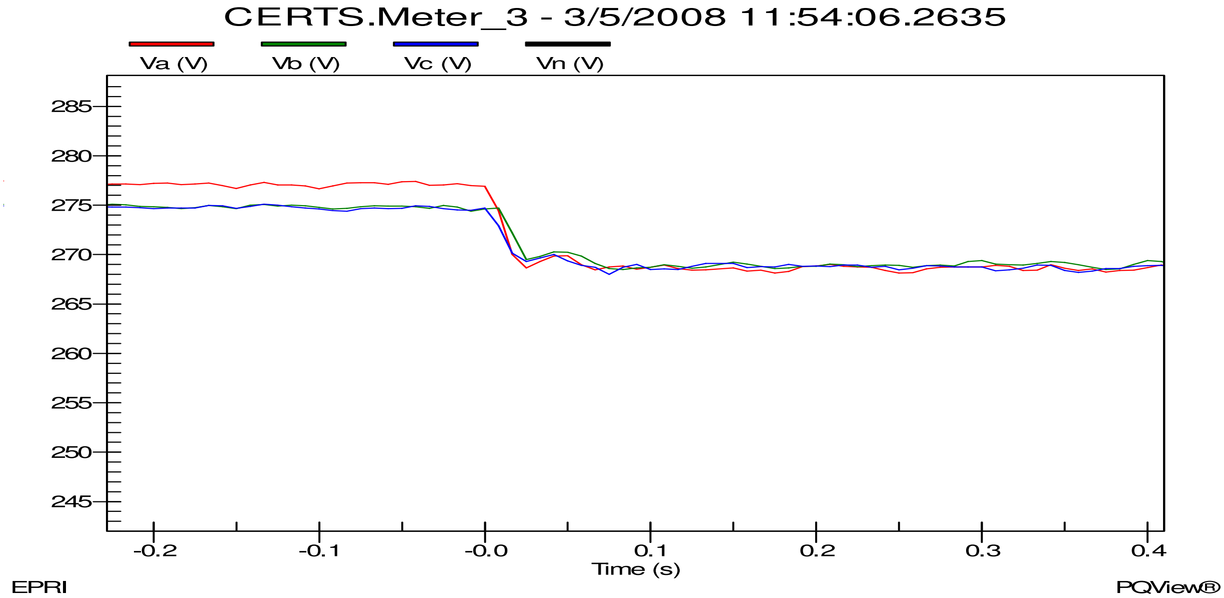

Figure 29c – Meter 3 voltage before/after the static switch opened, islanding the microgrid from the utility grid.

Frequency changed in the microgrid, shown in Figure 29d, from 60.008Hz to 59.974 Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed the Gen-sets to increase their output power to satisfy the load demands. Gen-set A1, A2 and B1 increased their output power to 37.5kW, 33.25kW and 25kW, respectively. Meter 3 indicated a negative value of -21kW, meaning it supplied all of LB3 load and 18kW of LB5 at Meter 5. Meter 4 indicated 0kW showing that Gen-set A2 supplied all of LB4 load. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the manual open signal was released and allowed the static switch to synchronize to the utility grid.

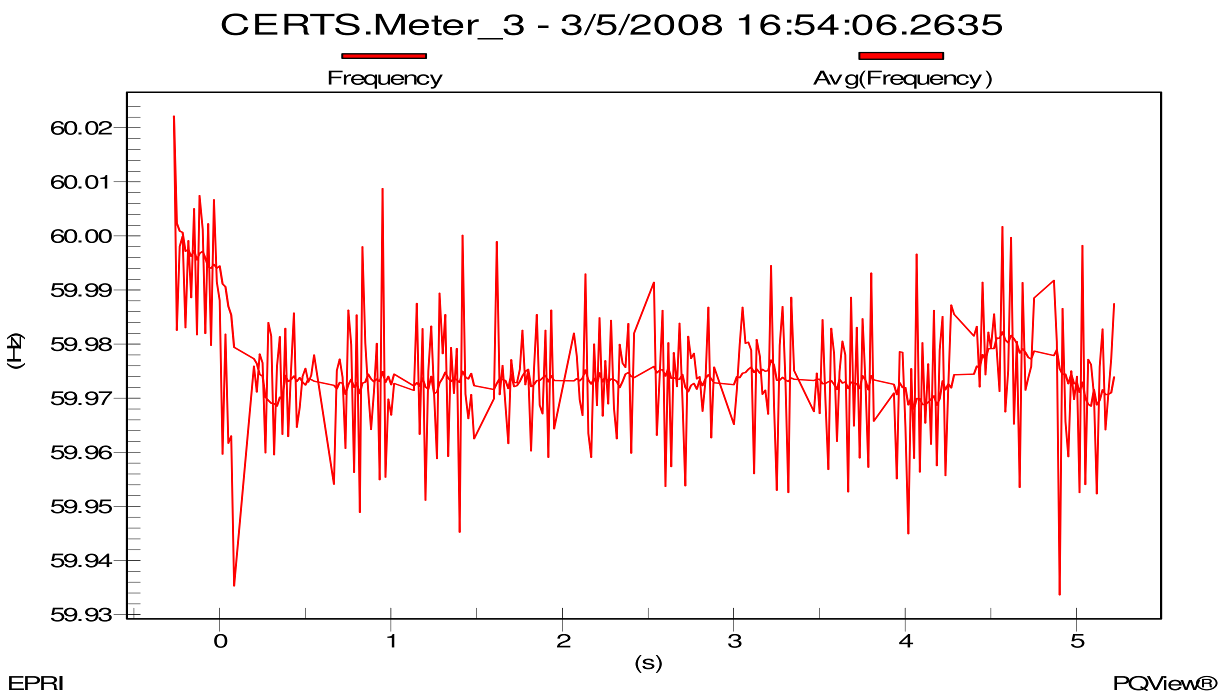

Figure 29d – Meter 3 frequency before/after the static switch opened, islanding the microgrid from the utility grid.

As soon as the static switch closed and steady-state conditions established, the measurements at the Gen-sets, Meters and Load Banks were compared to the initial conditions at the beginning of the test. The measured values were very similar to the initial test conditions which were approximately 30kW at Meter 1, 13kW at Meter 2, -12.5kW at Meter 3, 4.5kW at Meter 4, and 22.5kW at Meter 5 with 35.5kW produced by Gen-set A1, 31kW produced by Gen-set A2, and 22.5kW produced by Gen-set B1. Likewise, 18.2kW was at LB3, 34.9kW at LB4, 44.7kW at LB5 and 18.1kW at LB6. The microgrid voltage increased from 269V to 276V and frequency increased from 59.974Hz to 59.995Hz. The power factor of approximately 0.87 remained the same throughout the test for LB3, LB4 and LB6 and 0.91 for LB5. After all data was verified and recorded into the DAS Database, Gen-sets A1, A2 and B1 were shut down manually and all load banks/alarms were reset and prepared for the next test (9.1.9) in Table 16a.

For Test 9.1.9 the measured values, after the Gen-sets were warmed up and load banks brought on-line, were approximately 15kW at Meter 1, -13.5kW at Meter 2, -33 kW at Meter 3, -15kW at Meter 4, and 16.5kW at Meter 5. From the microgrid 40.5kW was produced by Gen-set A1, 32 kW produced by Gen-set A2, 28.5kW produced by Gen-set B1. The load banks were slightly less than planned with 23.25kW at LB3, 16kW at LB4, 45kW at LB5, and 28.6kW at LB6. These measurements were relatively close to the expected values in Table 16a but not exact, due to temperature, phase voltages and electrical losses in conductors. In addition, the desired kW settings for LB3, LB4, LB5 and LB6 were below the set values. This deviation of set values verses actual values was consistent for the other tests in this section. At the time of these measurements the voltage and frequency was 277V and 59.99Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 277V and 59.99Hz at Meter 3. The power factor at LB4 was approximately 0.85, 0.91 at LB3 and LB5, and 0.94 at LB6 which was close to the desired 0.9 power factor.

9.1.9												
	GENSET A1	GENSET A2	GENSET B1	METER 1	METER 2	METER 3	METER 4	METER 5	LB 3	LB 4	LB 5	LB 6
INITIAL SETUP	UNIT +40kW	UNIT +30kW	UNIT +30kW		-10kW	-30kW		+20kW	25kW	15kW	50kW	30kW
GRID-TO-ISLAND												
Start												
Voltage (V)					277	277						
Current (A)	47	39	38	60	45	50	22	22				
Real Power (kW)	40.5	32	28.5	15	-13.5	-33	-15	16.5	23.25	16	45	28.6
Reactive Power (kVAr)	-5	3	12.5	45	35	23	7	7	10.8	10	19.9	10.8
Power Factor (pf)	0.99	1.00	0.92						0.91	0.85	0.91	0.94
Frequency (Hz)					59.99	59.99						
End												
Voltage (V)					280	270						
Current (A)	44	37	39	39	30	0	15	26				
Real Power (kW)	35	26	23	30	0	-23	-11	21	22.25	15.3	43.4	29.65
Reactive Power (kVAr)	6	15	22	12	0	-1	-5	-3	10.3	9.55	19.2	11.2
Power Factor (pf)	0.99	0.87	0.72						0.91	0.85	0.91	0.94
Frequency (Hz)					59.986	60.03						
ISLAND-TO-GRID												
Start												
Voltage (V)					280	270						
Current (A)	44	37	39	39	0	30	15	26				
Real Power (kW)	35	26	23	30	0	-23	-10.5	21	22.3	15.35	43.4	29.6

Reactive Power (kVAr)	6	15	22	12	0	0	-5	-3	10.3	9.55	19.2	11.25
Power Factor (pf)	0.99	0.87	0.72						0.91	0.85	0.91	0.93
Frequency (Hz)					59.997	60.06						
End												
Voltage (V)					276	276						
Current (I)	50	40	38	60	47	50	21	22				
Real Power (kW)	40.5	32	29	13	-15	-34	-16	16	23.25	16.05	45	28.55
Reactive Power (kVAr)	-5	3	12.5	46	45	23	7	7	10.8	10	19.95	10.8
Power Factor (pf)	0.99	1.00	0.92						0.91	0.85	0.91	0.94
Frequency (Hz)					59.98	59.98						

Table 16d - Test 9.1.9 results with dark squares in the table meaning that measurements were not needed.

According to the measurements in Table 16d when connected to the utility grid, each Gen-set in the microgrid was set at 40kW for Gen-set A1, 30kW for Gen-set A2 and 30kW for Gen-set B1 which was enough to satisfy the loads in LB3, LB4 and LB5 and provided 13.5kW measured at Meter 2. The utility supplied approximately 15kW, measured in Meter 1, because it supplied the remaining portion of load at LB6. In addition, Meter 4 measured -15kW meaning that Gen-set A2 was supplying all the power to LB4, plus an additional 15kW. Meter 3 measured 33kW, meaning Gen-set A1 was supplying all the power to LB3 plus producing an additional 18kW. The excess of approximately 33kW, flowing out of Zone 3, was supplied to LB5 and LB6, measured by Meter 5 at 16.5kW and Meter 1 at 15kW. Once all data was verified and recorded into the DAS Database, the static switch was manually opened by the EMS.

When the static switch opened, Meter 1 increased to approximately 30kW satisfying the load demand in LB6, which was 29.65kW and not supplying any power beyond the static switch to microgrid loads. 0kW was measured at Meter 2, showing that power was not flowing through the static switch. LB3, LB4 and LB5 loads reduced slightly to 22.25kW, 15.3kW and 43.4kW, respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 29e, from approximately 277V (i.e., 277.5V on A-phase and 275.5V on B- and C-phases) when connected to the utility grid, to 270V on all three phases when islanded.

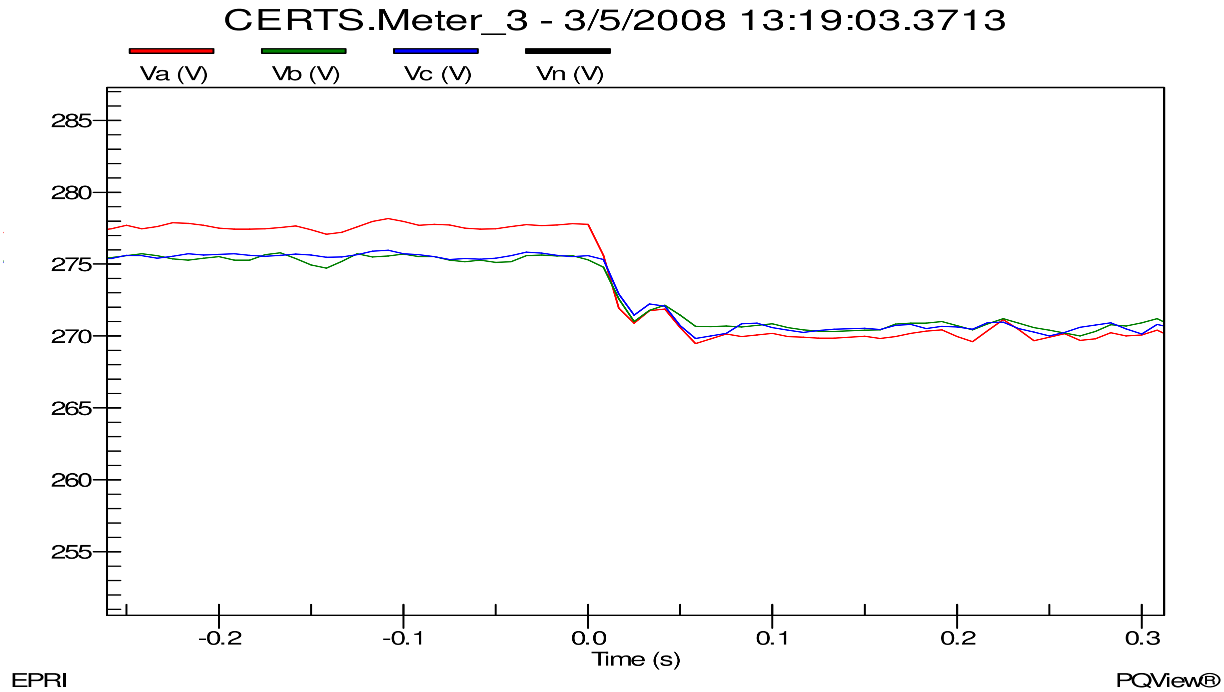

Figure 29e – Meter 3 voltage before/after the static switch opened, islanding the microgrid from the utility grid.

Frequency changed in the microgrid, shown in Figure 29f, and increased to approximately 60.03 Hz which was part of the CERTS algorithm which allowed the Gen-sets to decrease their output power to satisfy the load demands. Gen-set A1, A2 and B1 decreased their output power to approximately 35kW, 26kW and 23kW, respectively. Meter 4 measured approximately -11kW and Meter 3 measured -23kW. Gen-sets A1 and A2 supplied all the power to LB3 and LB4 plus supplied approximately 21kW of LB5 indicated on Meter5. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the manual open signal was released and allowed the static switch to synchronize to the utility grid.

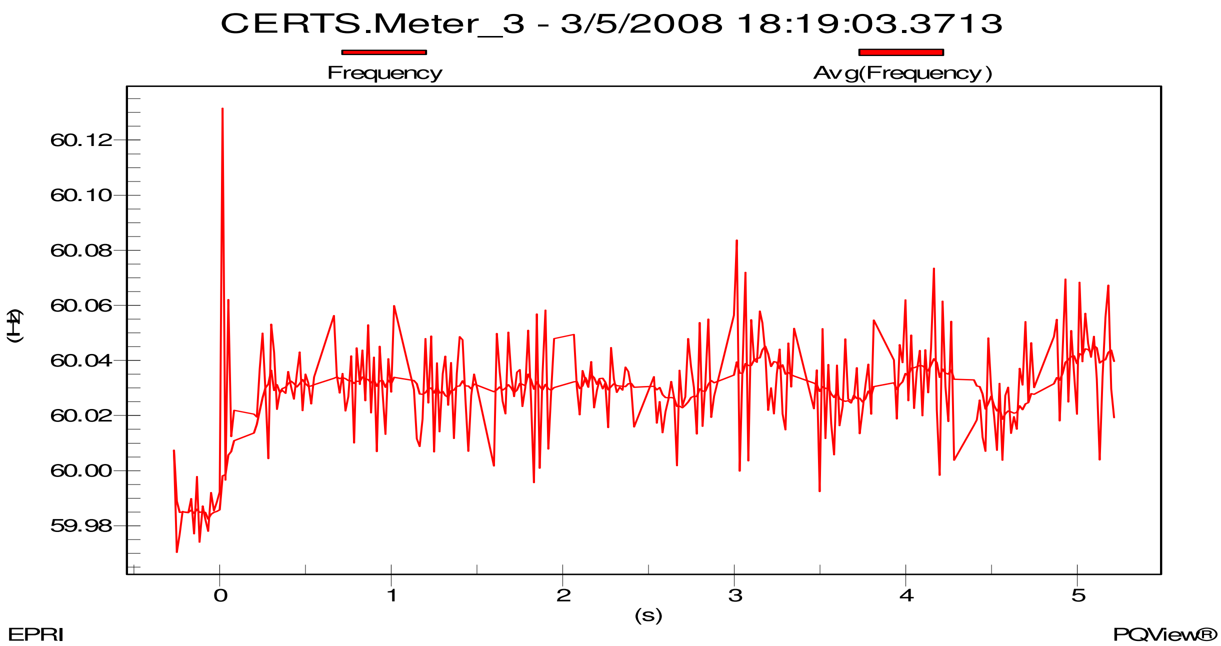

Figure 29f – Meter 3 frequency before/after the static switch opened, islanding the microgrid from the utility grid.

As soon as the static switch closed and steady-state conditions established, the measurements at the Gen-sets, Meters and Load Banks were compared to the initial conditions at the beginning of the test. The measured values were very similar to the initial test conditions which were 13kW at Meter 1, -15kW at Meter 2, -34kW at Meter 3, -16kW at Meter 4, and 16kW at Meter 5 with 40.5kW produced by Gen-set A1, 32kW produced by Gen-set A2, and 29kW produced by Gen-set B1. Likewise, 23.25kW was at LB3, 16.05kW at LB4, 45kW at LB5 and 28.55kW at LB6. The microgrid voltage increased from 270V to 276V and frequency decreased from 60.03Hz to 59.98Hz. The power factor of approximately 0.85 remained the same throughout the test for LB4, 0.91 for LB3 and LB5, and 0.94 for LB6. After all data was verified and recorded into the DAS Database, Gen-sets A1, A2 and B1 were shut down manually and all load banks/alarms were reset and prepared for the next test (9.1.10) in Table 16a.

For Test 9.1.10 the measured values, after the Gen-sets were warmed up and the load banks brought on-line, were approximately 36kW at Meter 1, 7.5kW at Meter 2, 26 kW at Meter 3, 12kW at Meter 4, and -21.5kW at Meter 5. From the microgrid 31.3kW was produced by Gen-set A1, 22.6kW produced by Gen-set A2, and 44.5kW produced by Gen-set B1. The load banks were slightly less than planned with 45.5kW at LB3, 34.55kW at LB4, 22.95 kW at LB5, and 28.35kW at LB6. These measurements were relatively close to the expected values in Table 16a but not exact, due to temperature, phase voltages, and electrical losses in conductors. In addition, the desired kW setting for LB3, LB4, LB5 and LB6 were below the set values. This deviation of set values verses actual values was consistent with other tests in this section. At the time of these measurements the voltage and frequency was 276V and 59.9785Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 276V and 59.977Hz at Meter 3. The power factor at LB4 was approximately 0.87, 0.91 at LB5, 0.92 at LB3, and 0.94 at LB6 which is close to the desired 0.9 power factor.

9.1.10												
	GENSET A1	**GENSET A2**	**GENSET B1**	**METER 1**	**METER 2**	**METER 3**	**METER 4**	**METER 5**	**LB 3**	**LB 4**	**LB 5**	**LB 6**
INITIAL SETUP	UNIT +30kW	UNIT +20kW	UNIT +45kW		+20kW	+40kW		-20kW	50kW	40kW	25kW	30kW
GRID-TO-ISLAND												
Start												
Voltage (V)					276	276						
Current (A)	37	31	55	75	46	54	21.5	26.5				
Real Power (kW)	31.3	22.6	44.5	36	7.5	26	12	-21.5	45.5	34.55	22.95	28.35
Reactive Power (kVAr)	-2	9	9.5	50	39	33	11	1	19.725	19.75	10.74	10.7
Power Factor (pf)	1.00	0.93	0.98						0.92	0.87	0.91	0.94
Frequency (Hz)					59.978	59.977						
End												
Voltage (V)					279	268						
Current (A)	41	40	61	37	0	27	13	31				
Real Power (kW)	32	23.3	45.4	29.6	0	21	9.5	-23	43.2	32.85	22	29.55
Reactive Power (kVAr)	10.9	21.5	19.5	2	0	5	-2.5	-9	18.75	18.75	10.25	11.2
Power Factor (pf)	0.95	0.73	0.92						0.92	0.87	0.91	0.94
Frequency (Hz)					59.9775	59.97						
ISLAND-TO-GRID												
Start												
Voltage (V)					281	270						
Current (A)	42	40	61	39	0	29	12	31				
Real Power (kW)	32.5	23.5	45.5	30	0	21	9	-23.2	43.3	32.9	22.1	29.7

Reactive Power (kVAr)	32.5	21	20	12	0	6	-2.5	-9.5	18.8	18.85	10.25	11.3
Power Factor (pf)	0.71	0.75	0.92						0.92	0.87	0.91	0.93
Frequency (Hz)					59.995	59.98						
End												
Voltage (V)					275	277						
Current (I)	37	27	54	80	52	59	22.5	25				
Real Power (kW)	30	21.25	43	40	12	29.5	13.75	-20	45.6	34.7	23.5	28.4
Reactive Power (kVAr)	30	8	9	51	40	35	11	1.9	19.8	19.85	10.75	10.75
Power Factor (pf)	0.71	0.94	0.98						0.92	0.87	0.91	0.94
Frequency (Hz)					59.99	59.99						

Table 16e - Test 9.1.9 results with dark squares in the table meaning that measurements were not needed.

According to the measurements in Table 16e, Gen-sets in the microgrid were set at 30kW for Gen-set A1, 20kW for Gen-set A2 and 45kW for Gen-set B1, which was not enough to satisfy the loads in LB3 and LB4 and needed approximately 7.5kW from the utility grid, measured by Meter 2. The utility grid supplied a total power of approximately 36kW, measured in Meter 1, because it met the demands of not only the microgrid loads, but the load at LB6l. Meter 5 measured approximately -21.5kW, meaning Gen-set B1 supplied all the power to LB5 and exported some power to LB3 and LB4. The power exported from the utility grid and Gen-set B1 was approximately 26kW into LB3 and LB4, measured by Meter 3. Meter 4 measured 12kW meaning that LB3 needed an additional 14kW on top of the power produced by Gen-set A1 and LB4 needed an additional 12kW on top of the power produced by Gen-set A2. Once all data was verified and recorded into the DAS Database, the static switch was manually opened by the EMS.

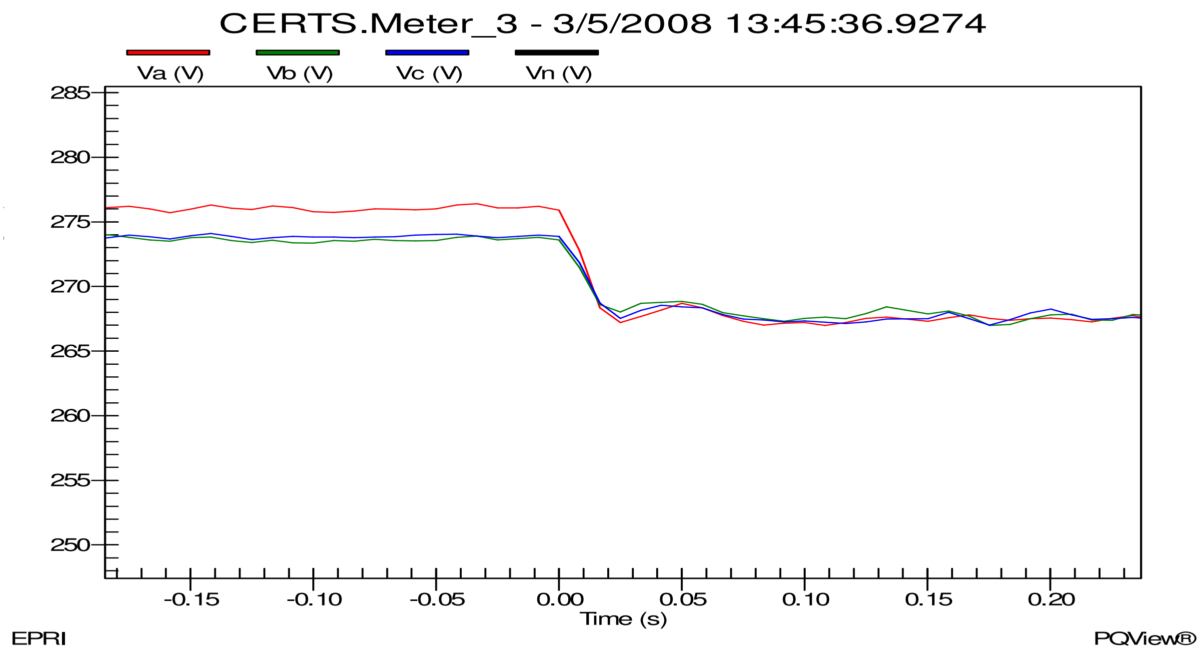

Figure 29g – Meter 3 voltage before/after the static switch opened, islanding the microgrid from the utility grid.

When the static switch opened, Meter 1 decreased to approximately 29.6kW satisfying the load demand in LB6, which was approximately 29.55kW and not supplying any power beyond the static switch to microgrid loads. 0kW was measured at Meter 2, showing that power was not flowing through the static switch. LB3, LB4 and LB5 loads reduced slightly to 43.2kW, 32.85kW and 22kW, respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 29g, from approximately 276V (i.e., 276V on A-phase and 274V on B- and C-phases), when connected to the grid, to 268V on all three phases when islanded.

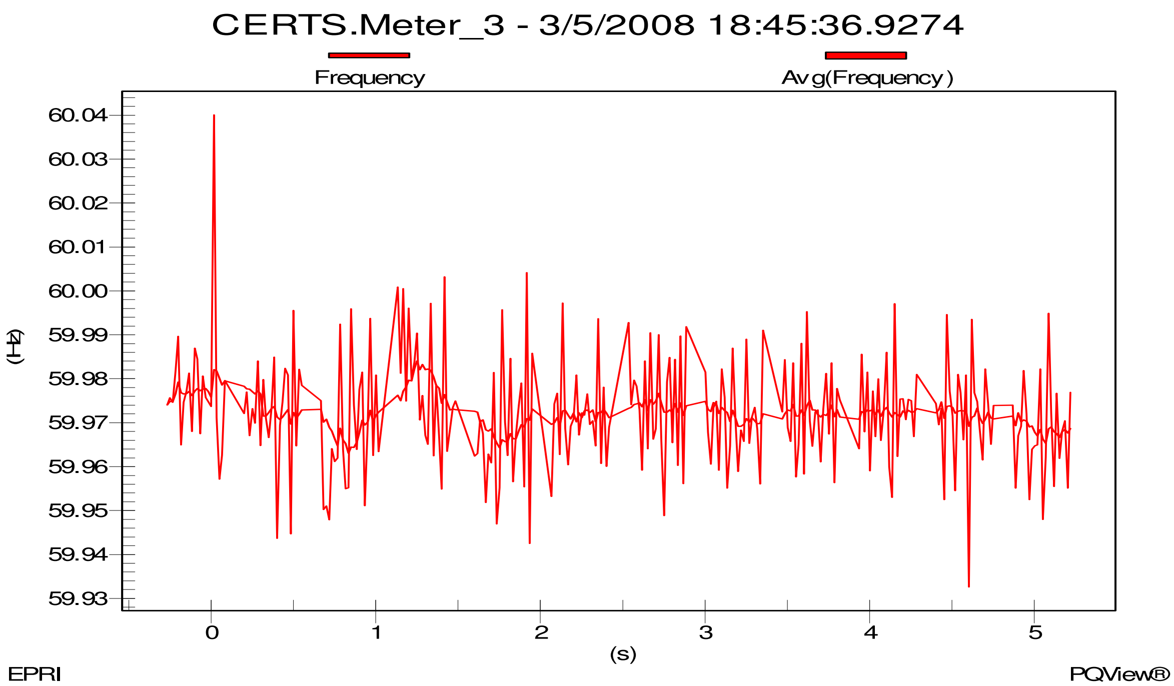

Figure 29h – Meter 3 frequency before/after the static switch opened, islanding the microgrid from the utility grid.

Frequency in the microgrid changed slightly, as shown in Figure 29h to approximately 59.97 Hz which was part of the CERTS algorithm which allowed the Gen-sets to increase their output power to satisfy the load demands. Gen-set A1, A2 and B1 increased output power to approximately 32kW, 23.3kW and 45.5kW, respectively. Meter 5 measured approximately -23kW meaning that Gen-set B1 supplied all the power to LB5 and exported some of its power to LB3 and LB4. The power exported from Gen-set B1 was approximately 21kW into LB3 and LB4, measured by Meter 3. Meter 4 measured approximately 9.5kW, meaning LB3 needed an additional 11.5kW on top of the power produced by Gen-set A1 and LB4 needed and additional 9.5kW on top of the power produced by Gen-set A2. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before manual open signal was released and allowed the static switch to synchronize to the utility grid.

As soon as the static switch closed and steady-state conditions established, the measurement values in Table 16e were compared to the initial conditions at the beginning of the test. The measured values were very similar to initial test conditions which were approximately 40kW at Meter 1, 12kW at Meter 2, 29.5kW at Meter 3, 13.75kW at Meter 4, and -20kW at Meter 5 with 30kW produced by Gen-set A1, 21.25kW produced by Gen-set A2, and 43kW produced by Gen-set B1. Likewise, 45.6kW was at LB3, 34.7kW at LB4, 23.5kW at LB5 and 28.4kW at LB6. The microgrid voltage increased from 270V to 277V and frequency increased from 59.98Hz to 59.99Hz. The power factor remained the same throughout the test with 0.87 for LB4, 0.91 for LB5, 0.92 for LB3 and

0.94 for LB6. After all data was verified and recorded into the DAS Database the Gen-sets A1, A2 and B1 were shut down manually by the EMS, and all the loads/alarms were reset and prepared for the next planned tests.

7.0 CONCLUSION

The tests in section 9.0 "Demonstration Tests of Control Power Flow" were all successfully performed to as predicted. These successful tests provide confidence that the CERTS algorithms real power versus frequency and reactive power versus voltage work for the Gen-sets in unit and zone power control modes while utility connected and islanded.