Arnold Schwarzenegger
Governor

CERTS MICROGRID LABORATORY TEST BED

Test Plan Section 10.0
Difficult Loads

APPENDIX M

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Lawrence Berkeley National Laboratory

CERTS
Consortium for Electric Reliability Technology Solutions

Month Year
CEC-500-XXXX-XXX-APM

Prepared By:
Lawrence Berkeley National Laboratory
Joseph H. Eto, Principal Investigator
Berkeley, CA 94720
Ben Schenkman, Sandia National Laboratory
Harry Volkommer and Dave Klapp, American Electric Power
Robert Lasseter, University of Wisconsin-Madison
Ed Linton and Hector Hurtado, Northern Power Systems

Commission Contract No. 500-03-024

Prepared For:
Public Interest Energy Research (PIER)
California Energy Commission

Bernard Treanton
Contract Manager

Mike Gravely
Program Area Lead
ENERGY SYSTEMS INTEGRATION

Mike Gravely
Office Manager
ENERGY SYSTEMS RESEARCH

Martha Krebs, Ph.D.
PIER Director

Thom Kelly, Ph.D.
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

Melissa Jones
Executive Director

CERTS MICROGRID TEST REPORT

SECTION 10.0

"Difficult Load Tests"

Table of Contents

List Of Figures

List of Tables

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 10.0 "Difficult Load 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 <u>MICROGRID TESTBED SETUP</u>

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.

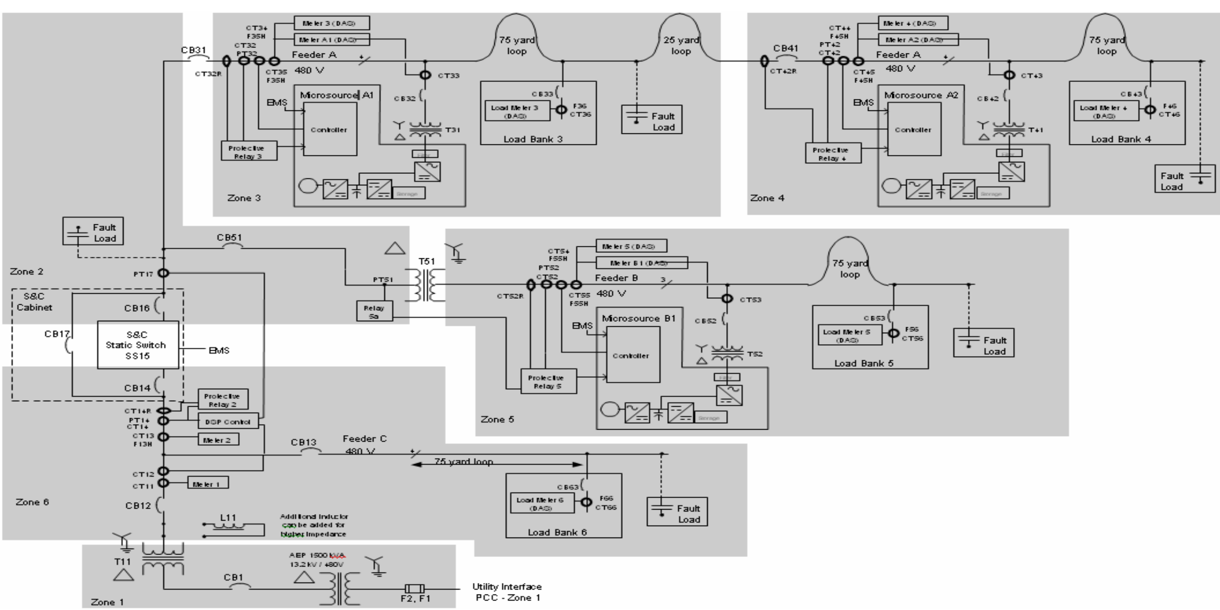

Figure 2 - One Line Diagram of CERTS Microgrid Test Bed

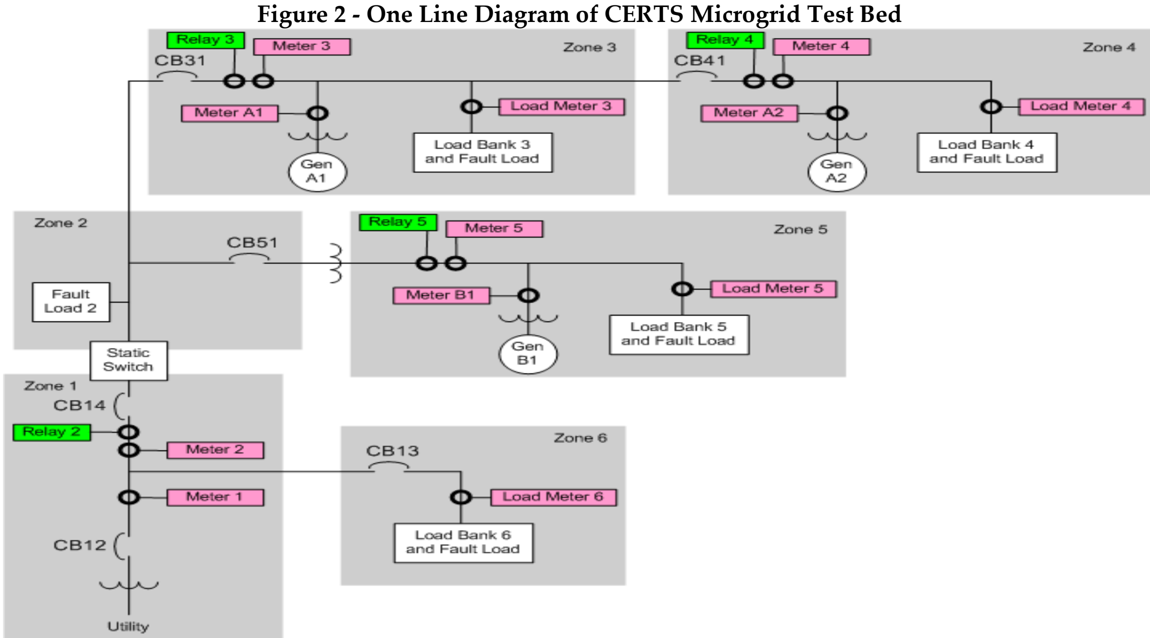

Figure 3 - Simplified diagram of Test Bed showing Meter and Relay locations

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.

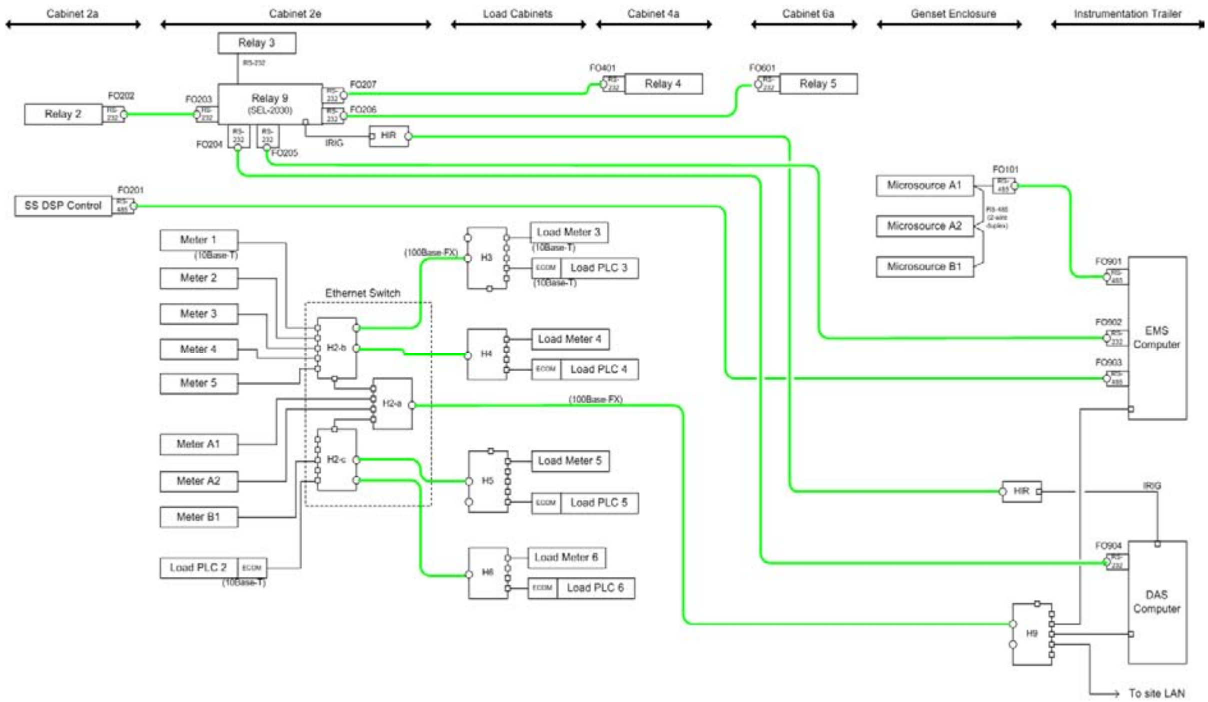

Figure 4 - Diagram of DAS & EMS Data networks

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 <u>PROPOSED TEST PLAN</u>

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 <u>TESTS PERFORMED IN SECTION 10.0</u>

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 10 tests were developed to determine operation limits of the Microgrid (i.e., power quality, protection and inverter limits) with low power factor (pf) loads, motor loads, harmonic load and unbalance loads.

For Section 10, weak grid conditions were planned in the beginning of the test plan to minimize any damage to equipment. However, time constraints forced a decision by the Team to postpone strong grid testing to a later date with concentration on weak grid testing. Motor start tests done in Test 10.2 had balanced loads at 0.9 in power factor in a weak grid scenario, while connected to the utility grid and islanded. These tests were to verify and document power flow, Microgrid frequency changes and protection design with different Gen-set settings during motor starts when utility connected and then repeat motor start test during an islanded mode of operation. Test 10.3 is similar to Test 10.2, except that the loads are now unbalanced with a 0.9 power factor.

In Test 10.4 tests were created to verify and document power flow, Microgrid frequency changes and protection design with different Gen-set settings during changes of unbalanced load in Load Banks. Test 10.5 is similar to Test 10.4, except that the loads are balanced. Power factor tests with unbalanced loads were tested in Test 10.6 which was designed to verify and document power flow, Microgrid frequency changes and protection design with different Gen-set settings during changes of power factor of unbalanced load in Load Banks.

Tests 10.7 – 10.15 are similar tests that verify and document power flow, Microgrid frequency changes and protection design with different Gen-set settings. Changes of harmonic loads in different Zones with a motor start and balanced load in Load Banks were planned.

6.0 ANALYSES OF TEST RESULTS

6.1 SECTION 10 – DIFFICULT LOAD TESTS

To maintain a common understanding of Gen-set control modes and power flows during tests described in the following sections, it is important to know the difference between unit power control mode and zone control mode and positive versus negative power flow.

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.

Positive power flow recorded by Meter 1, Meter 2, Meter 3, Meter 4 and Meter 5 are in the direction from the utility going downstream into the microgrid. Negative power flow through these meters means that the power is flowing from the Gen-sets out towards the utility. For example, if Meter 2 (i.e., static switch) recorded a power flow of -20kW + j35kVAr then real power is flowing from the Gen-sets through the static switch out into Zone 6 and reactive power is flowing in the opposite direction from Zone 6 into the critical loads of the microgrid (Zones 2, 3, 4 and 5). Positive power flow recorded by Meters A1, A2 and B1 are what the Gen-sets are producing and negative power flow is what the Gen-sets are absorbing. This is vice versa for Meters LB3, LB4, LB5 and LB6 meaning that a positive power flow is what the Load Bank is absorbing. Load Bank meters will never have a negative power flow.

6.1.1 Motor Start Tests, Weak Grid, Balanced Load with 0.9 Power Factor

Performance Goal:

Verify and document power flow, Micro-grid frequency changes and protection design with different Gen-set settings during motor starts when utility connected and then repeat motor start test during an islanded mode of operation.

Six tests were completed in this section with each test event and settings listed in Table 1. During each test Gen-sets A1 and A2 were both set for either unit or zone power control mode of operation. Each of the six tests varied the output power command set-point in each Gen-set, along with varying the load settings in load banks LB3, LB4 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	Meter 1	Meter 2	Meter 3	Meter 4	LB 3	LB 4	LB 6
10.2.12	Unit	Unit	+20kW	-20kW	-20kW	+10kW	10kW	40kW	40kW

	+40kW	+30kW							
10.2.14	Unit +40kW	0kW	+10kW	-30kW	-30kW	0kW	10kW	0kW	40kW
10.2.15	Unit +40kW	Unit +30kW	+70kW	+30kW	+30kW	+20kW	50kW	50kW	40kW
10.2.17	Unit +40kW	0kW	+20kW	-20kW	-20kW	0kW	20kW	0kW	40kW
10.2.18	Zone - 10kW	Zone +10kW	+30kW	-10kW	-10kW	+10kW	20kW	40kW	40kW
10.2.20	Zone - 20kW	0kW	+20kW	-20kW	-20kW	0kW	20kW	0kW	40kW

Table 1 -Balance Load, Weak Grid, Before Motor Start settings of Gen-sets and Load Banks

The procedure for each test event began with setting the kW and kVAr load (i.e., balanced load) conditions, as indicated in Table 1. Before loads were brought on-line, Gen-sets A1 and A2 or just Gen-set A1 depending on the test setup, 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 1, 2, 3 and 4. The measurements were then compared with the expected values in Table 1. When the measured values coincided with the expected values from the table, then a 10Hp motor was started in Zone 3 with the dynamometer set in ft-lbs at 100% motor rating. When all measurements were verified and recorded in the DAS Database for before and after the motor start, the motor was turned off and the manual open signal to the static switch was initiated. This allowed the static switch to open and separate 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 and LB6) and that a smooth transition occurred. When all the measurements were verified and recorded in the DAS Database, the 10Hp motor was started again with the dynamometer set in ft-lbs for 100% motor rating. Once all measurements were verified and recorded in the DAS Database for before and after the motor start, the manual open signal to the static switch was released. Releasing the manual open signal allowed the static switch to synchronize and reclose. All data (i.e., from the manual open event and the reconnection event) was verified and recorded in the DAS Database. Loads, power control set-points and operation modes were then changed to the settings for the next test. Test results are explained in the following paragraphs.

For Test 10.2.12 the measured values, after the Gen-sets were warmed up and load banks brought on-line, were approximately 12kW + j24kVAr at Meter 1, -24kW + j22kVAr at Meter 2, -27kW + j16kVAr at Meter 3 and 3.5kW + j5kVAr at Meter 4. From the microgrid, 41kW – j12kVAr was produced by Gen-set A1 and 33kW – j3kVAr was produced by Gen-set A2. The load banks were 11kW + j0kVAr at LB3, 35.9kW + j0.645kVAr at LB4 and 35.9kW + j0.6975kVAr at LB6. These measurements were relatively close to the expected values in Table 1, but not exact due to temperature, phase voltages and electrical losses in conductors. In addition, the 40kW settings for LB4 and LB6 were also below selected set values. The deviation of selected values versus actual values was consistent for the other five tests in this section. At the time of these measurements, the voltage and frequency was 281.5V on A-phase, 279V on B-phase and 279V on C-phase and 59.98Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 282V on A-phase, 280V on B-phase and 280V on C-phase and 59.98Hz at Meter 3.

The Gen-sets in this test were set up to produce more power than Load Banks 3 and 4 needed which approximately 24kW of excess power was exported through the static switch to Load Bank 6. Since Load Bank 6 was approximately 35.9kW + j0.6975kVAr, the utility had to supply approximately 12kW to satisfy the load. Reactive power had to be imported in from the utility of approximately 22kVAr because Gen-sets A1 and A2 needed approximately 15kVAr between the two and the reactive power of Load Banks 3 and 4. Once all data was verified and recorded into the DAS Database, the 10Hp induction motor was started in Zone 3.

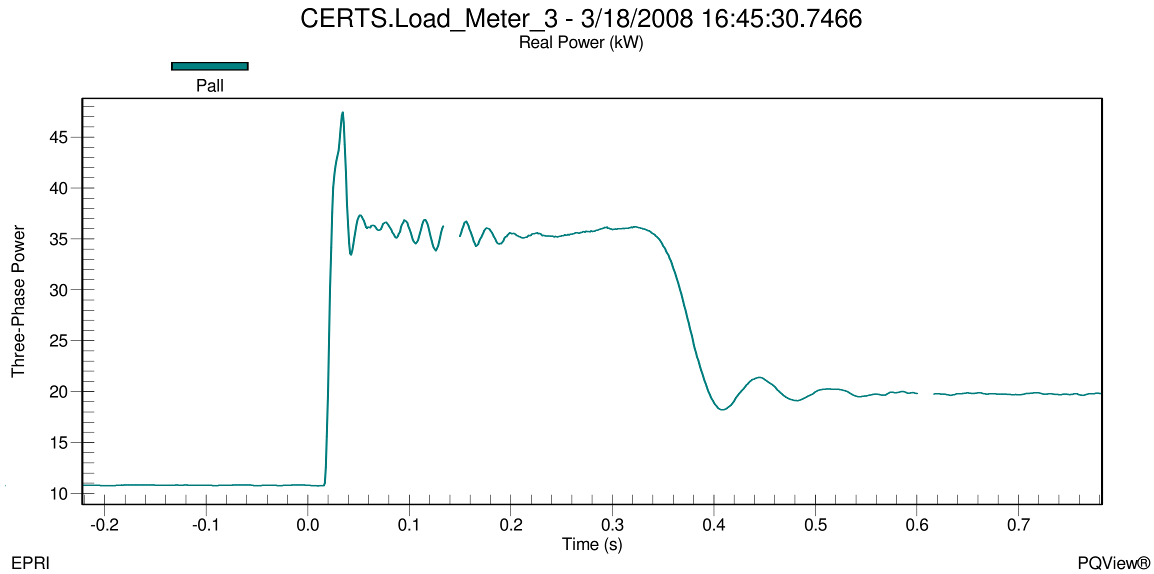

Figure 5a - Load Bank 3 Real Power Motor Start and Utility Connected for Test 10.2.12

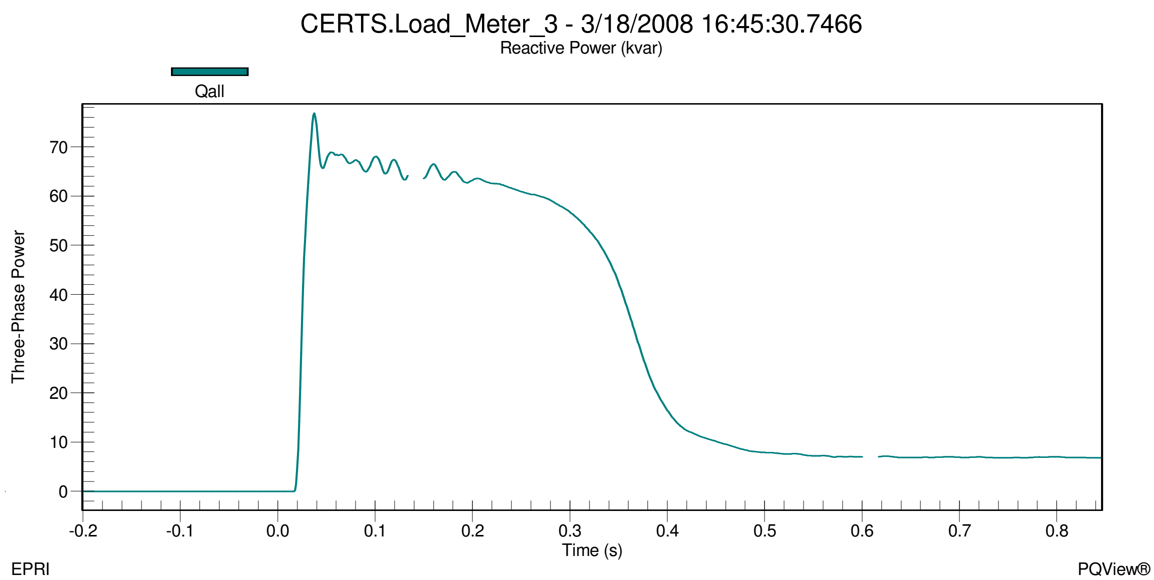

Figure 5b - Load Bank 3 Reactive Power during Motor Start and Utility Connected for Test 10.2.12

In Figures 5a and 5b it can be seen that the load in Zone 3 was approximately 10.9kW + j0kVAr before the start of the induction motor and increased to approximately 47.4kW + j77kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 35.6kW + j64kVAr during the warm up phase which lasted about 24 cycles (0.40 seconds). When the motor reached steady state, the load in Zone 3 was approximately 19.9kW + j6.9kVAr.

The voltage and frequency at the static switch before the motor start was approximately 281.2V on A-phase, 278.7V on B-phase and 279V on C-phase shown in Figure 5c and approximately 59.97Hz shown in Figure 5d. When the motor started, the voltage at the static switch during the inrush decreased to approximately 274.3V on A-phase, 271.4V on B-phase and 272.4V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.90Hz and quickly increased back to the starting frequency of approximately 59.97Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 280.6V on A-phase, 278.4V on B-phase and 278V on C-phase at an approximate frequency of 59.97Hz.

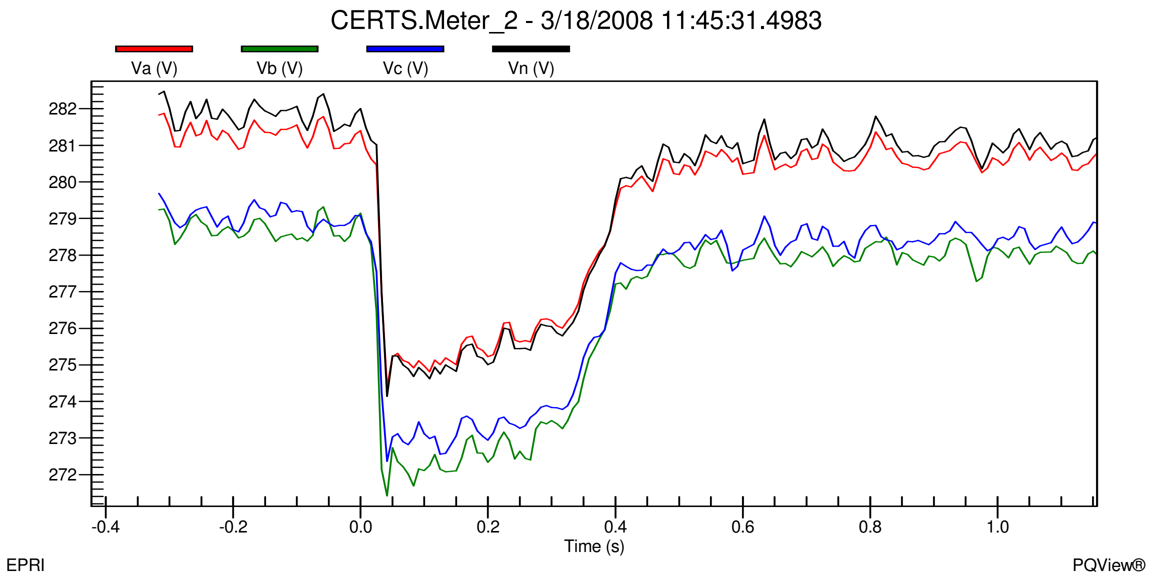

Figure 5c – Static Switch Line-to-Ground Voltages during Motor Start and Utility Connected for Test 10.2.12

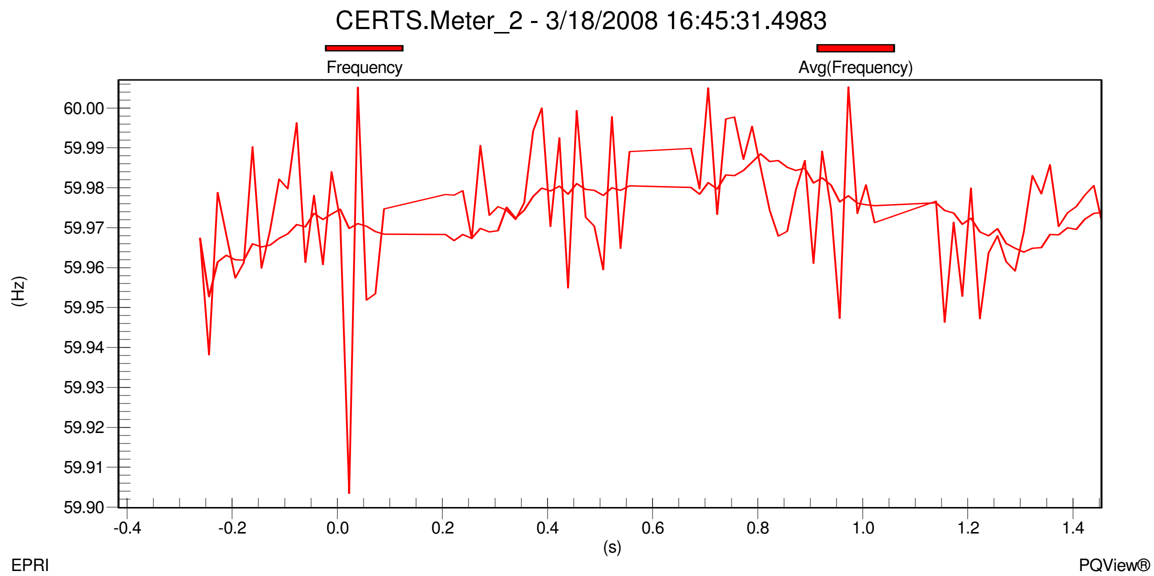

Figure 5d – Static Switch Frequency during Motor Start and Utility Connected for Test 10.2.12

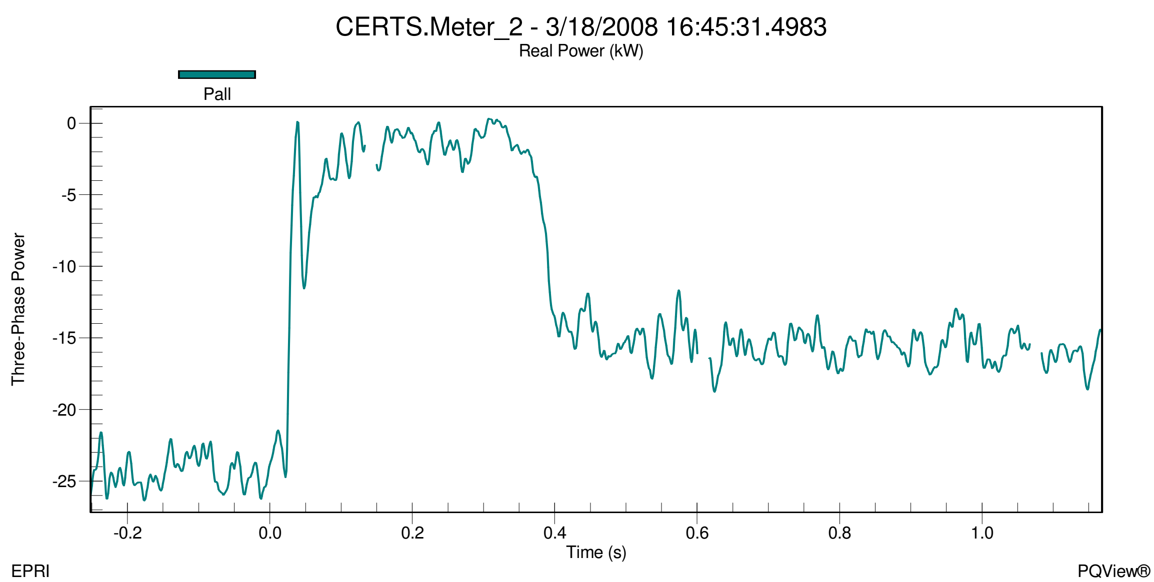

Figure 5e - Static Switch Real Power during Motor Start and Utility Connected for Test 10.2.12

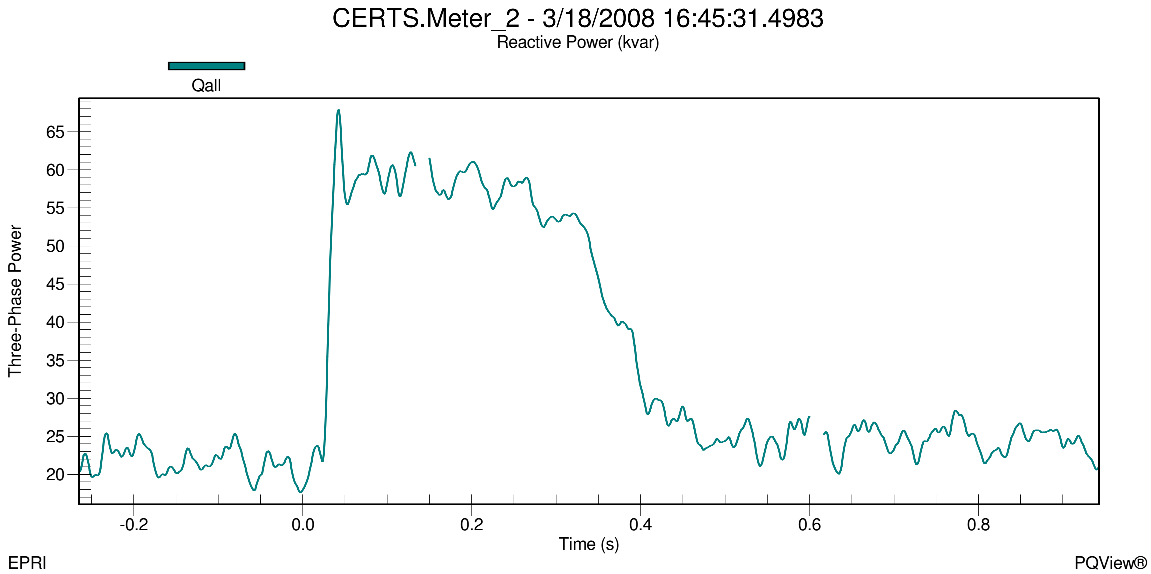

Figure 5f - Static Switch Reactive Power during Motor Start and Utility Connected for Test 10.2.12

Before the motor started Gen-sets A1 and A2 were producing approximately 41.1kW – j12kVAr and 32.6kW – j3.8kVAr, respectively. This was enough for the load demands of Zones 3 and 4 with real power being exported to Zone 6 of approximately 24kW shown in Figure 5e. The grid was supporting the reactive power of the microgrid with approximately 22kVAr shown in Figure 5f. When the motor started the inrush caused the utility to supply approximately 68kVAr and to pick up the load demand of Load Bank 6. The power that was being supplied by Gen-sets A1 and A2 to Load Bank 6 was now supplying the motor inrush which can be seen in Figure 5e as the real power through the static switch becomes 0kW. Gen-sets A1 and A2 increased their real and reactive power output levels to approximately 45.9kW + j1.5kVAr and 40.4kW + j15.9kVAr, respectively. Notice the signs of the VAr output changed from negative to positive for both Gen-sets in order to support the induction motor load in Zone 3.

When the motor reached steady state, the real and reactive power through the static switch was approximately -15.8kW + j24.2kVAr which meant that Gen-sets A1 and A2 were supplying the power for the induction motor and approximately 15.8kW of Load Bank 6. Gen-sets A1 and A2 real power returned to the values before the motor started of approximately 41.1kW and 32.6kW, respectively, and the reactive power increased to approximately -10.5kVAr in Gen-set A1 and -1.9 in Gen-set A2. Once all data was verified and recorded into the DAS Database, the motor was shut down and the static switch was directed by the EMS to manually open.

As soon as the static switch opened, Meter 1 recorded real power increased to approximately 37kW and reactive power decreased to 0kVAr satisfying the load demand in Load Bank 6 which was approximately 36.6kW + j0kVAr and not supplying any power beyond the static switch to Load Banks 3 and 4. 0kW + j0kVAr was recorded at the static switch, indicating that power was not flowing through the static switch. Load Banks 3 and 4 loads reduced slightly to 10.5kW – j0.039kVAr and 34.5kW + j0.685kVAr, respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 5g, from approximately 282V on A-phase, 280V on B-phase and 280V on C-phase when connected to the utility grid to 275V on A-phase, 275V on B-phase and 276V on C-phase at Meter 3 when islanded.

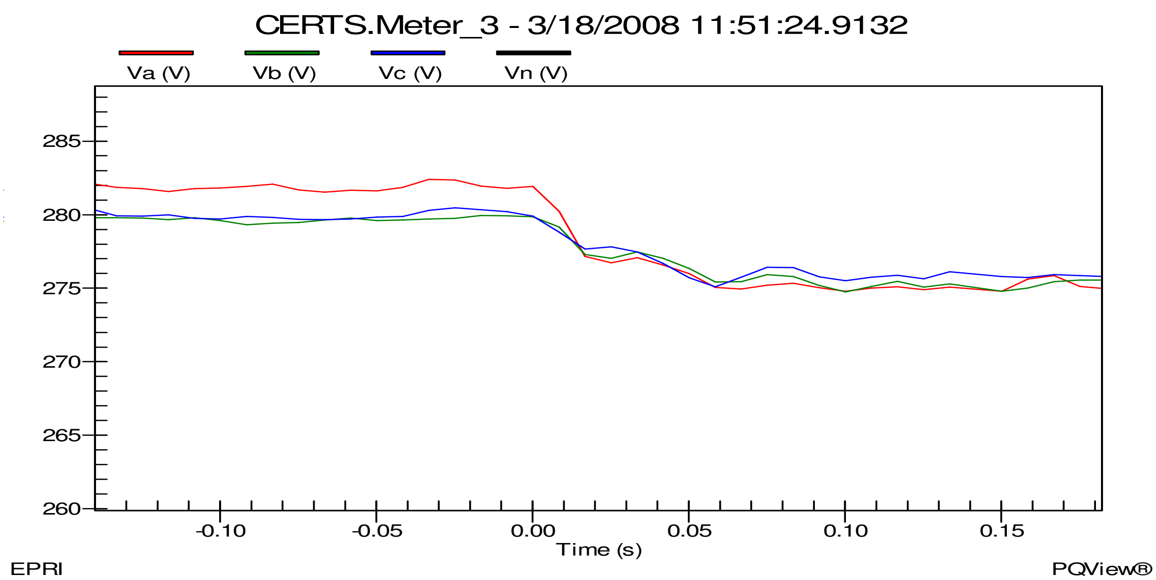

Figure 5g – Meter 3 Line-to-Ground Voltages during Utility Connected to Island mode for Test 10.2.12

Frequency change in the microgrid, shown in Figure 5h, increased from approximately 60.02Hz when connected to the utility grid to approximately 60.08Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed the Gen-sets to decrease their output power to satisfy the load demands. Gen-set A1 and A2 decreased their output real power to approximately 28.5kW and 19.5kW, respectively and increased their output reactive power to approximately 2.5kVAr and 2.5kVAr, respectively. Meter 3 was approximately -3.8kW + j0.4kVAr indicating that the Gen-sets were satisfying the loads in the microgrid and the power losses in the electrical lines. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the 10Hp induction motor was started in Zone 3.

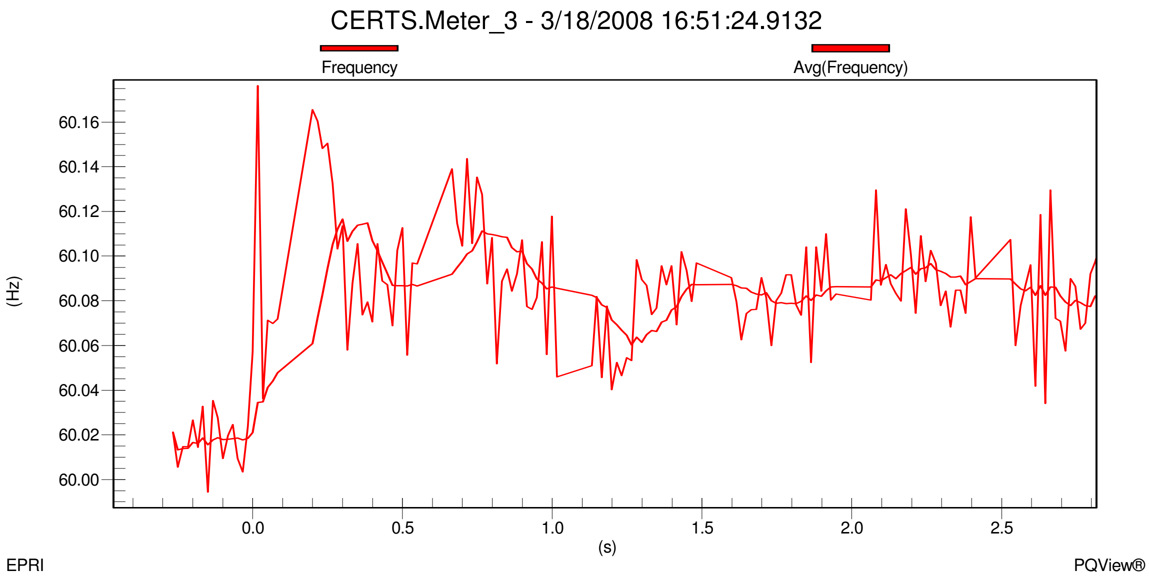

Figure 5h - Meter 3 Frequency during Utility Connected to Island mode for Test 10.2.12

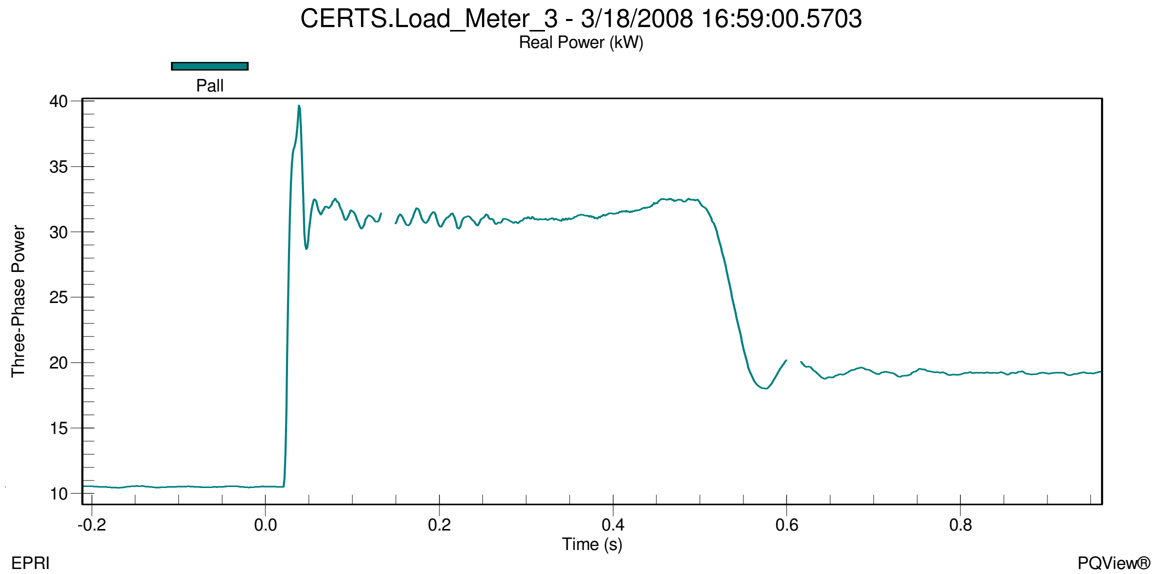

Figure 5i - Load Bank 3 Real Power during Motor Start and Islanded for Test 10.2.12

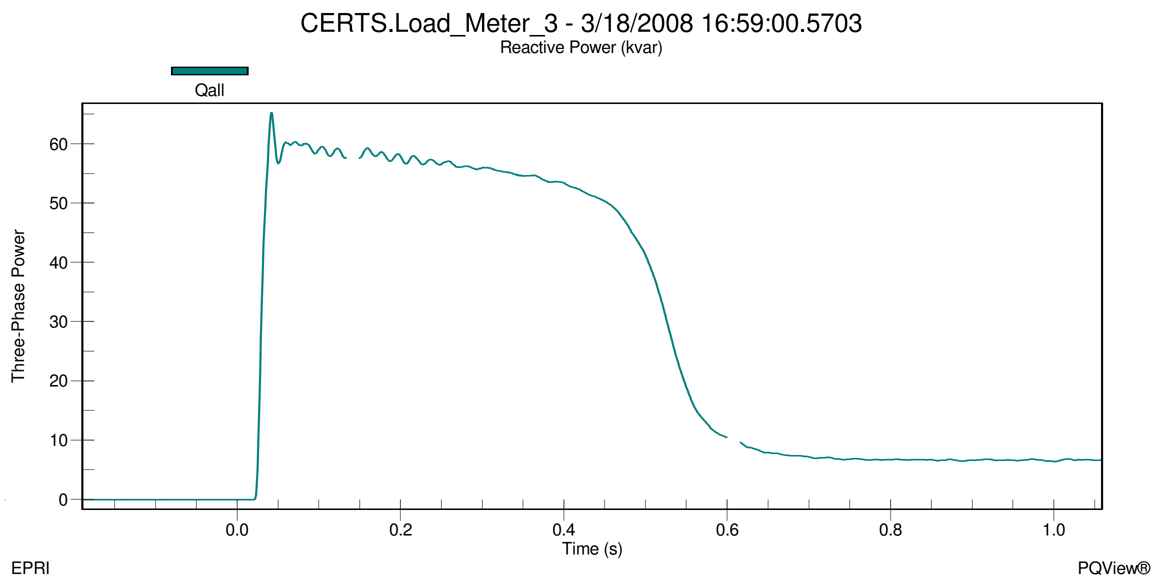

Figure 5j - Load Bank 3 Reactive Power during Motor Start and Islanded for Test 10.2.12

In Figures 5i and 5j it can be seen that the load in Zone 3 was approximately 10.5kW + j0kVAr before the start of the induction motor and increased to approximately 39.7kW + j65kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 31kW + j56kVAr during the warm up phase which lasted about 39 cycles (0.65 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 19.2kW + j6kVAr.

The voltage and frequency at Meter 3 before the motor start was approximately 275V (i.e., 275V on A-Phase, 275V on B-Phase and 275V on C-phase) shown in Figure 5k and approximately 60.09Hz shown in Figure 5l. When the motor started, the voltage at Meter 3 during the inrush decreased to approximately 256V (i.e., 256V on A-Phase, 256V on B-Phase and 256V on C-Phase) for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.99Hz and quickly increased to approximately 60.01Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 273V (i.e., 273V on A-Phase, 273V on B-Phase and 273V on C-Phase) at an approximate frequency of 60.05Hz.

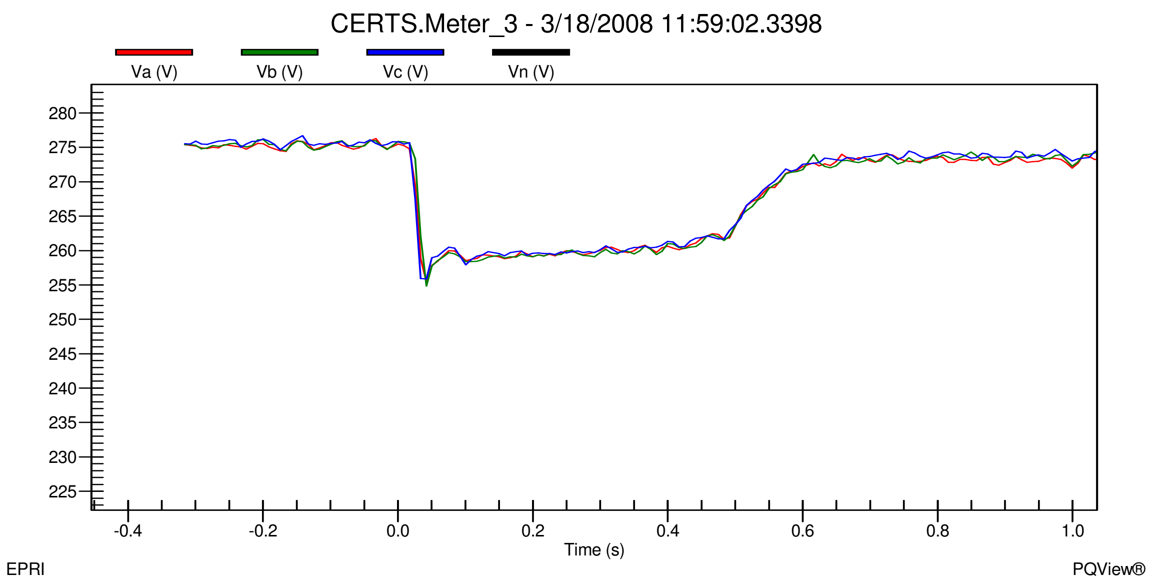

Figure 5k – Meter 3 Line-to-Ground Voltage during Motor Start and Islanded for Test 10.2.12

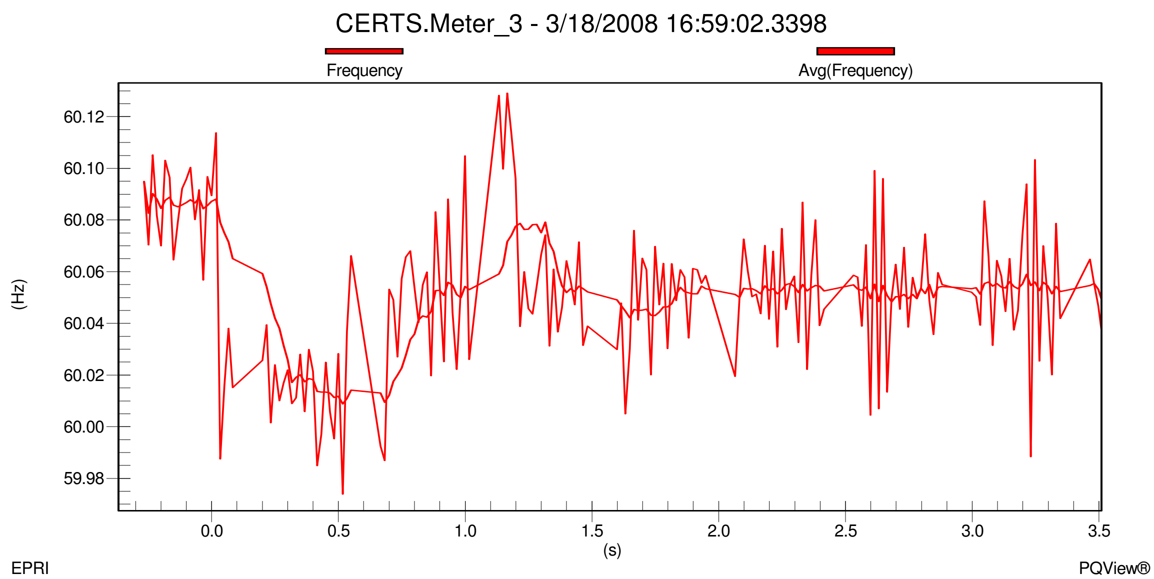

Figure 5l – Meter 3 Frequency during Motor Start and Islanded for Test 10.2.12

Before the motor started Gen-sets A1 and A2 were producing approximately 28.1kW - j2.8kVAr and 19.4kW + j7kVAr, respectively shown in Figures 5m – 5p. The power generated by both Gen-sets was satisfying the loads in Load Banks 3 and 4 and all the electrical losses in the microgrid system. When the motor started the inrush caused the Gen-sets to increase their output levels to 38.9kW + j30.5kVAr for Gen-set A1 and 32.5kW + j37.7kVAr for Gen-set A2. The Gen-sets decreased their output levels while the motor was warming up and eventually dropped to 32kW + j0.2kVAr for Gen-set A1 and 23.6kW + j10kVAr for Gen-set A2 when the motor reached steady state. Once all the data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually close.

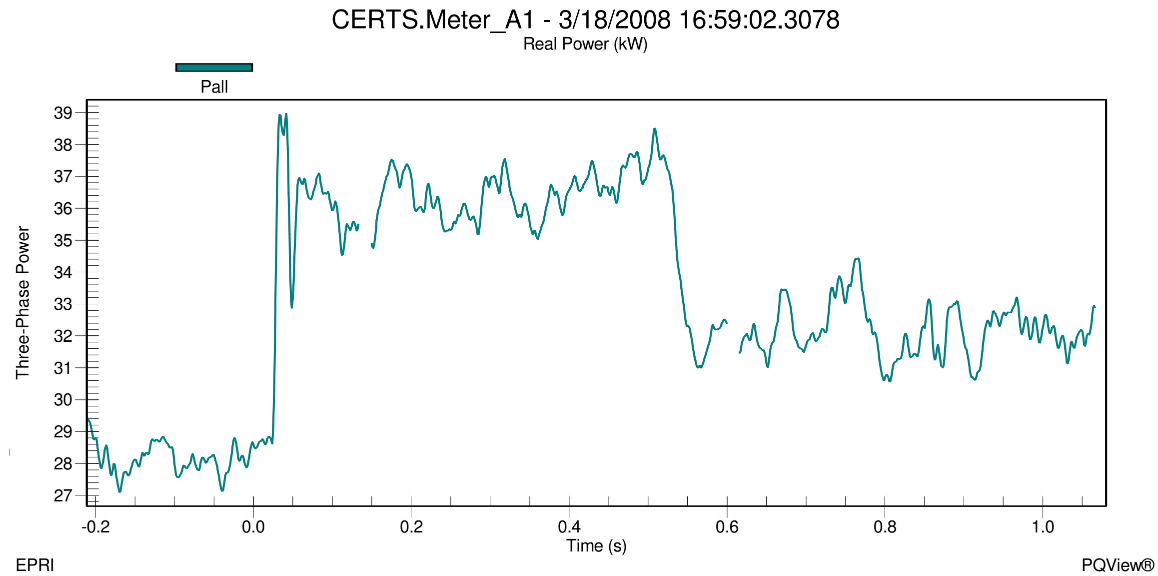

Figure 5m - Gen-set A1 Real Power during Motor Start and Islanded for Test 10.2.12

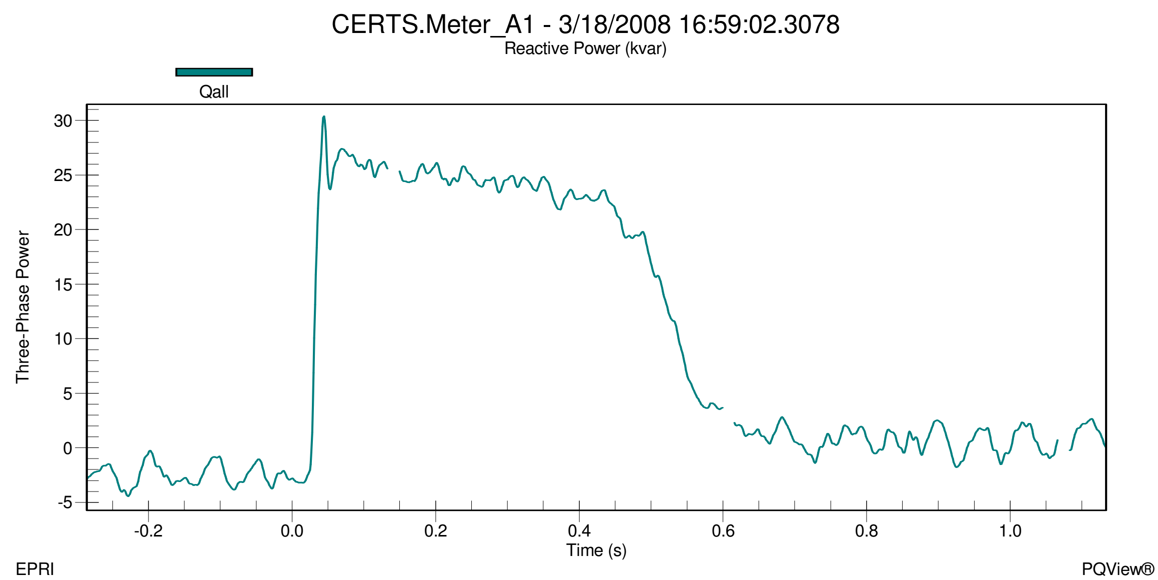

Figure 5n - Gen-Set A1 Reactive Power during Motor Start and Islanded for Test 10.2.12

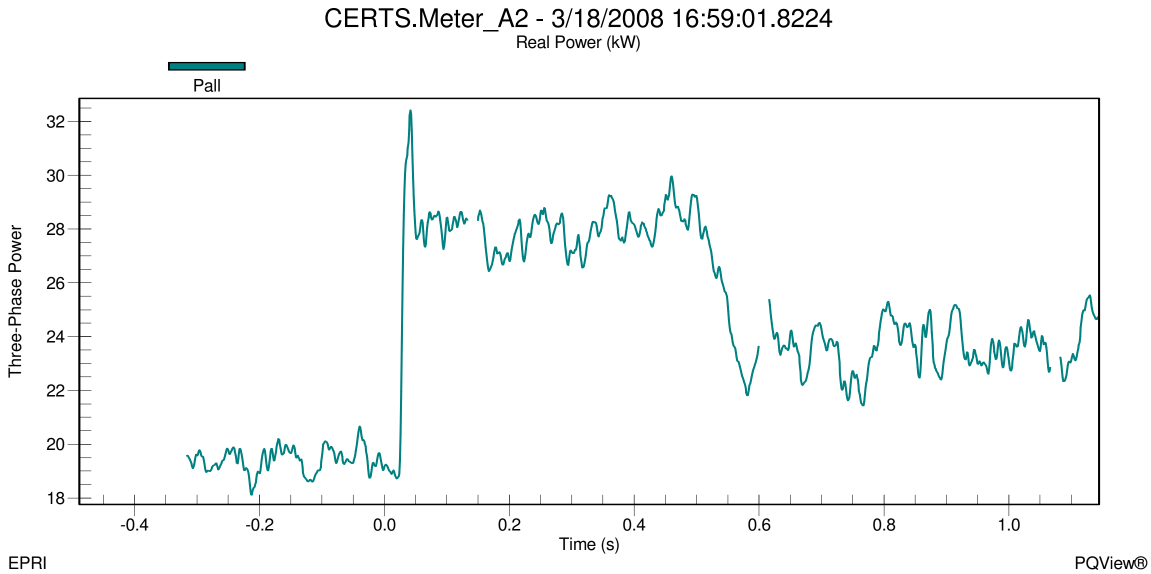

Figure 5o - Gen-set A2 Real Power during Motor Start and Islanded for Test 10.2.12

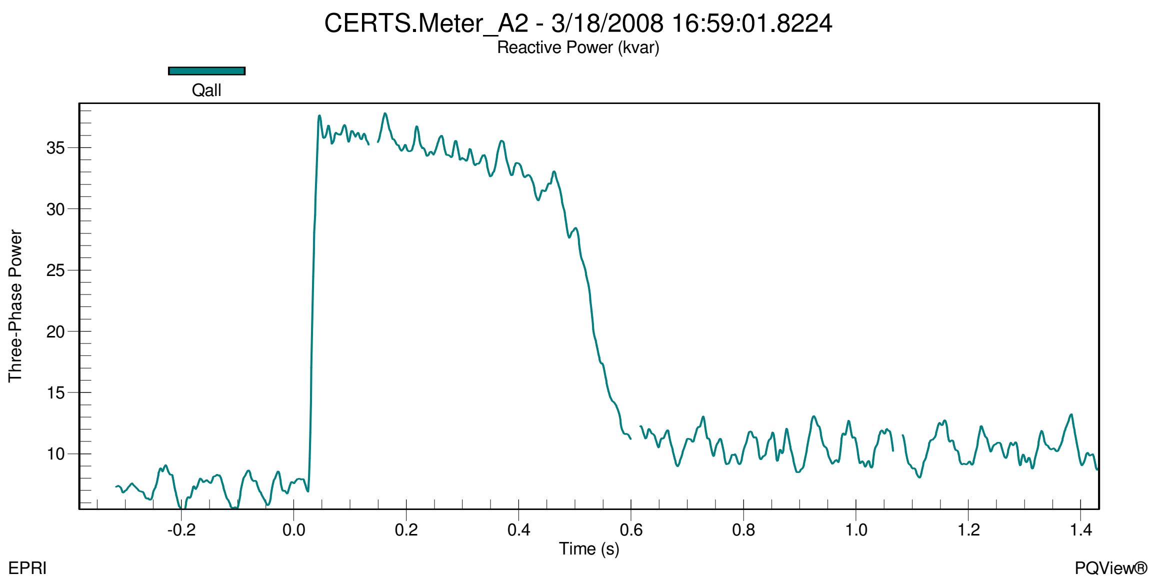

Figure 5p - Gen-set A2 Reactive Power during Motor Start and Islanded for Test 10.2.12

As soon as the static switch closed, Meter 1 recorded real power decreased from approximately 37kW to 24kW and reactive power increased from approximately 0kVAr to 28kVAr which means that the utility was satisfying a portion of the load demand in Load Bank 6 and all the reactive power in the microgrid. Figures 5q and 5r show the static switch decreasing from approximately 0kW to -11.5kW and increasing from approximately 0kVAr to 27kVAr. At the beginning of the test, the initial power flow through the static switch was -24kW + j22kVAr which is not the same recorded at this point in the test because the 10Hp motor load is on in Zone 3. The Gen-sets have picked up the motor load and supporting Load Bank6 with approximately 11.5kW.

Load Banks 3 and 4 loads increased slightly to 35.7kW + j0.71kVAr and 17.95kW + j6.15kVAr, respectively. This slight load increase is a result from a voltage rise in the microgrid, shown in Figure 5s, from approximately 273.8V (i.e., 273.8V on A-phase, 273.8V on B-phase and 273.8V on C-phase) when islanded to 281.8V on A-phase, 279.2V on B-phase and 279.2V on C-phase at Meter 3 when connected to the utility grid.

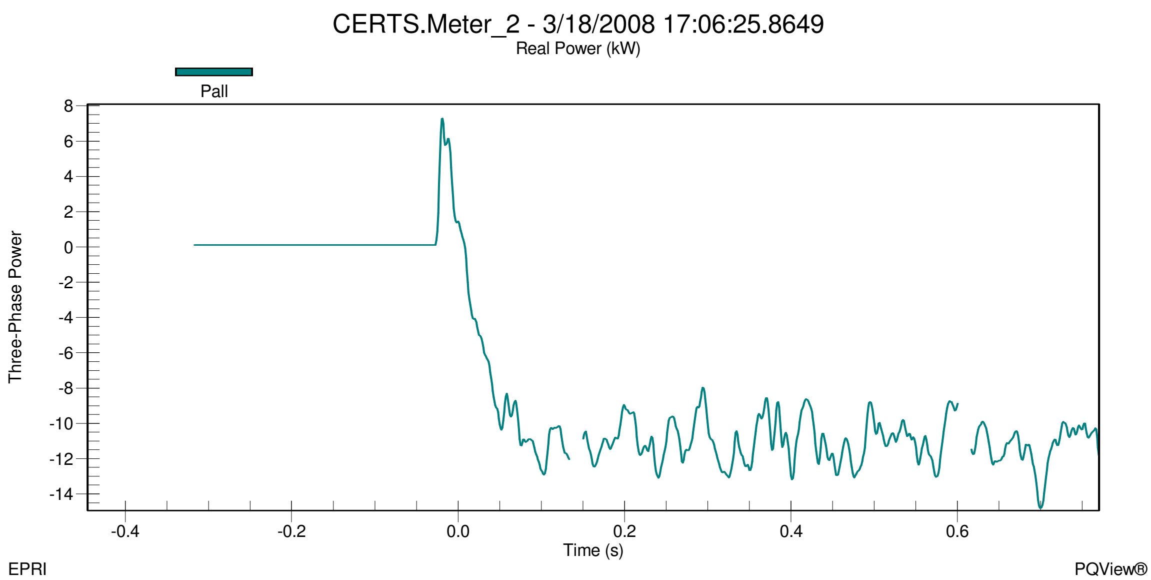

Figure 5q – Static Switch Real Power during Island to Utility Connected mode for Test 10.2.12

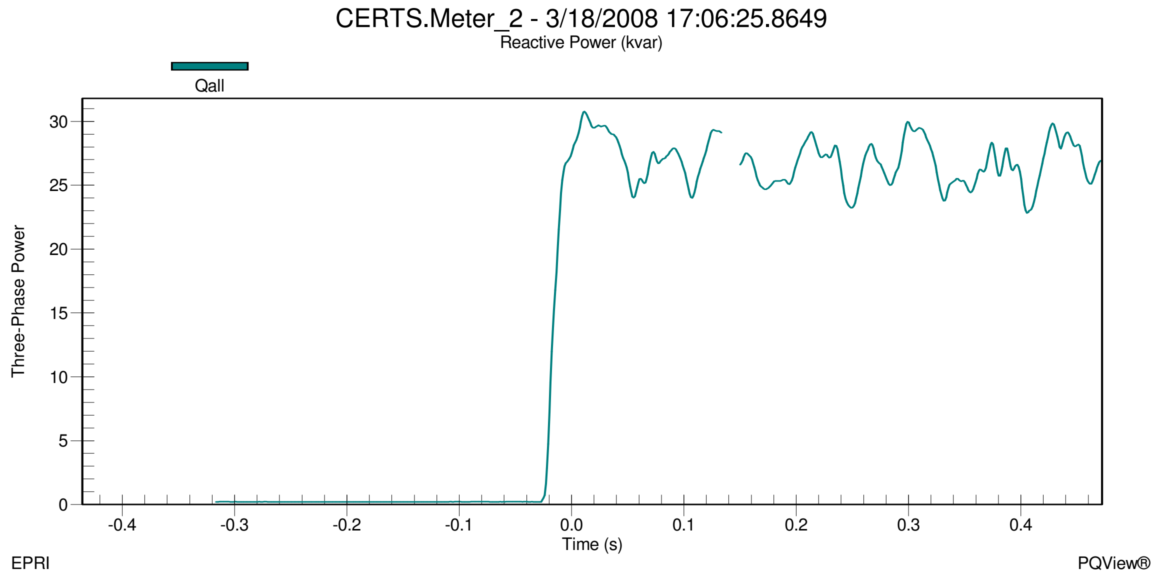

Figure 5r – Static Switch Reactive Power during Island to Utility Connected mode for Test 10.2.12

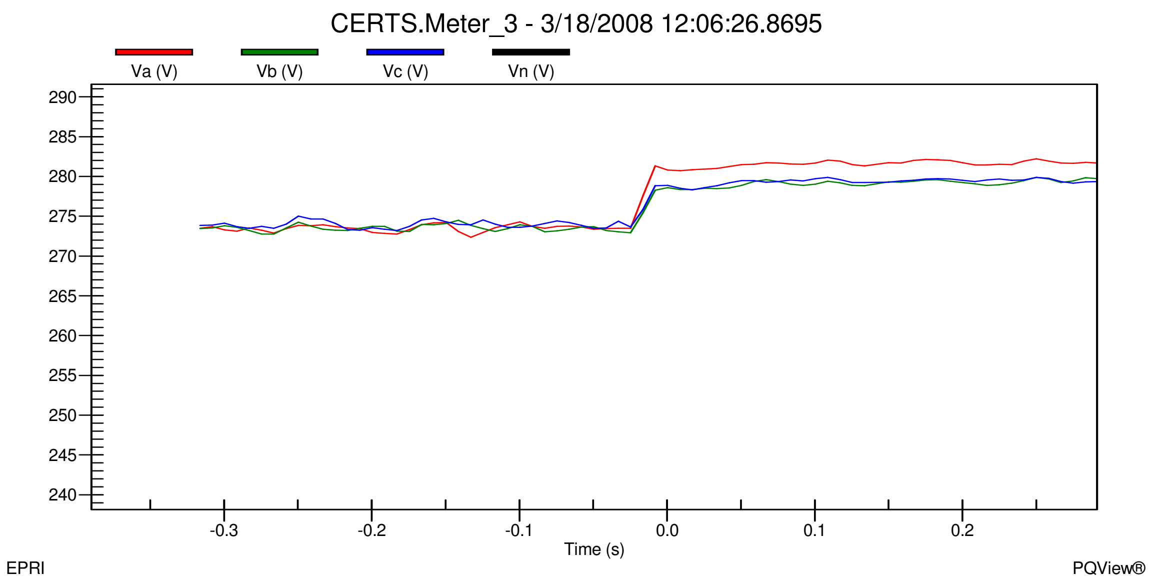

Figure 5s - Meter 3 Line-to-Ground Voltages during Island to Utility Connected mode for Test 10.2.12

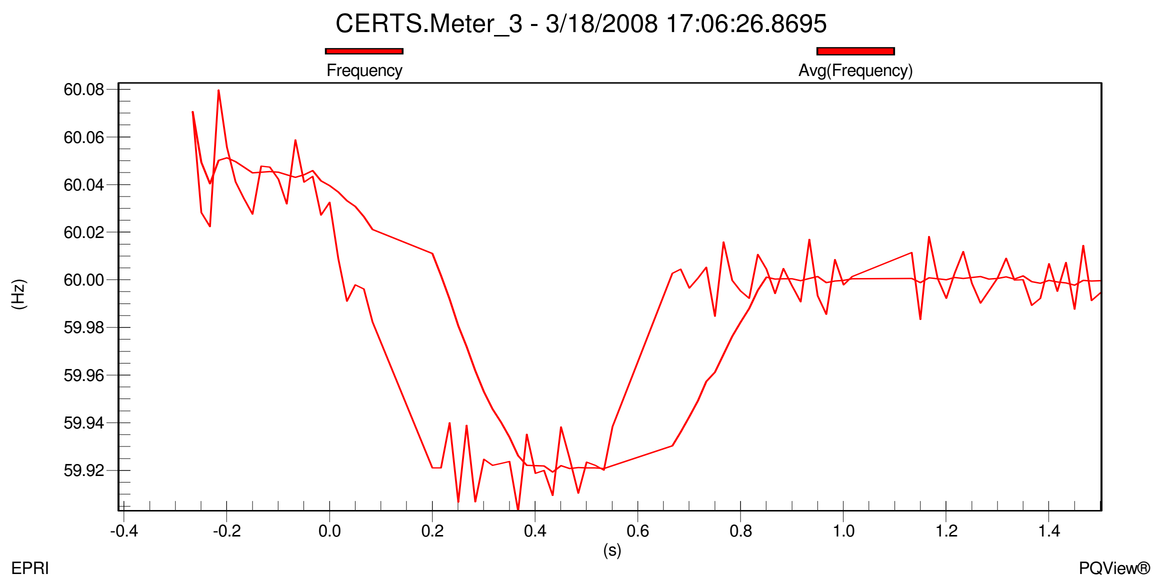

Figure 5t - Meter 3 Frequency during Island to Utility Connected mode for Test 10.2.12

Frequency change in the microgrid, shown in Figure 5t, decreased from approximately 60.05Hz when islanded to approximately 60.00Hz when connected to the utility grid. This change in frequency is due to the frequency no longer being established by the Gen-sets using the CERTS algorithm but by the utility. Gen-sets A1 and A2 are in unit power control mode therefore when the static switch closed back into the utility the Gen-sets produced real power based on their set-points initialized at the beginning of the test. The output power for both Gen-sets were relatively close to the values at the beginning of the test with Gen-set A1 producing approximately 38kW – j12kVAr and Gen-set A2 producing approximately 30kW – j3kVAr. After all the data was verified and recorded into the DAS Database, the motor was turned off and the Gen-sets and Load Banks set-points were changed according to the next test (10.2.14) in Table 1.

For Test 10.2.14 the measured values, after Gen-set A1 was warmed up and load banks brought on-line, were approximately 10kW + j20kVAR at Meter 1, -26kW + j20kVAr at Meter 2 and -29kW + j15kVAR at Meter 3. From the microgrid, 40kW – j14kVAr was produced by Gen-set A1. The Load Banks were 11kW + j0kVAr at LB3 and 36.1kW + j0.745kVAr at LB6. At the time of these measurements, the voltage and frequency was 282.8 on A-phase, 279.6V on B-phase and 279.8V on C-phase and 59.986Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 283V on A-phase, 280V on B-phase and 280V on C-phase at Meter 3.

Gen-set A1 was setup in this test to produce more power than Load Bank 3 needed which approximately 26kW of excess power was exported through the static switch to Load Bank 6. Since Load Bank 6 was approximately 36.1kW + j0.0745kVAr, the utility had to supply approximately 10kW to satisfy the load. Reactive power had to be imported in from the utility of approximately 20kVAr because Gen-set A1 needed approximately 14kVAr and the reactive power absorbed in the electrical lines. Once all data was verified and recorded into the DAS Database, the 10Hp induction motor was started in Zone 3.

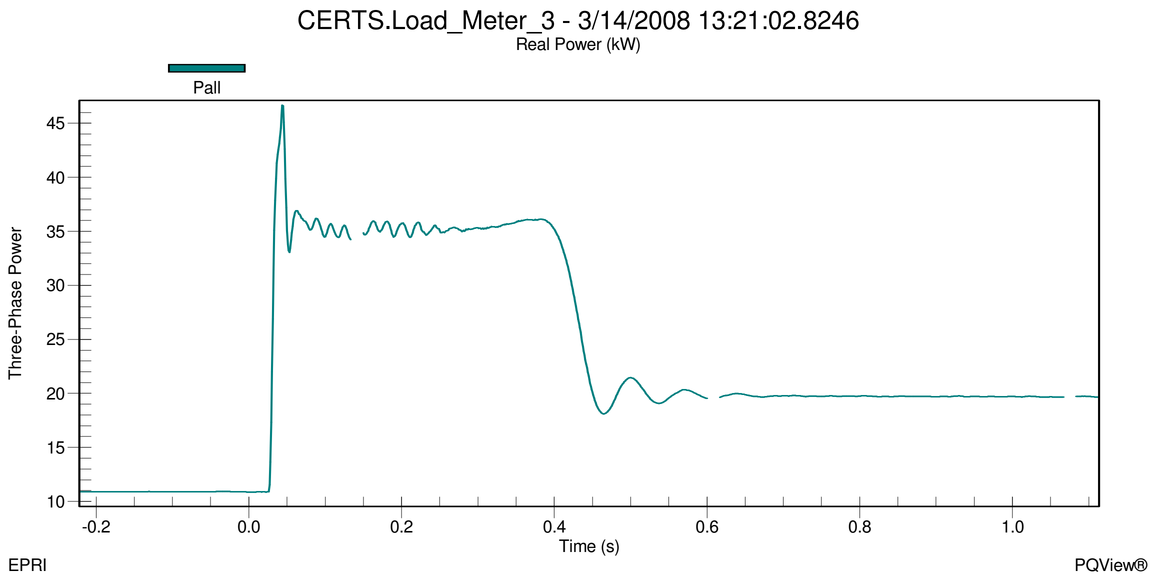

Figure 6a - Load Bank 3 Real Power during Motor Start and Utility Connected for Test 10.2.14

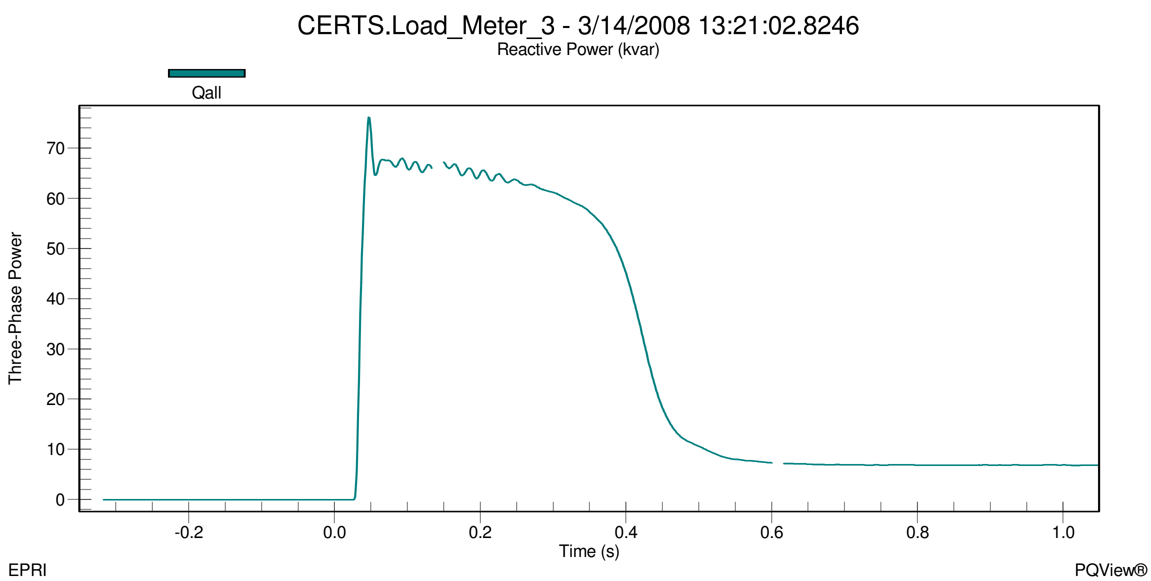

Figure 6b - Load Bank 3 Reactive Power during Motor Start and Utility Connected for Test 10.2.14

In Figures 6a and 6b it can be seen that the load in Zone 3 was approximately 11kW + j0kVAr before the start of the induction motor and increased to approximately 46.8kW + j76kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 35kW + j63kVAr during the warm up phase which lasted about 33 cycles (0.55 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 19.8kW + j7kVAr.

The voltage and frequency at the static switch before the motor start was approximately 282.8V on A-phase, 279.6V on B-phase and 279.8V on C-phase shown in Figure 6c and approximately 59.99Hz shown in Figure 6d. When the motor started, the voltage at the static switch during the inrush decreased to approximately 274.6V on A-phase, 271.7V on B-phase and 271V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.92Hz and quickly increased back to the starting frequency of approximately 59.99Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 282V on A-phase, 278.8V on B-phase and 279V on C-phase at an approximate frequency of 59.98Hz.

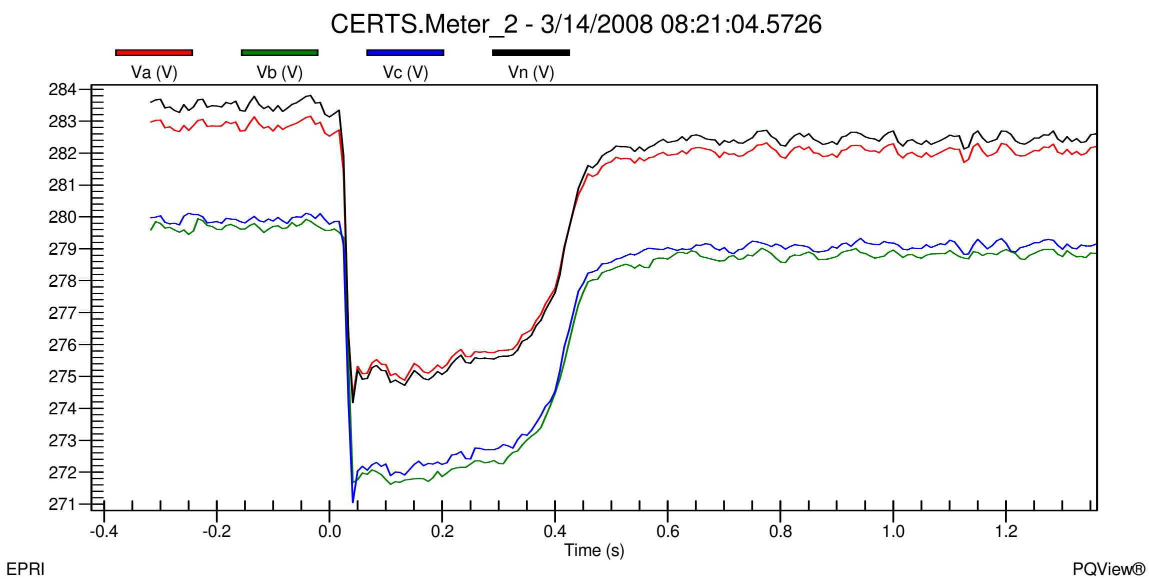

Figure 6c - Static Switch Line-to-Ground Voltages during Motor Start and Utility Connected for Test 10.2.14

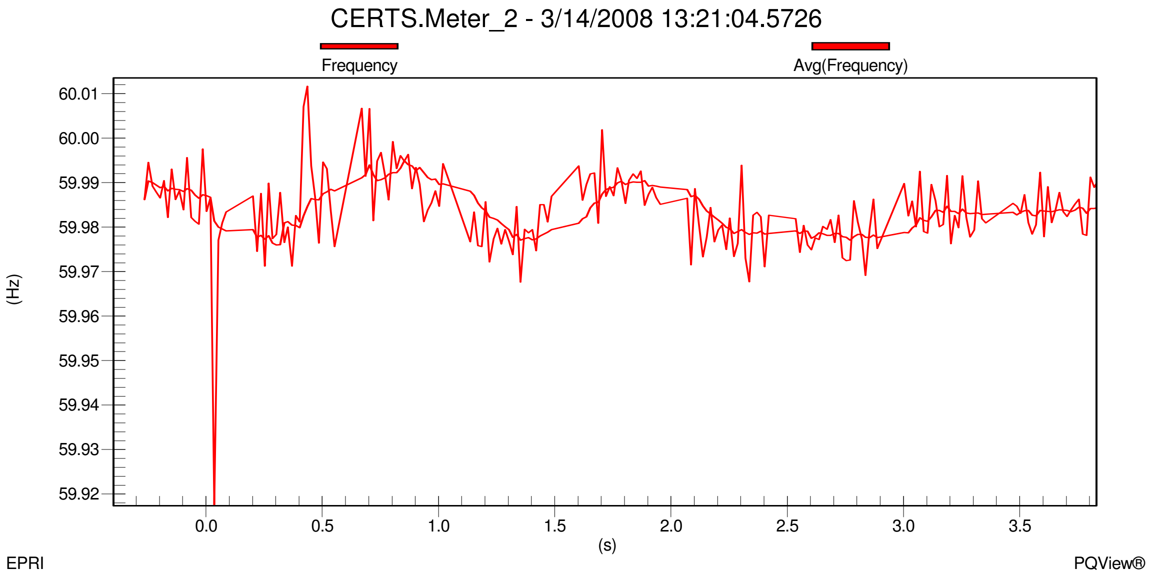

Figure 6d - Static Switch Frequency during Motor Start and Utility Connected for Test 10.2.14

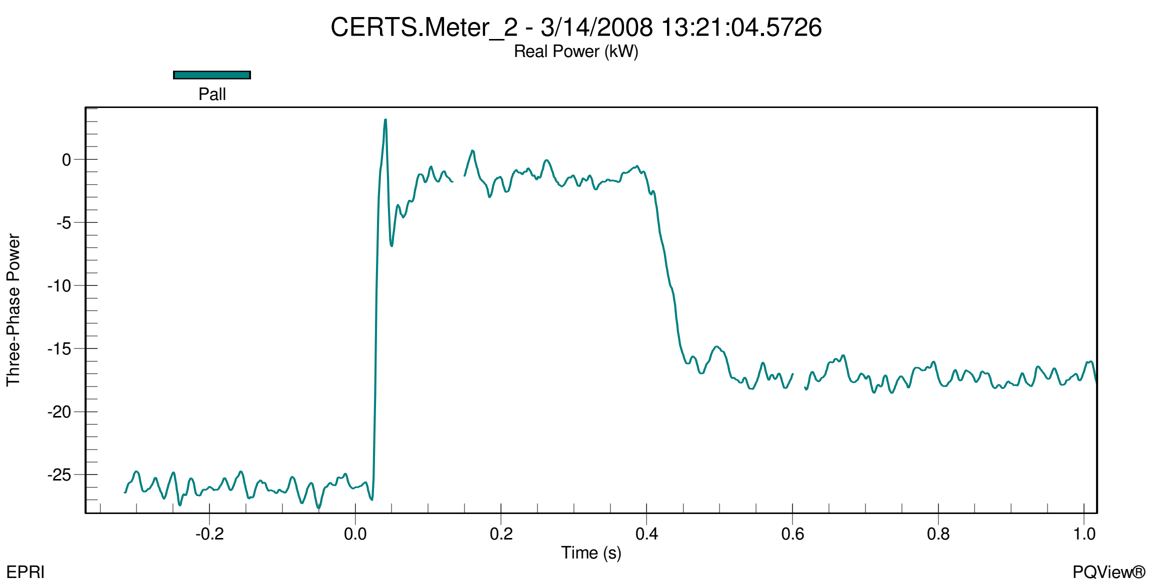

Figure 6e - Static Switch Real Power during Motor Start and Utility Connected for Test 10.2.14

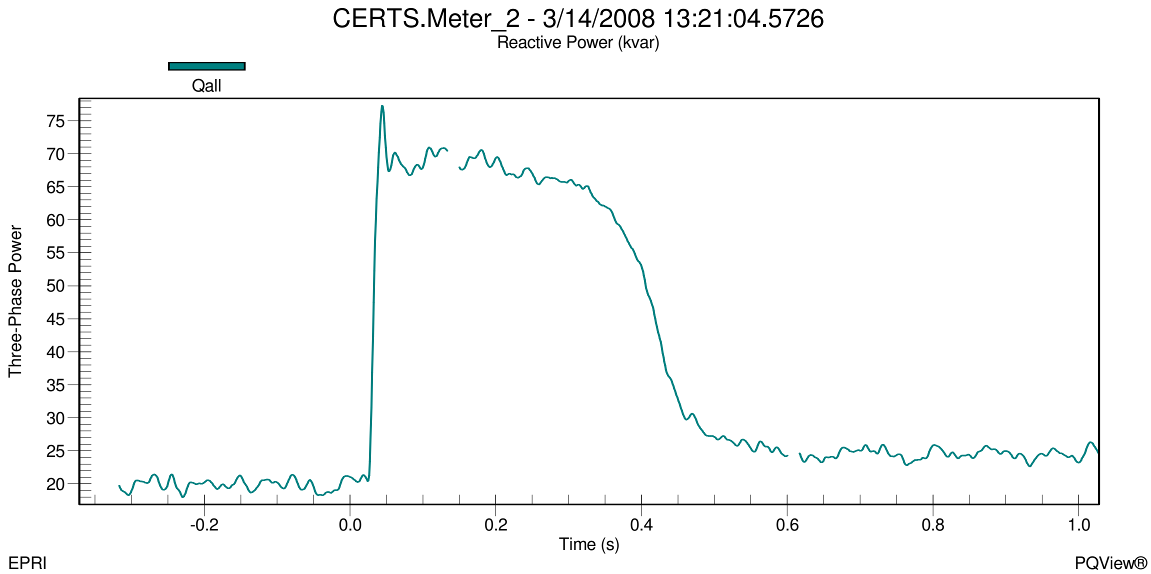

Figure 6f - Static Switch Reactive Power during Motor Start and Utility Connected for Test 10.2.14

Before the motor started Gen-set A1 was producing approximately 40kW – j14kVAr. This was enough for the load demands of Zone 3 with real power being exported to Zone 6 of approximately 26kW shown in Figure 6e. The grid was supporting the reactive power of the microgrid with approximately 20kVAr shown in Figure 6f. When the motor started the inrush caused the utility to supply approximately 77.1kVAr and to pick up the load demand in Load Bank 6 along with approximately 3kW of the load in Zone 3. The power being supplied by Gen-set A1 to Load Bank 6 was now supplying the motor inrush which can be seen in Figure 6e as the real power through the static switch becomes positive. Gen-set A1 increased its real and reactive power output level to approximately 46.9kW + j5kVAr. Notice the sign of the VAr output changed from negative to positive for Gen-set A1 in order to support the induction motor load in Zone 3.

When the motor reached steady state, the real and reactive power through the static switch was approximately -17.2kW + j24kVAr which meant that Gen-set A1 was supplying the power for the induction motor and approximately 17.2kW of Load Bank 6. Gen-set A1 real power returned to the value before the motor started of approximately 40kW and the reactive power increased to approximately -12kVAr. Once all the data was verified and recorded into the DAS Database, the motor was shut down and the static switch was directed by the EMS to manually open.

As soon as the static switch opened, Meter 1 recorded real power increased to approximately 37kW and reactive power decreased to 0kVAr satisfying the load demand in Load Bank 6 which was approximately 36.6kW + j0kVAr and not supplying any power beyond the static switch to Load Bank 3. 0kW + j0kVAr was recorded at the static switch, indicating that power was not flowing through the static switch. Load Bank 3 loads was slightly reduced to 10.3kW – j0.041kVAr. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 6g, from approximately 283V on A-phase, 280V on B-phase and 280V on C-phase when connected to the utility grid to 273V on A-phase, 271.5V on B-phase and 273V on C-phase at Meter 3 when islanded.

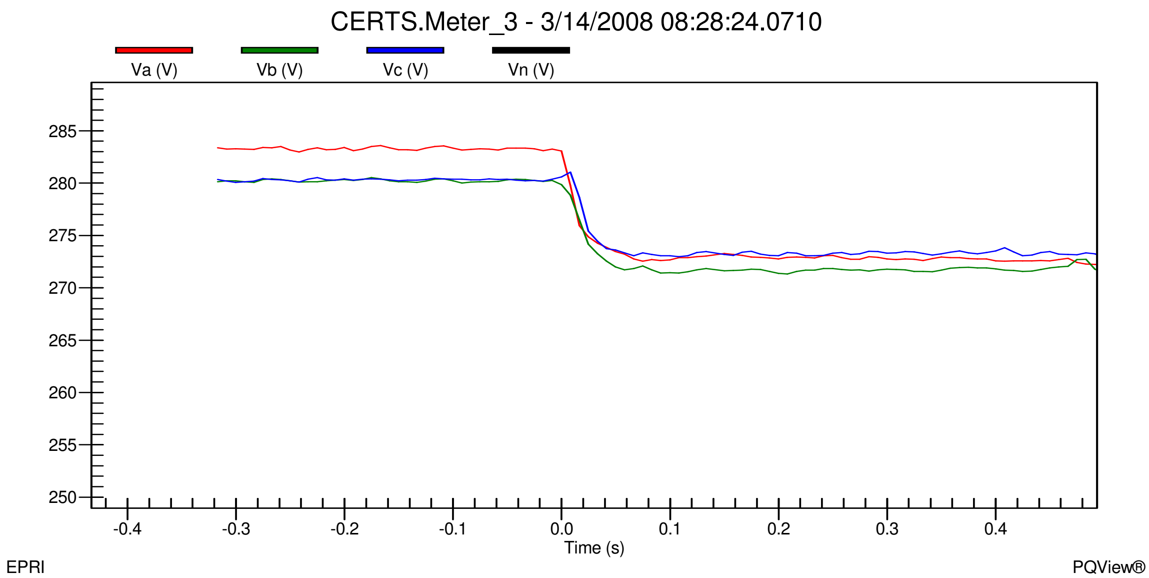

Figure 6g - Meter 3 Line-to-Ground Voltages during Utility Connected to Island mode for Test 10.2.14

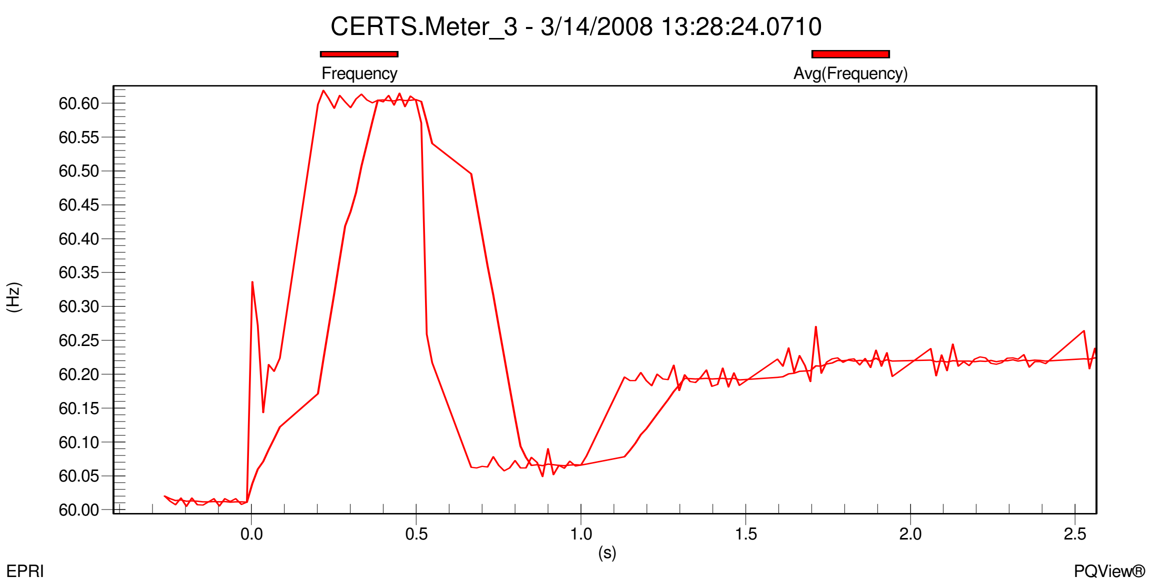

Figure 6h - Meter 3 Frequency during Utility Connected to Island mode for Test 10.2.14

Frequency change in the microgrid, shown in Figure 6h, increased from approximately 60.01Hz when connected to the utility grid to approximately 60.22Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed Gen-set A1 to decrease its output power to satisfy the load demands. Gen-set A1 decreased its output real power to approximately 13kW and increased its output reactive power to approximately 3.5kVAr. Meter 3 was approximately -3.5kW - j3.9kVAr indicating that Gen-set A1 was satisfying the load in Load Bank 3 and the power losses in the electrical lines. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the 10Hp induction motor was started in Zone 3.

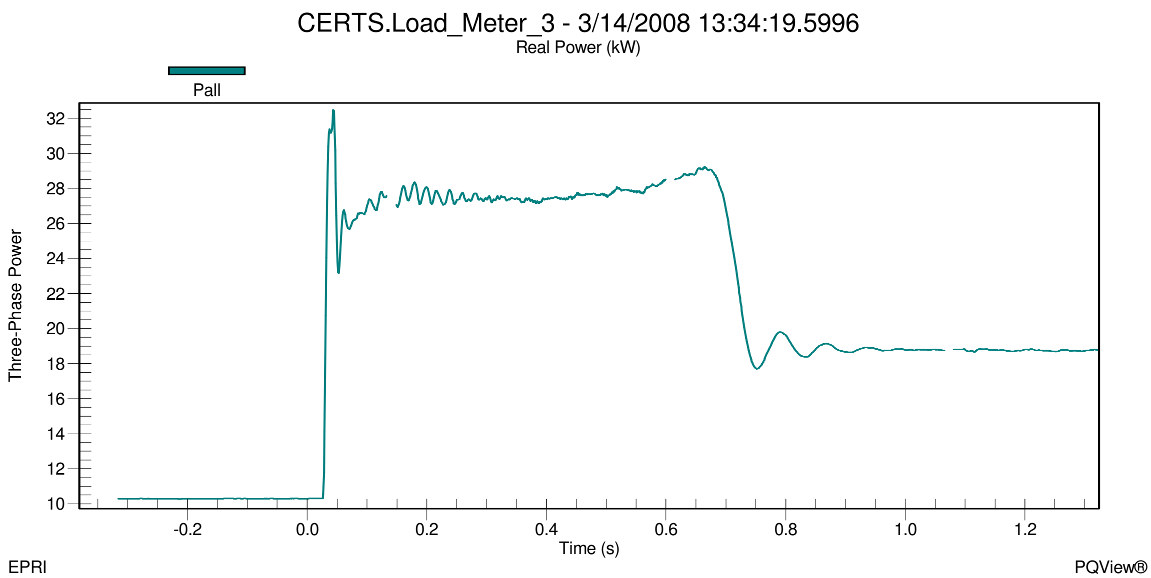

Figure 6i - Load Bank 3 Real Power during Motor Start and Islanded for Test 10.2.14

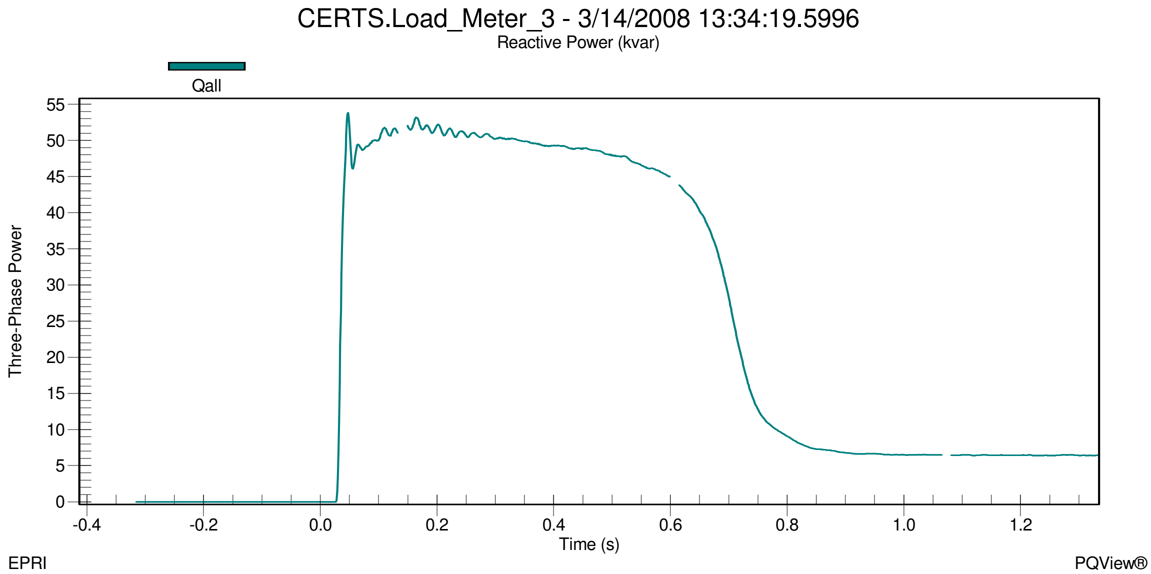

Figure 6j - Load Bank 3 Reactive Power during Motor Start and Islanded for Test 10.2.14

In Figures 6i and 6j it can be seen that the load in Zone 3 was approximately 10.4kW + j0kVAr before the start of the induction motor and increased to approximately 32.5kW + j54kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 28kW + j50kVAr during the warm up phase which lasted about 51 cycles (0.85 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 18.8kW + j6.8kVAr.

The voltage and frequency at Meter 3 before the motor start was approximately 272.5V on A-phase, 272.5V on B-phase and 272.5V on C-phase shown in Figure 6k and approximately 60.22Hz shown in Figure 6l. When the motor started, the voltage at Meter 3 during the inrush decreased to approximately 235V on A-phase, 235V on B-phase and 235V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.88Hz and quickly increased to approximately 60.15Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 268.8V on A-phase, 268.8V on B-phase and 268.8V on C-phase at an approximate frequency of 60.15Hz.

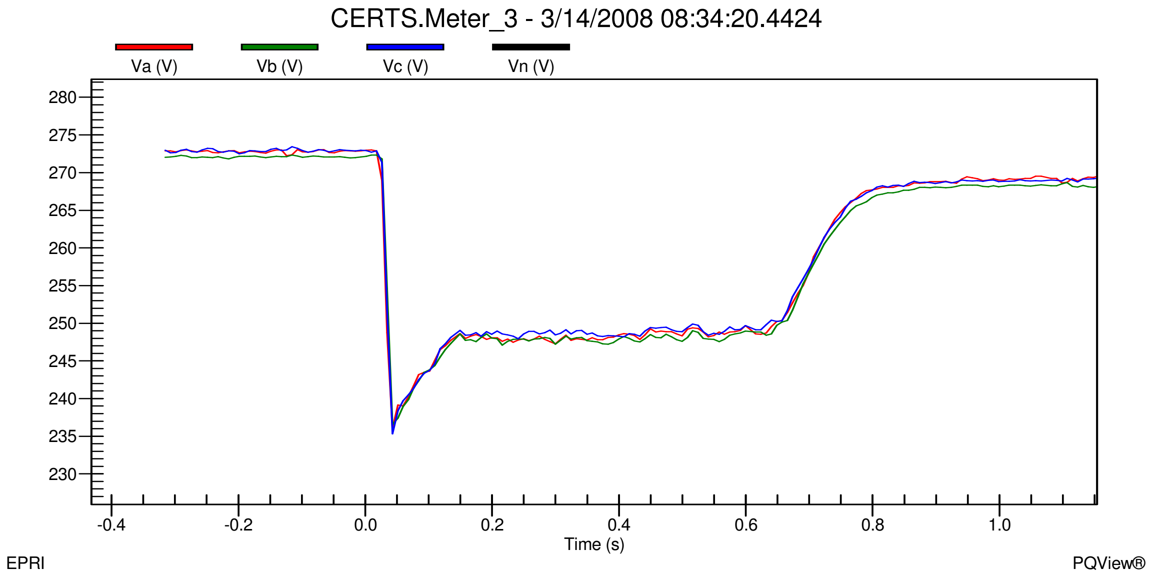

Figure 6k – Meter 3 Line-to-Ground Voltages during Motor Start and Islanded for Test 10.2.14

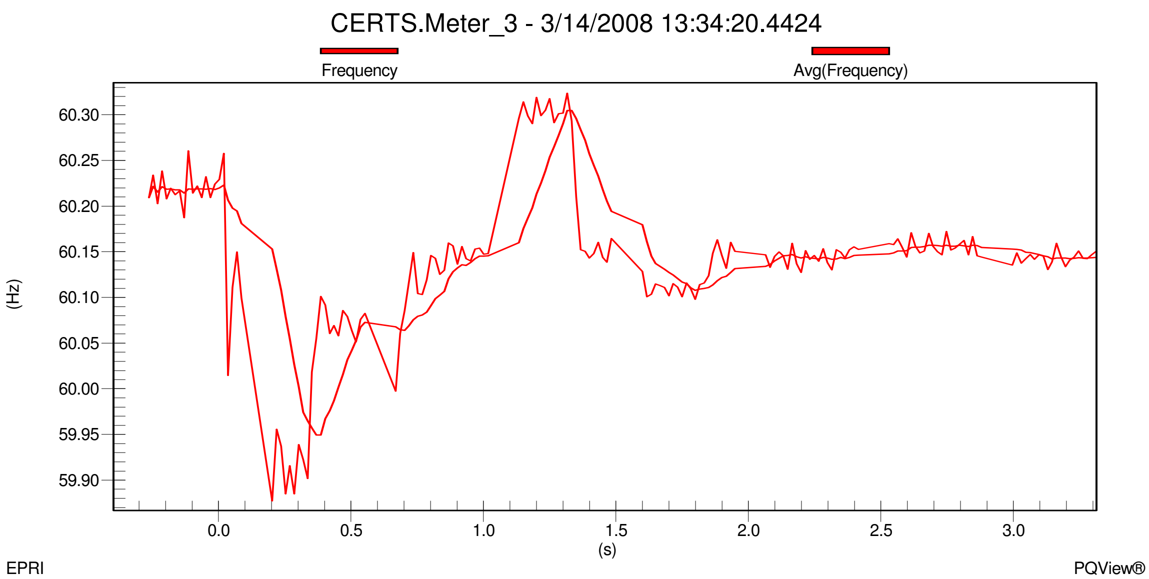

Figure 6l – Meter 3 Frequency during Motor Start and Islanded for Test 10.2.14

Before the motor started, Gen-set A1 was producing approximately 12.5kW + j3.5kVAr shown in Figures 6m and 6n. The power generated by Gen-set A1 was satisfying the loads in Load Bank 3 and all the electrical losses in the microgrid system. When the motor started the inrush caused the Gen-set to increase its output level to 34.3kW + j55kVAr. Gen-set A1 decreased its output level while the motor was warming up and eventually dropped to 21kW +j9.8kVAr when the motor reached steady state. Once all the data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually close.

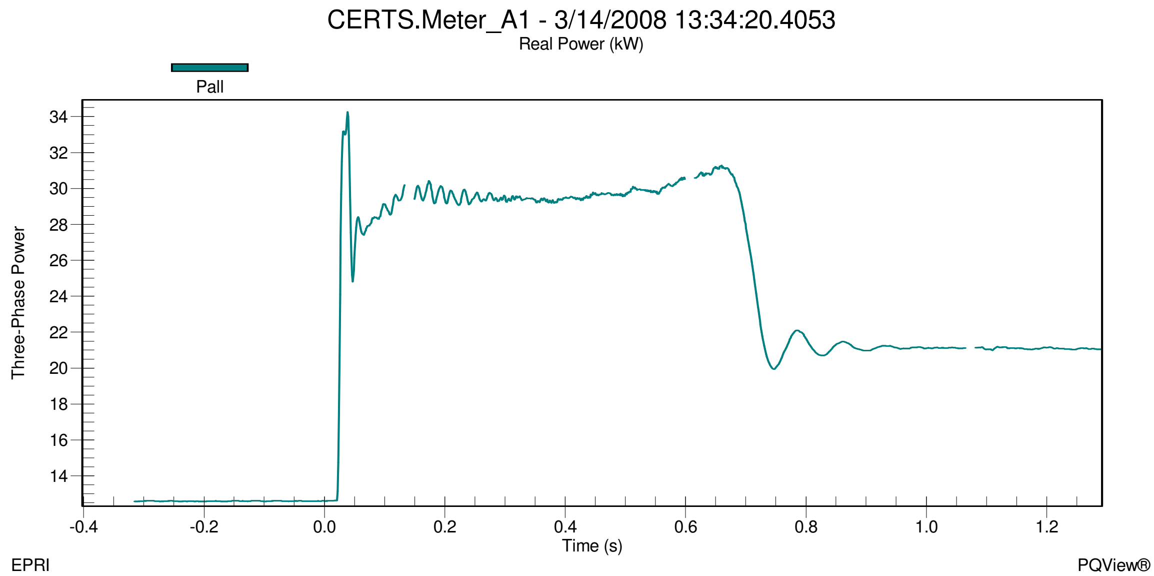

Figure 6m - Gen-set A1 Real Power during Motor Start and Islanded for Test 10.2.14

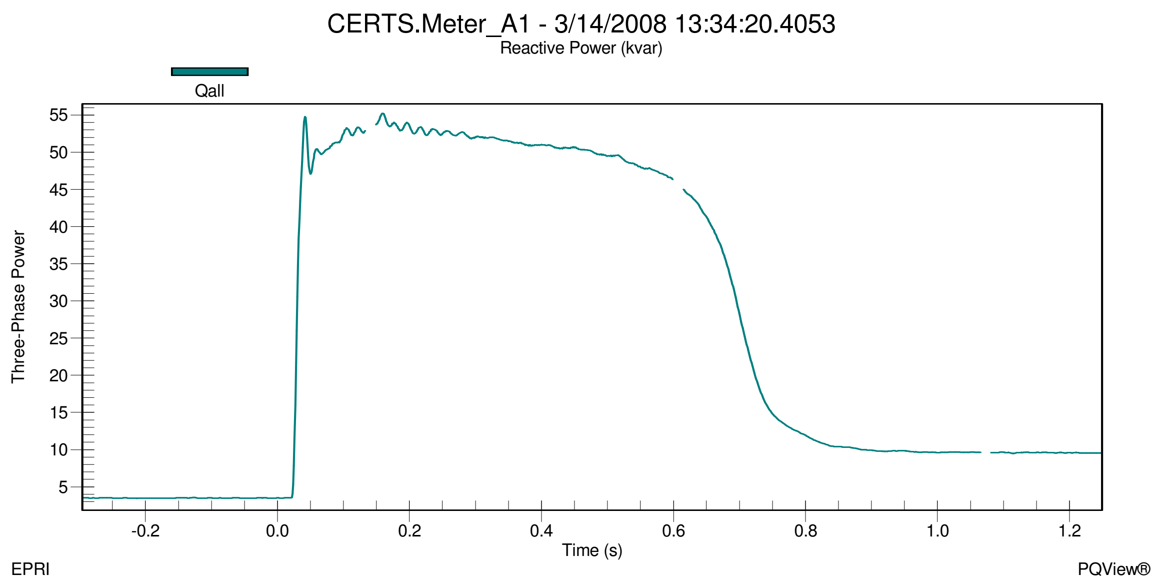

Figure 6n - Gen-set A1 Reactive Power during Motor Start and Islanded for Test 10.2.14

As soon as the static switch closed, Meter 1 recorded real power decreased from approximately 37kW to 18kW and reactive power increased from approximately 0kVAr to 25kVAr which means that the utility was satisfying a portion of the load demand in Load Bank 6 and all the reactive power in the microgrid. Figures 6o and 6p show the static switch decreasing from approximately 0kW to -17.7kW and increasing from approximately 0kVAr to 24kVAr. At the beginning of the test, the initial power flow through the static switch was -26kW + j20kVAr which was not the same recorded at this point in the test because the 10Hp motor load is on in Zone 3. Gen-set A1 has picked up the motor load and is supporting Load Bank 6 with approximately 17.7kW.

Load Bank 3 loads increased slightly to 17.65kW + j6.1kVAr. This slight increase is a result from a voltage rise in the microgrid, shown in Figure 6q, from approximately 269V on A-phase, 269V on B-phase and 269V on C-phase when islanded to 282V on A-phase, 280V on B-phase and 280V on C-phase at Meter 3 when connected to the utility grid.

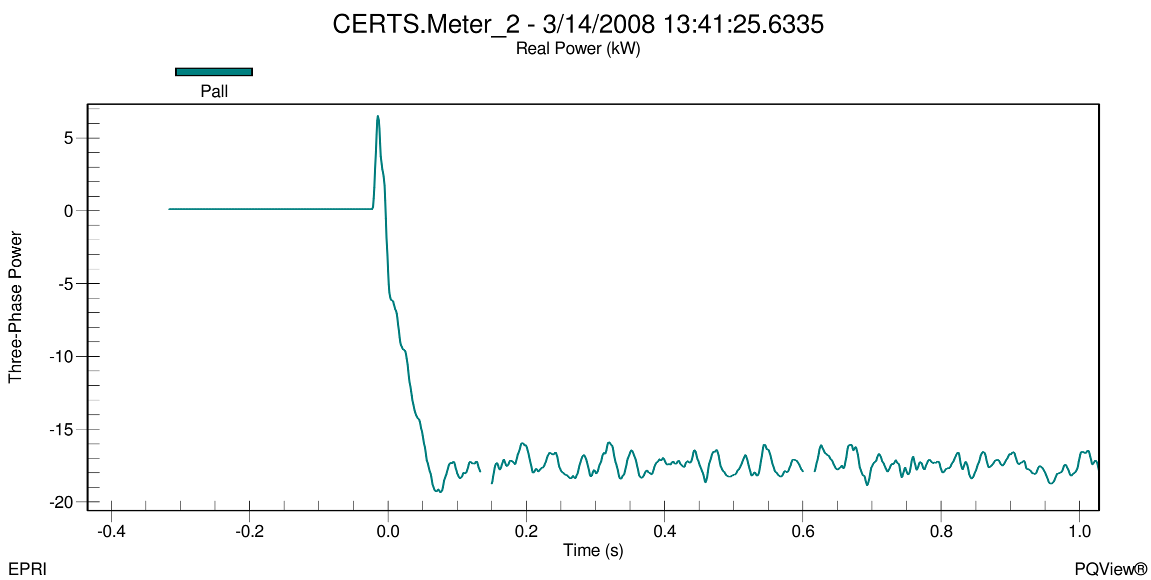

Figure 6o – Static Switch Real Power during Island to Utility Connected mode for Test 10.2.14

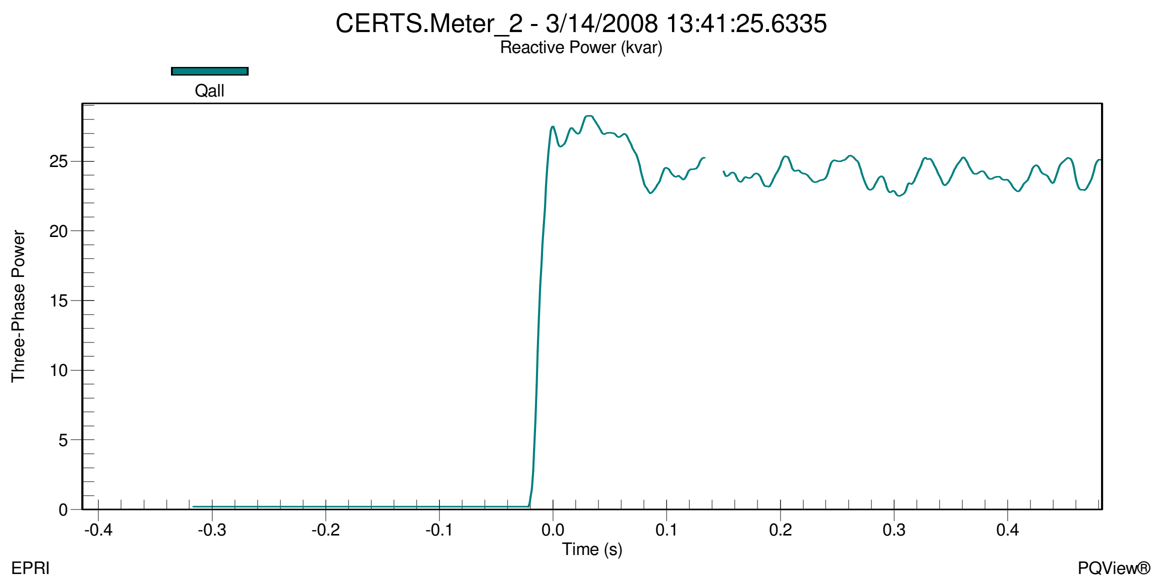

Figure 6p – Static Switch Reactive Power during Island to Utility Connected mode for Test 10.2.14

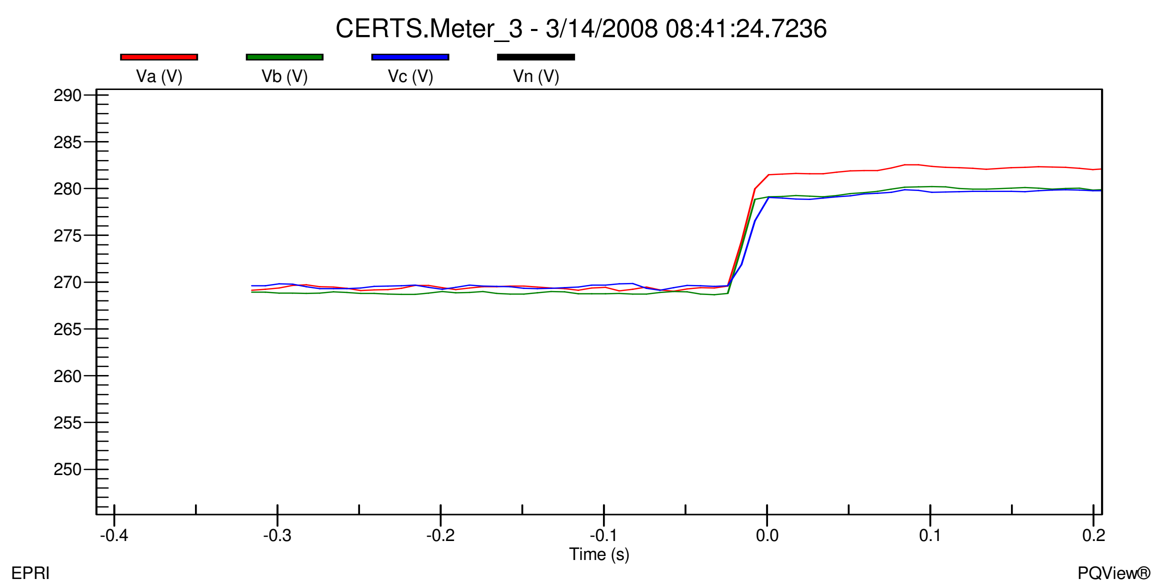

Figure 6q - Meter 3 Line-to-Ground Voltages during Island to Utility Connected mode for Test 10.2.14

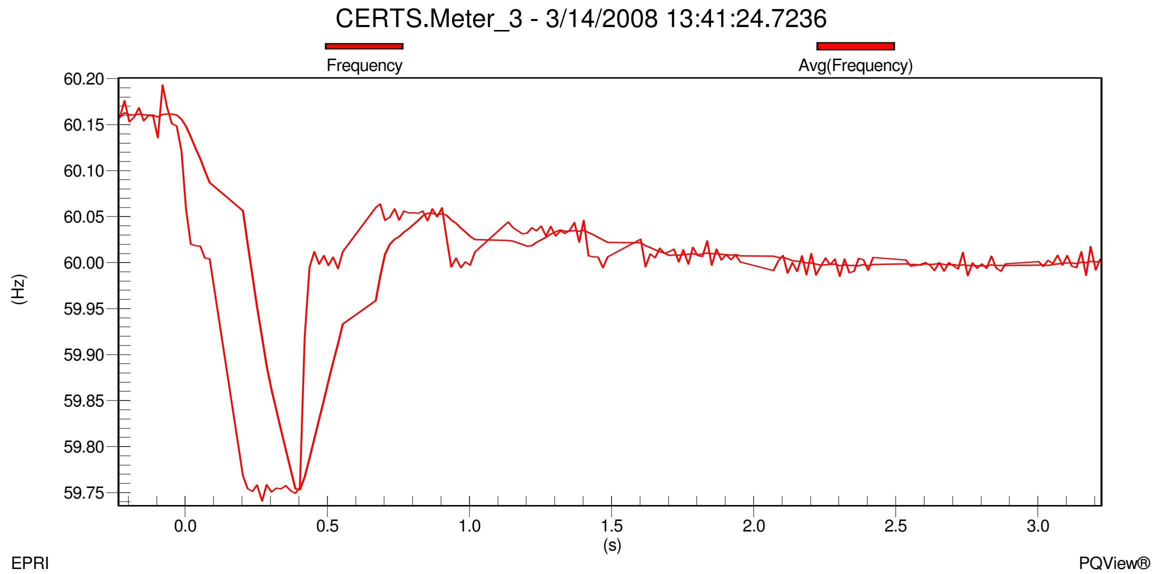

Figure 6r - Meter 3 Frequency during Island to Utility Connected mode for Test 10.2.14

Frequency change in the microgrid, shown in Figure 6r, decreased from approximately 60.16Hz when islanded to approximately 60.00Hz when connected to the utility grid. This change in frequency is due to the frequency no longer being established by Gen-set A1 using the CERTS algorithm but by the utility. Gen-set A1 is in unit power control mode therefore when the static switch closed back into the utility the Gen-set produced real power based on the set-point initialized at the beginning of the test. The output power for Gen-set A1 was relatively close to the values at the beginning of the test with Gen-set A1 producing approximately 38kW – j12kVAr. After all the data was verified and recorded into the DAS Database, the motor was turned off and the Gen-sets and Load Banks set-points were changed according to the next test (10.2.15) in Table 1.

For Test 10.2.15 the measured values, after the Gen-sets were warmed up and load bank brought on-line, were approximately 64kW + 17kVAr at Meter 1, 28kW + j16kVAr at Meter 2, 25kW + j10kVAr at Meter 3 and 16kW + j1kVAr. From the microgrid, 38.4kW – j10kVAr was produced by Gen-set A1 and 30kW + j0kVAr was produced by Gen-set A2. The load banks were 47kW + j0kVAr at LB3, 46.9kW + j0.715kVAr at LB4 and 35.8kW + j0.766kVAr at LB6. These measurements were relatively close to the expected values in Table 1, but not exact due to temperature, phase voltages and electrical losses in conductors. In addition, the 50kW settings for LB3 and LB4 and the 40kW setting for LB6 were also below selected set values. At the time of these measurements, the voltage and frequency was 281.6V on A-phase, 279.1V on B-phase and 279.1V on C-phase and 60.02Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 281.6V on A-phase, 279.1V on B-phase and 279.1V on C-phase and 60.02Hz at Meter 3.

The Gen-sets in this test were set up to produce less power than the microgrid loads needed which approximately 28kW of power was imported from the utility through the static switch to support Load Banks 3 and 4. Since Load Bank 6 was approximately 35.8kW + j0.766kVAr, the utility had to supply approximately 64kW to satisfy the load demand of Load Bank 6 and the microgrid loads. Reactive power had to be imported in from the utility of approximately 16kVAr because Gen-set A1 and A2 needed approximately 10kVAr between the two and the reactive power of Load Banks 3 and 4 and electrical wires. Once all data was verified and recorded into the DAS Database, the 10Hp induction motor was started in Zone 3.

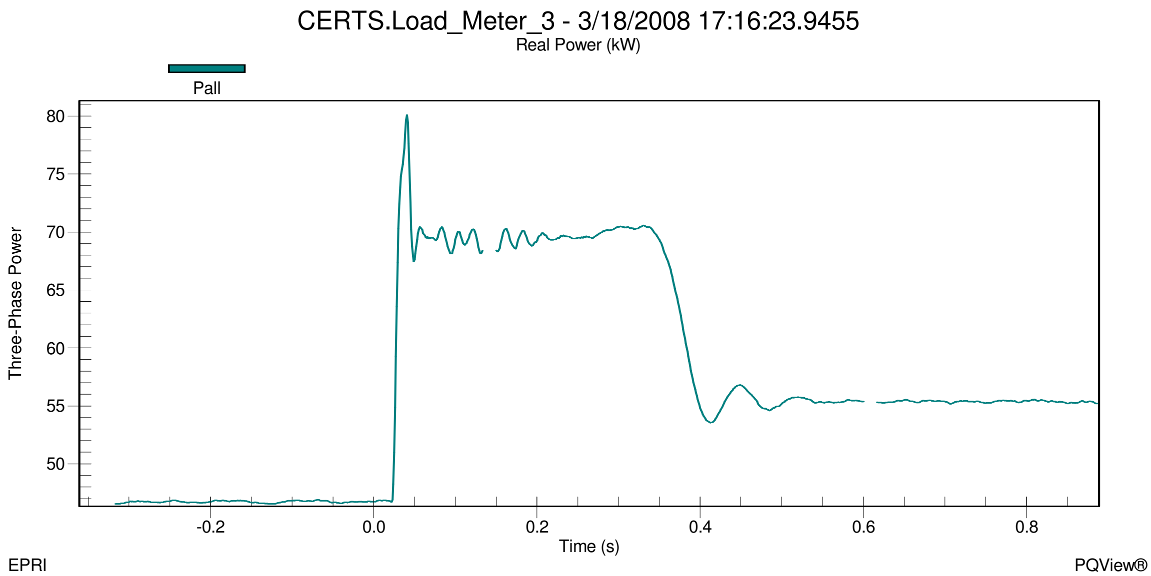

Figure 7a - Load Bank 3 Real Power during Motor Start Utility Connected for Test 10.2.15

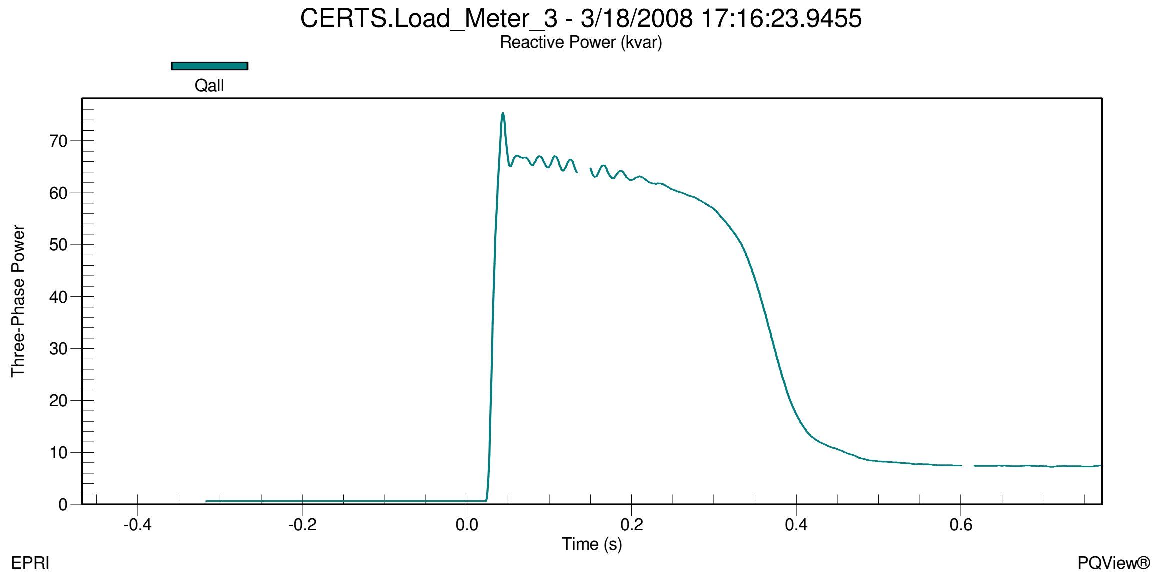

Figure 7b - Load Bank 3 Reactive Power during Motor Start Utility Connected for Test 10.2.15

In Figures 7a and 7b it can be seen that the load in Zone 3 was approximately 46.9kW + j0.715kVAr before the start of the induction motor and increased to approximately 80kW + j75kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 69.5kW + j64kVAr during the warm up phase which lasted about 33 cycles (0.55 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 55.5kW + j7kVAr.

The voltage and frequency at the static switch before the motor start was approximately 281.6V on A-phase, 279.1V on B-phase and 279.1V on C-phase shown in Figure 7c and approximately 60.02Hz shown in Figure 7d. When the motor started, the voltage at the static switch during the inrush decreased to approximately 274.6V on A-phase, 271.6V on B-phase and 272.1V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.95Hz and quickly increased back to approximately 60.00Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 280.8V on A-phase, 278.2V on B-phase and 278.4V on C-phase at an approximate frequency of 60.00Hz.

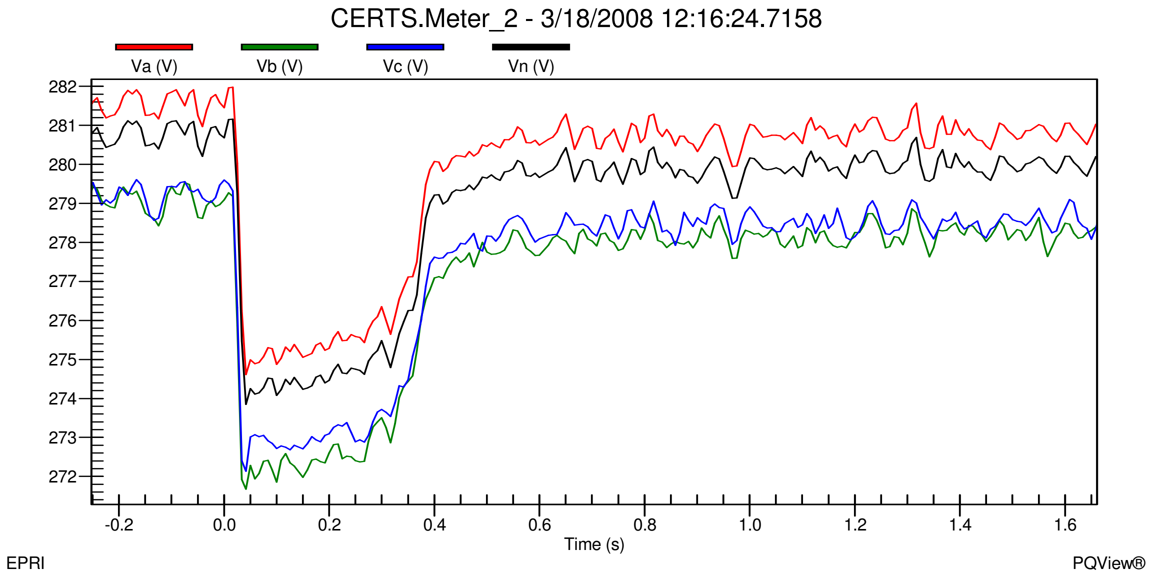

Figure 7c - Static Switch Line-to-Ground Voltages during Motor Start and Utility Connected for Test 10.2.15

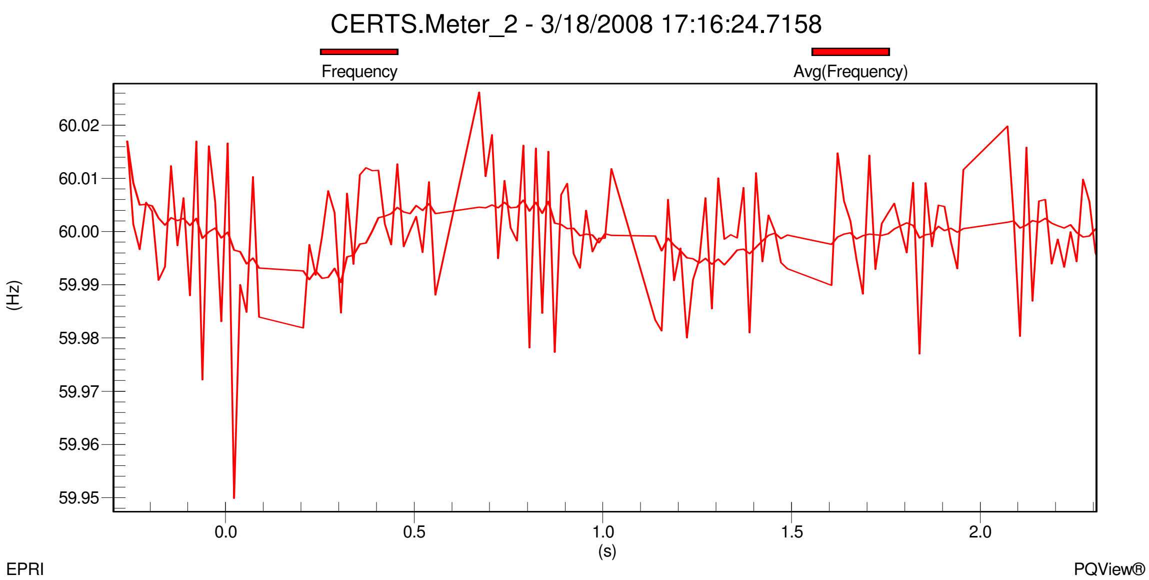

Figure 7d - Static Switch Frequency during Motor Start and Utility Connected for Test 10.2.15

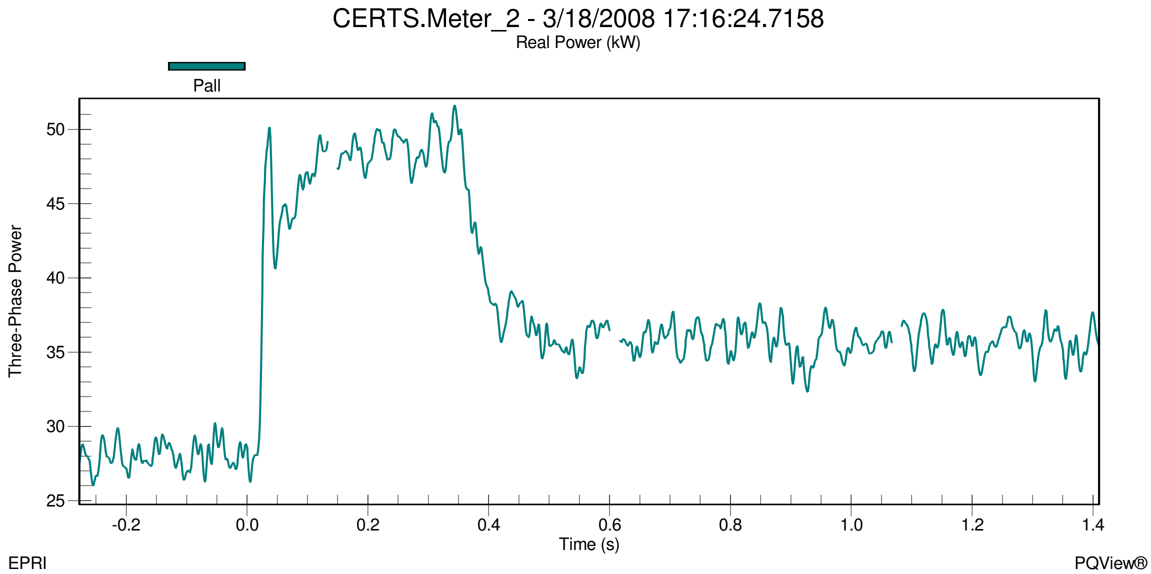

Figure 7e - Static Switch Real power during Motor Start and Utility Connected for Test 10.2.15

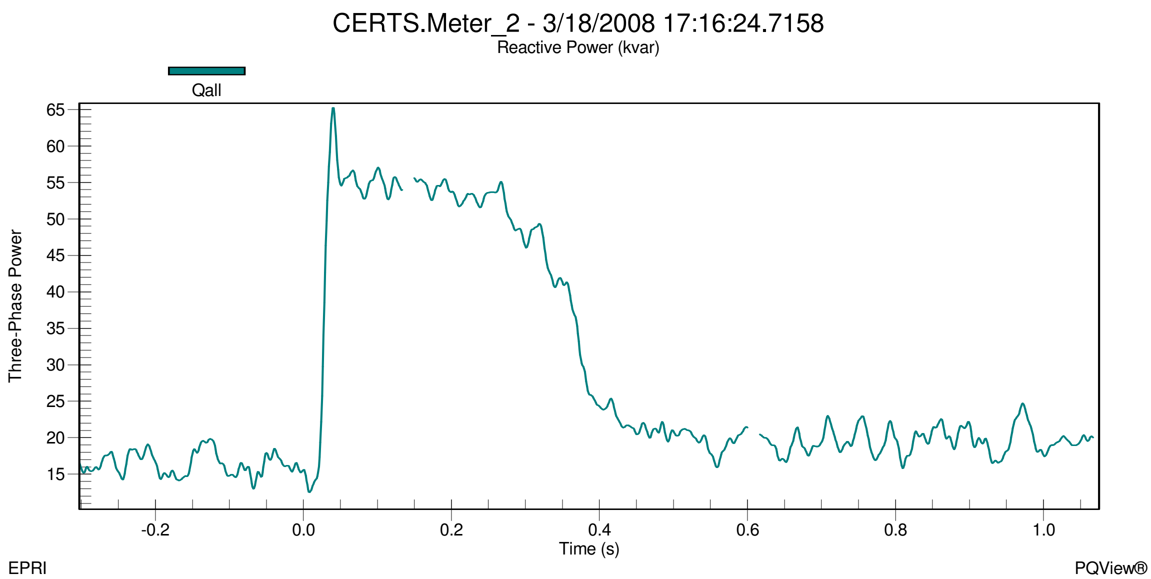

Figure 7f - Static Switch Reactive Power during Motor Start and Utility Connected for Test 10.2.15

Before the motor started Gen-sets A1 and A2 were producing approximately 38.4kW – j10kVAr and 30kW + j0kVAr, respectively. The load demands of Load Banks 3 and 4 were greater than the power being produced by both Gen-sets therefore the utility had to supply approximately 28kW shown in Figure 7e. The utility was supporting the reactive power of the microgrid with approximately 16kVAr shown in Figure 7f. When the motor started the inrush caused the utility to supply approximately 50kW + j65kVAr to the microgrid loads, shown in Figures 7e and 7f, and Gen-sets A1 and A2 increased their output power levels to 41.8kW + j5kVAr and 35.5kW + j14.5kVAr, respectively.

Notice the sign of the VAr output changed from negative to positive for Gen-set A1 and 0kVAr to 14.5kVAr for Gen-set A2 in order to support the induction motor load in Zone 3.

When the motor reached steady state, the real and reactive power through the static switch was approximately 35.5kW + j19kVAr which meant that the utility was supplying the power for the induction motor. Gen-sets A1 and A2 real power returned to the values before the motor started of approximately 38.4kW and 30kW, respectively, and the reactive power slightly increased to approximately -9kVAr in Gen-set A1 and 2kVAr in Gen-set A2. Once all the data was verified and recorded into the DAS Database, the motor was shut down and the static switch was directed by the EMS to manually open.

As soon as the static switch opened, Meter 1 recorded real and reactive power decreased to approximately 37kW + j1.4kVAr satisfying the load demand in Load Bank 6 which was approximately 36.6kW + j0.78kVAr and not supplying any power beyond the static switch to Load Banks 3 and 4. 0kW + j0kVAr was recorded at the static switch, indicating that power was not flowing through the static switch. Load Banks 3 and 4 loads reduced slightly to 44.9kW + j0.645kVAr and 44.4kW + j0.688kVAr, respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 7g, from approximately 280.8V on A-phase, 278.2V on B-phase and 278.2V on C-phase when connected to the utility grid to 274.1V on A-phase, 274.1V on B-phase and 274.1V on C-phase at Meter 3 when islanded.

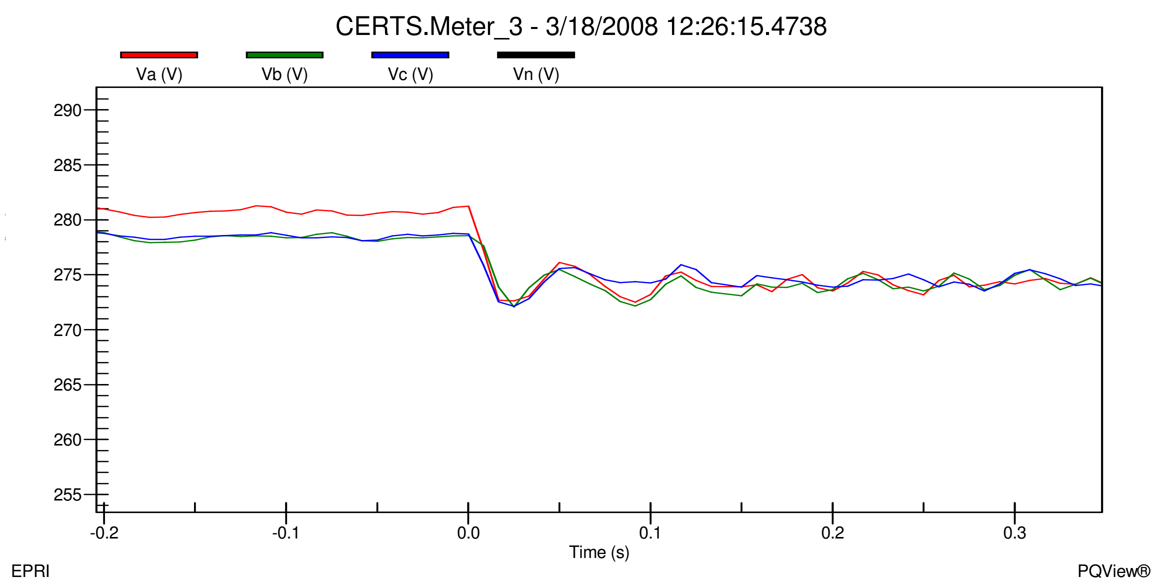

Figure 7g - Meter 3 Line-to-Ground Voltages during Utility Connected to Island mode for Test 10.2.15

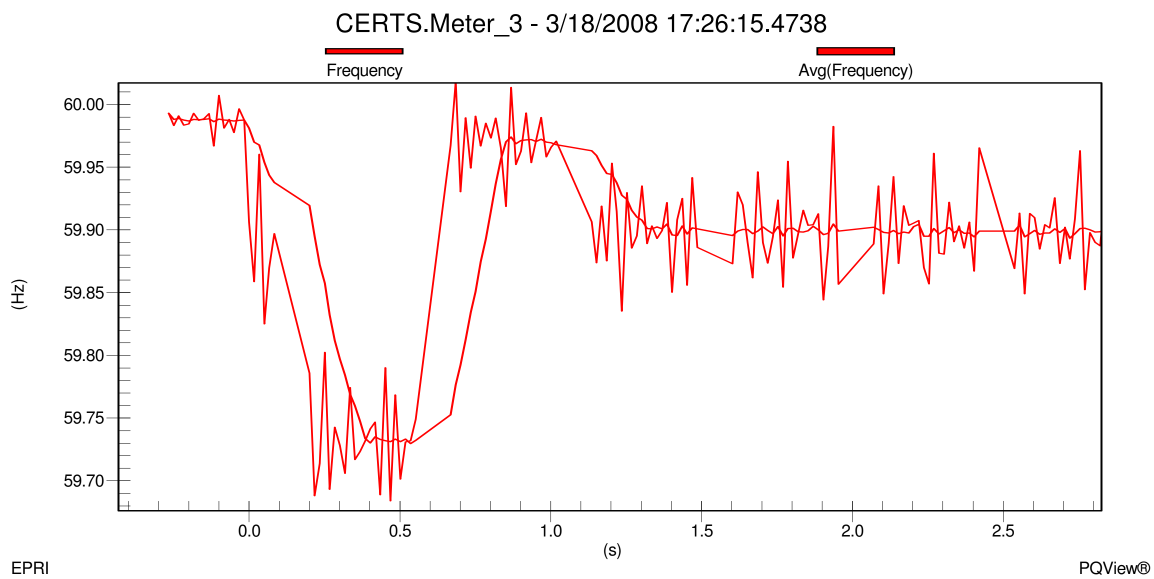

Figure 7h - Meter 3 Frequency during Utility Connected to Island mode for Test 10.2.15

Frequency change in the microgrid, shown in Figure 7h, decreased from approximately 59.99Hz when connected to the utility grid to approximately 59.90Hz 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 and A2 increased their output real and reactive powers approximately 49.6kW – j2kVAr and 41.9kW + j7kVAr, respectively. Meter 3 was approximately -2kW – j3kVAr indicating that the Gen-sets were satisfying the loads in the microgrid and the power losses in the electrical lines. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the 10Hp induction motor was started in Zone 3.

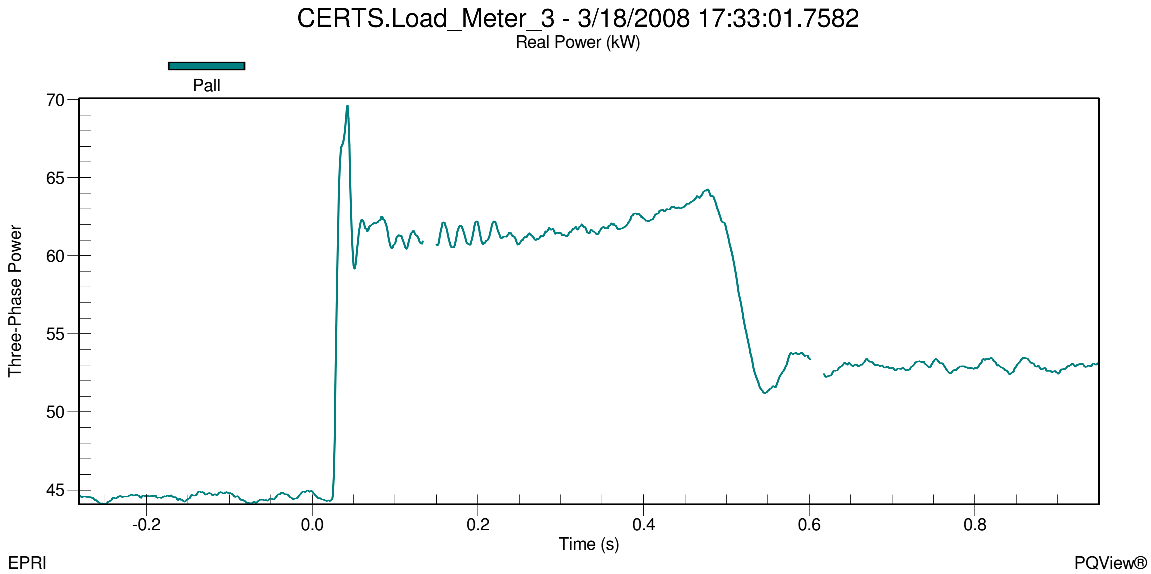

Figure 7i - Load Bank 3 Real Power during Motor Start and Islanded for Test 10.2.15

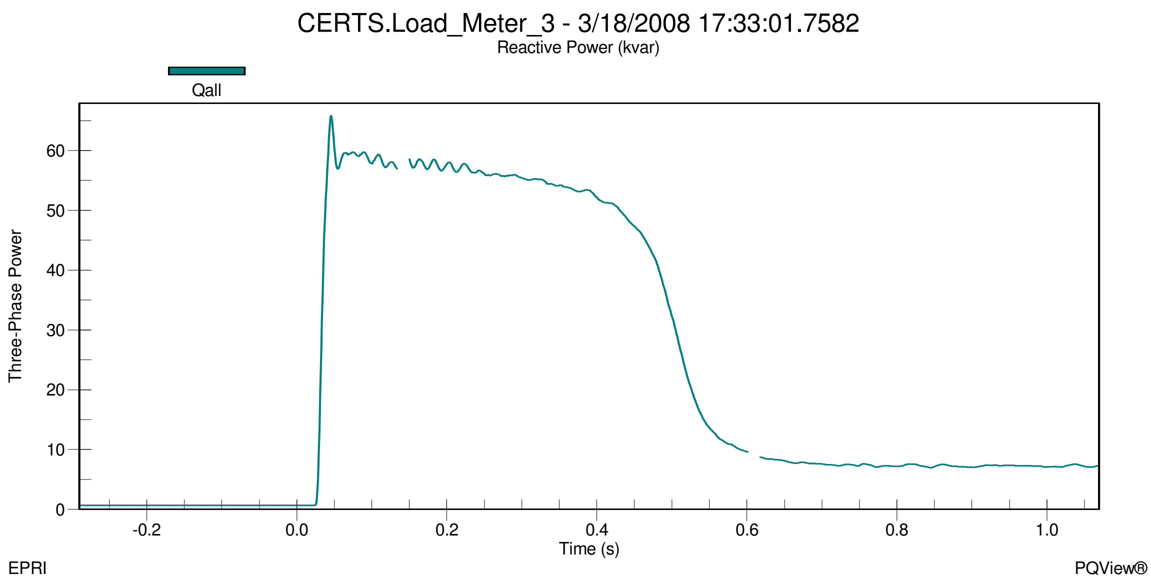

Figure 7j - Load Bank 3 Reactive Power during Motor Start and Islanded for Test 10.2.15

In Figures 7i and 7j it can be seen that the load in Zone 3 was approximately 44.5kW + j1kVAr before the start of the induction motor and increased to approximately 69.6kW + j66kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 61.8kW + j56kVAr during the warm up phase which lasted about 39 cycles (0.65 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 53kW + j7.5kVAr.

The voltage and frequency at Meter 3 before the motor start was approximately 274V on A-Phase, 274V on B-Phase and 274V on C-phase shown in Figure 7k and approximately 59.90Hz shown in Figure 7l. When the motor started, the voltage at Meter 3 during the inrush decreased to approximately 254.8V on A-Phase, 254.8V on B-Phase and 254.8V on C-Phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.81Hz and quickly increased to approximately 59.84Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 272V on A-Phase, 272V on B-Phase and 272V on C-Phase at an approximate frequency of 59.87Hz.

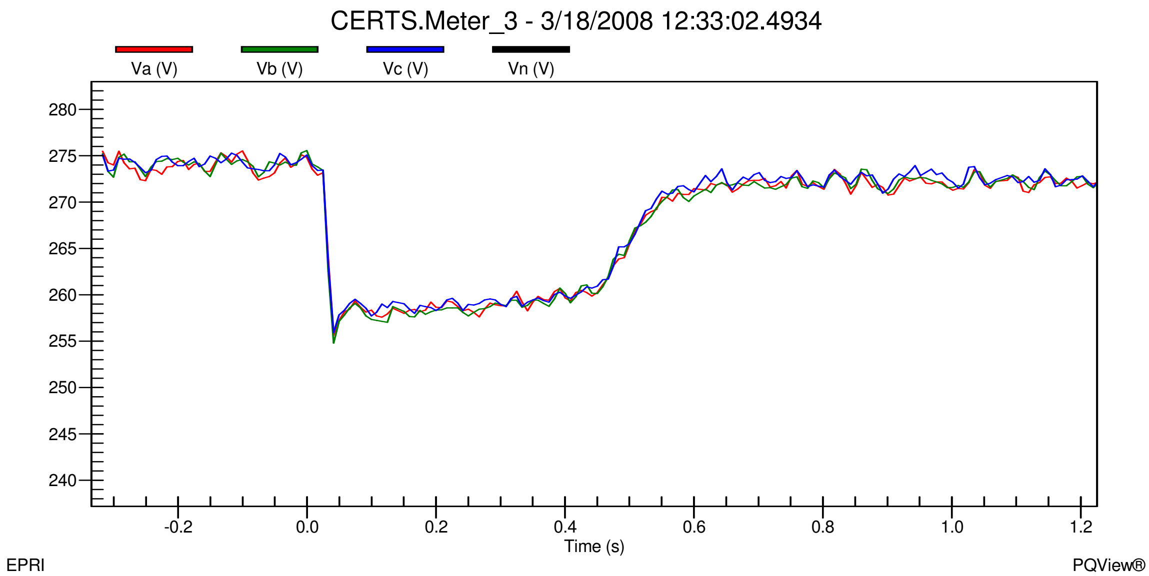

Figure 7k – Meter 3 Line-to-Ground Voltages during Motor Start and Islanded for Test 10.2.15

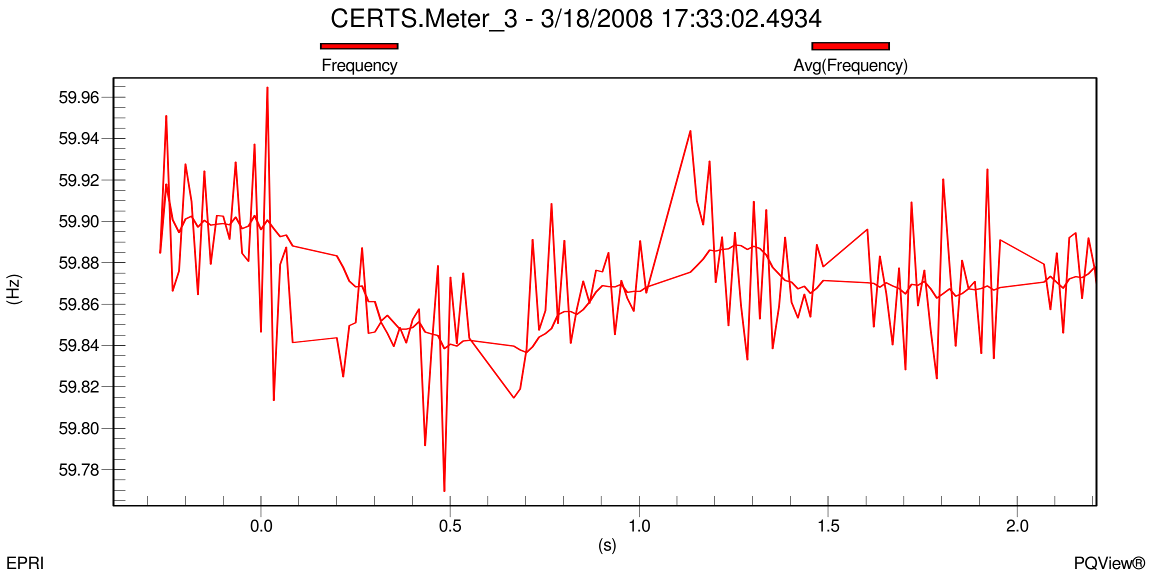

Figure 7l – Meter 3 Frequency during Motor Start and Islanded for Test 10.2.15

Before the motor started Gen-sets A1 and A2 were producing approximately 49.6kW – j2kVAr and 41.9kW + j7kVAr, respectively shown in Figures 7m – 7p. The power generated by both Gen-sets was satisfying the loads in Load Banks 3 and 4 and all the electrical losses in the microgrid system. When the motor started the inrush caused the Gen-sets to increase their output levels to 59kW + j30.7kVAr for Gen-set A1 and 52kW + j38kVAr for Gen-set A2. The Gen-sets decreased their output levels while the motor was warming up and eventually dropped to 53.4kW + j1kVAr for Gen-set A1 and 45.5kW + j10.5 for Gen-set A2 when the motor reached steady state. Once all the data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually close.

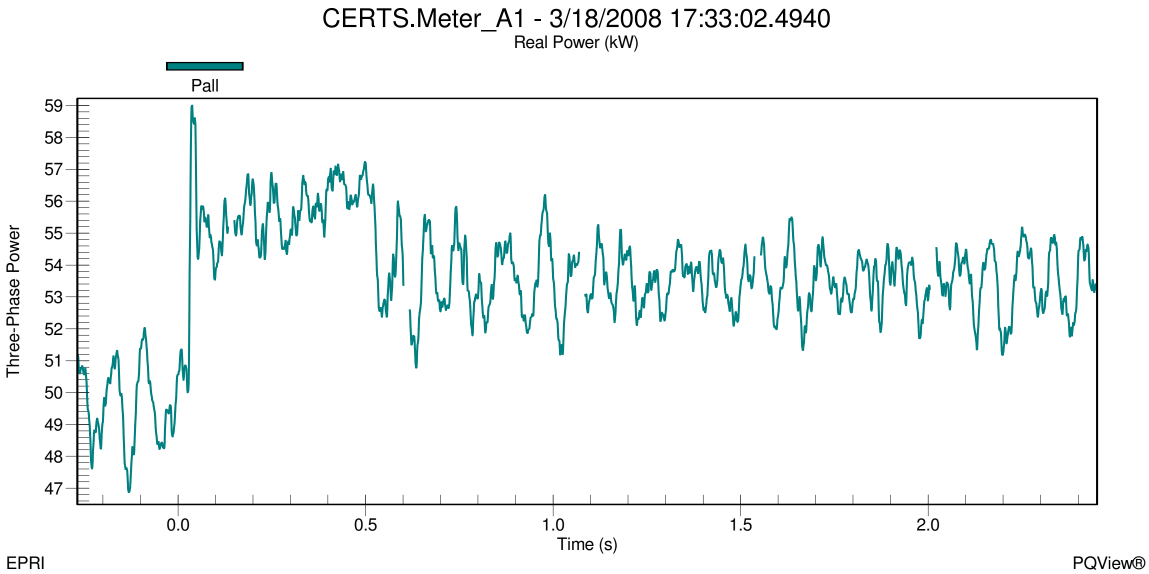

Figure 7m - Gen-set A1 Real Power during Motor Start and Islanded for Test 10.2.15

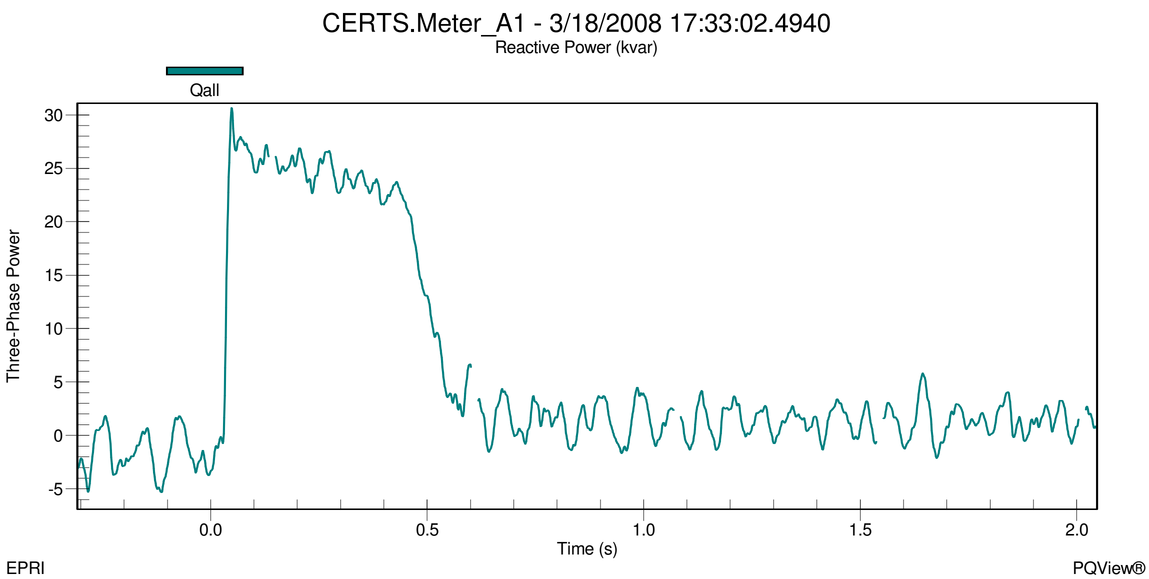

Figure 7n - Gen-set A1 Reactive Power during Motor Start and Islanded for Test 10.2.15

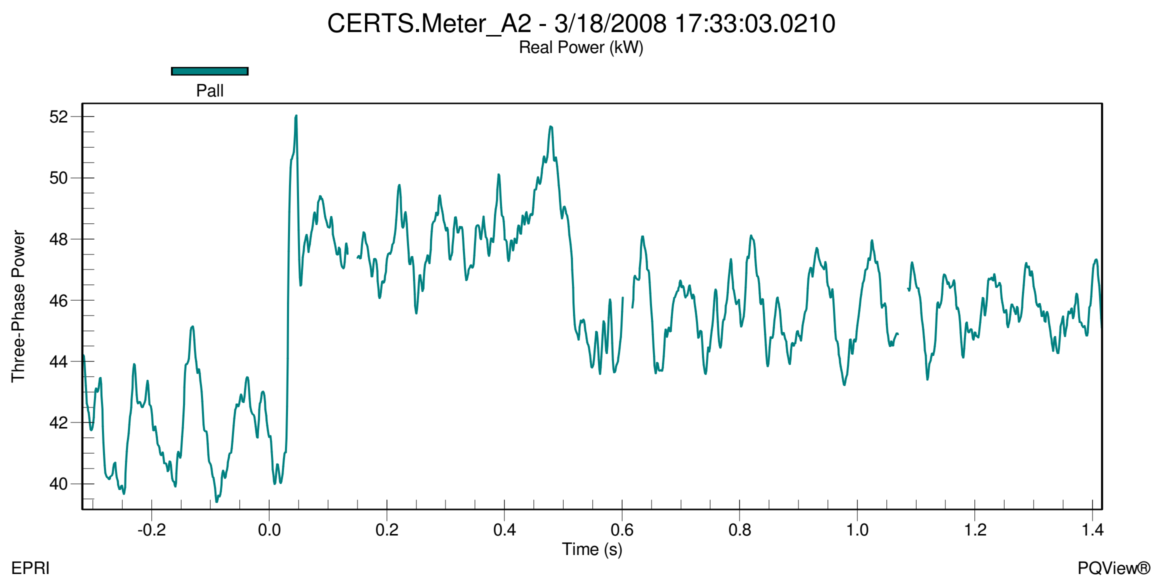

Figure 7o - Gen-set A2 Real Power during Motor Start and Islanded for Test 10.2.15

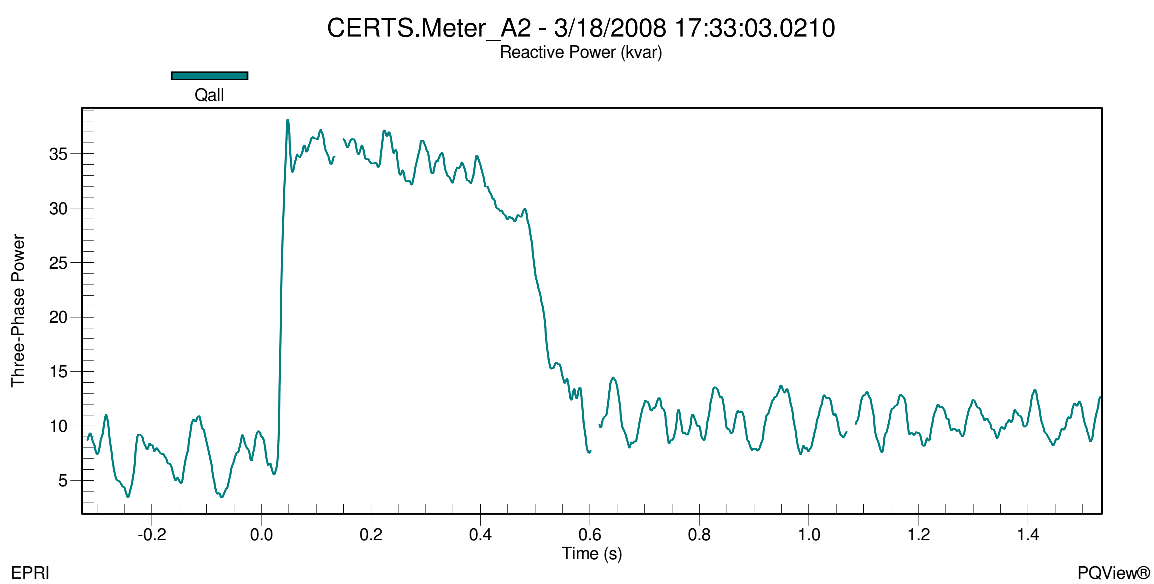

Figure 7p - Gen-set A2 Reactive Power during Motor Start and Islanded for Test 10.2.15

As soon as the static switch closed, Meter 1 recorded real and reactive powers increased from approximately 37kW + j1.1kVArto 70kW + j23kAVr which means that the utility was satisfying not only the load demand of Load Bank 6 but also all the reactive power and a portion of the real power for the microgrid loads. Figures 7q and 7r show the static switch increasing from approximately 0kW + j0kVAr to 34.5kW + j21kVAr. At the beginning of the test, the initial power flow through the static switch was 28kW + j16kVAr which is not the same recorded at this point in the test because the 10Hp motor load is on in Zone 3. The Gen-sets A1 and A2 output power levels reduced to approximately 37.2kW – j9.5kVAr and 30kW + j1.5kVAr, respectively, which are relatively close to the initial values at the beginning of the test. Since the motor is on in Zone 3 and the Gen-sets returned to their initial values at the beginning of the test before the motor was turned on means that the induction motor is completely being powered by the utility.

Load Banks 3 and 4 loads increased slightly to 53kW + j6.7kVAr and 45.7kW + j0.707kVAr, respectively. This slight load increase is a result from a voltage rise in the microgrid, shown in Figure 7s, from approximately 272.5V on A-phase, 272.5V on B-phase and 272.5V on C-phase when islanded to 280V on A-phase, 278V on B-phase and 278V on C-phase at Meter 3 when connected to the utility grid.

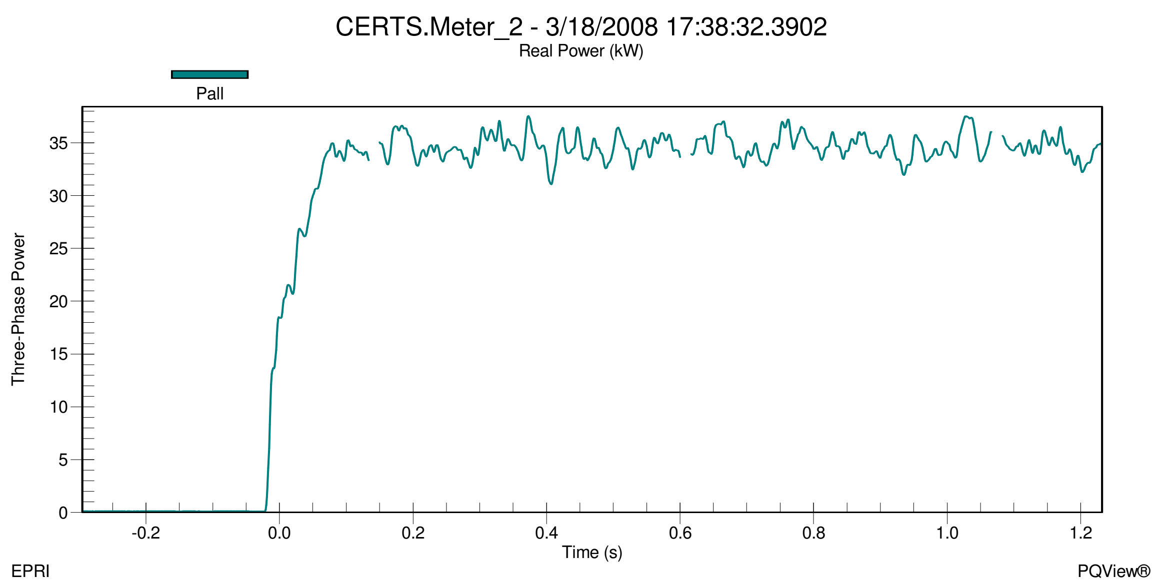

Figure 7q – Static Switch Real Power during Island to Utility Connected mode for Test 10.2.15

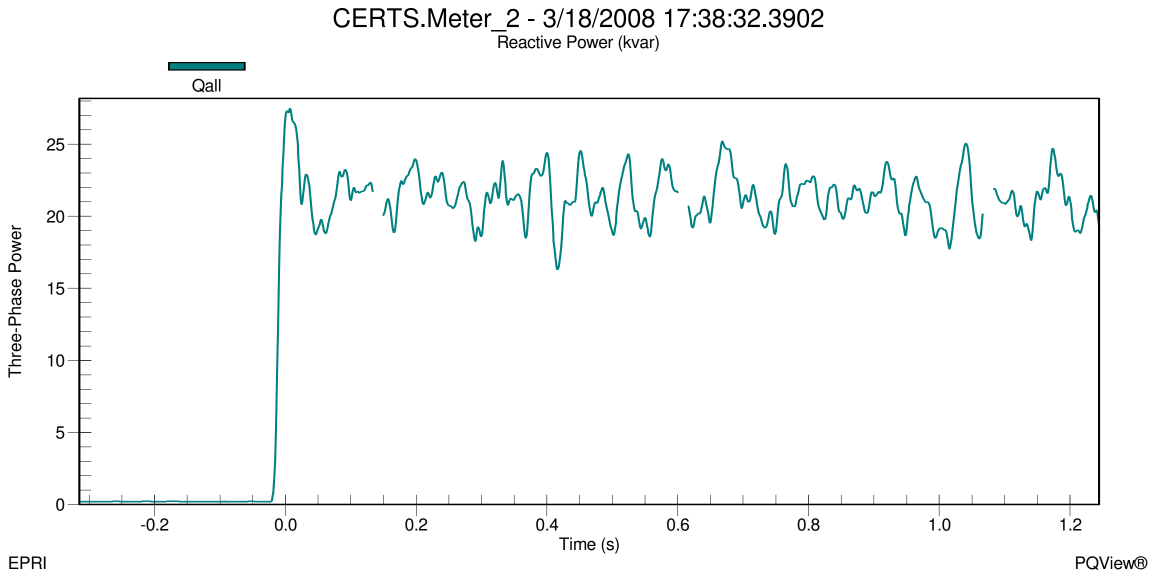

Figure 7r – Static Switch Reactive Power during Island to Utility Connected mode for Test 10.2.15

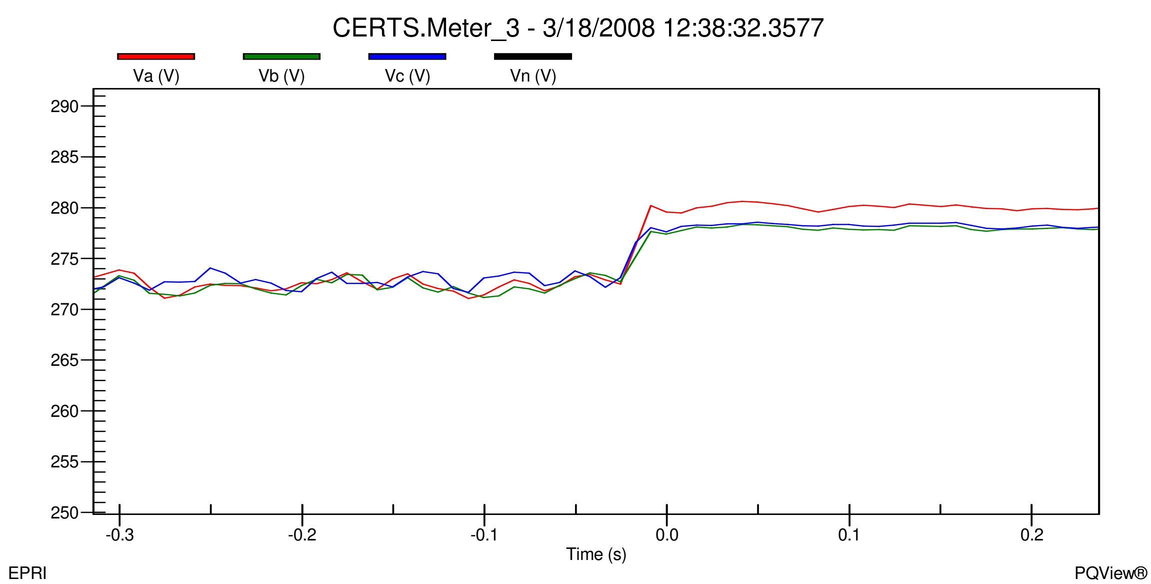

Figure 7s - Meter 3 Line-to-Ground Voltages during Island to Utility Connected mode for Test 10.2.15

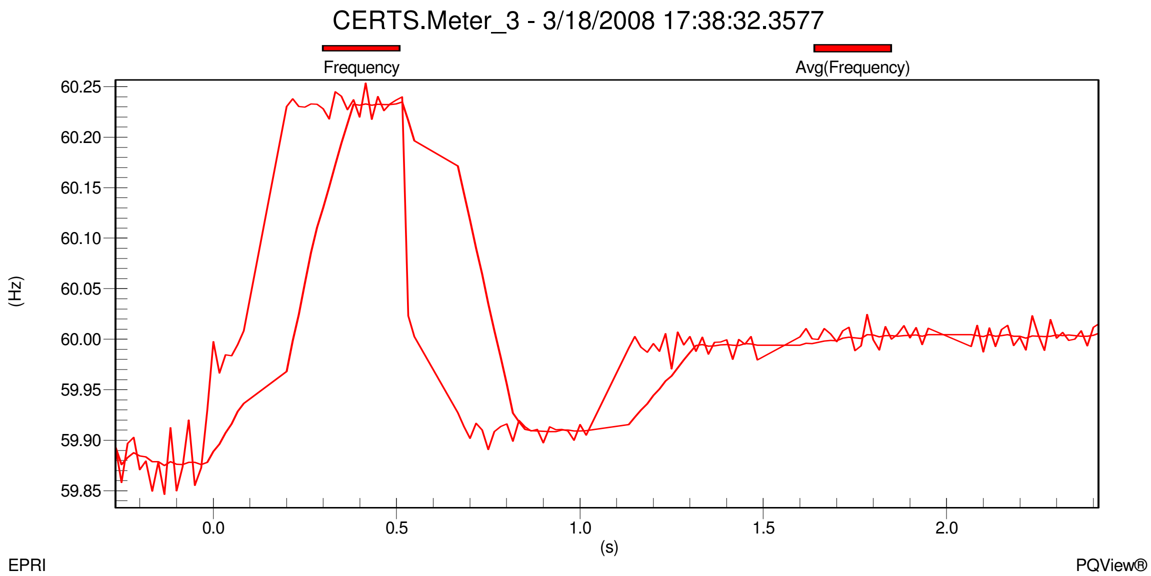

Figure 7t - Meter 3 Frequency during Island to Utility Connected mode for Test 10.2.15

Frequency change in the microgrid, shown in Figure 7t, increased from approximately 59.88Hz when islanded to approximately 60.00Hz when connected to the utility grid. This change in frequency is due to the frequency no longer being established by the Gen-sets using the CERTS algorithm but by the utility. Gen-sets A1 and A2 are in unit power control mode therefore when the static switch closed back into the utility the Gen-sets produced real power based on their set-points initialized at the beginning of the test. After all the data was verified and recorded into the DAS Database, the motor was turned off and the Gen-sets and Load Banks set-points were changed according to the next test (10.2.17) in Table 1.

For Test 10.2.17 the measured values, after Gen-set A1 was warmed up and load banks brought on-line, were approximately 19kW + j20kVAr at Meter 1, -17kW + j19.8kVAr at Meter 2 and -20kW + j 14kVAr at Meter 3. From the microgrid, 38.5kW – j13kVAr was produced by Gen-set A1. The Load Banks were 18.2kW + j0kVAr at LB3 and 35.92kW + j0.78kVAr at LB6. At the time of these measurements, the voltage and frequency was 282.6V on A-phase, 279.2V on B-phase and 279.4V on C-phase and 60.00Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 282.6V on A-phase, 280V on B-phase and 280V on C-phase at Meter 3.

Gen-set A1 was setup in this test to produce more power than Load Bank 3 needed which approximately 17kW of excess power was exported through the static switch to Load Bank 6. Since Load Bank 6 was approximately 35.92kW + j0.78kVAr, the utility had to supply approximately 19kW to satisfy the load. Reactive power had to be imported in from the utility of approximately 19.8kVAr because Gen-set A1 needed approximately 13kVAr and the reactive power absorbed in the electrical lines. Once all data was verified and recorded into the DAS Database, the 10Hp induction motor was started in Zone 3.

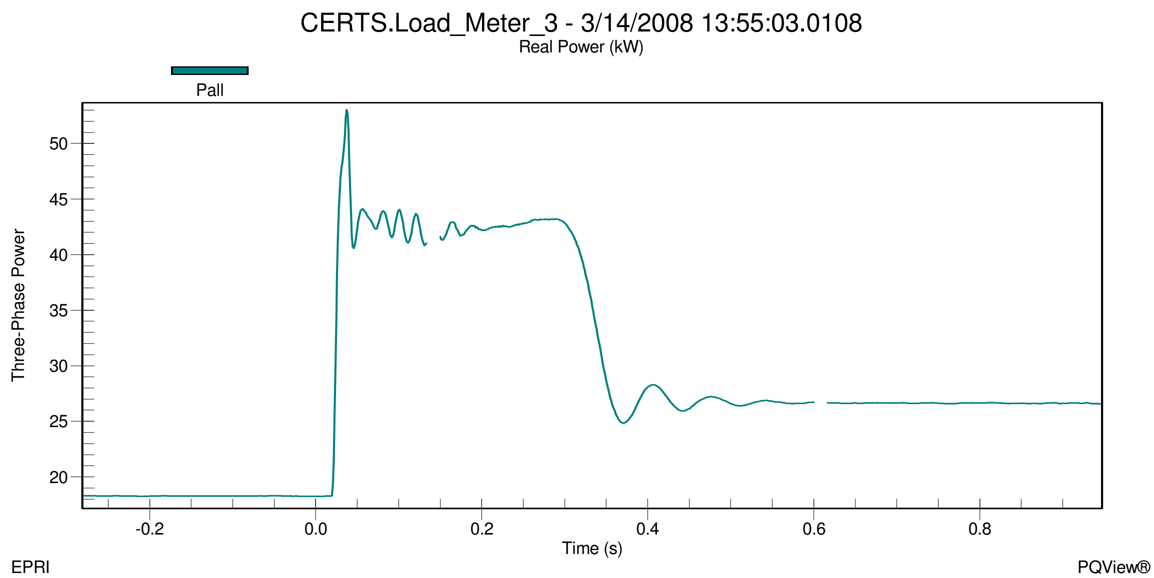

Figure 8a - Load Bank 3 Real Power during Motor Start and Utility Connected for Test 10.2.17

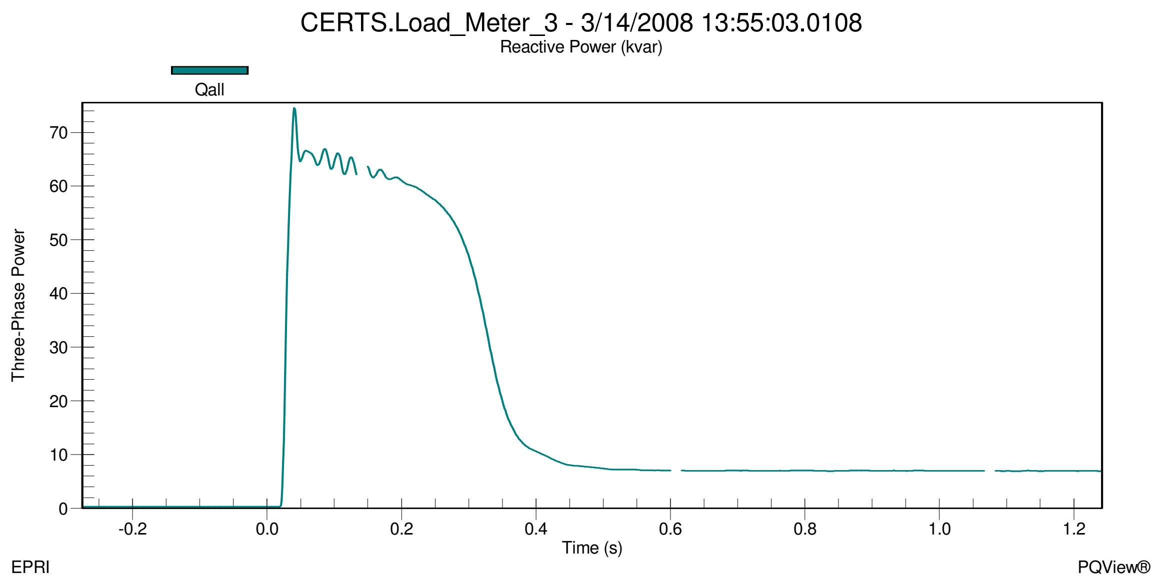

Figure 8b - Load Bank 3 Reactive Power during Motor Start and Utility Connected for Test 10.2.17

In Figures 8a and 8b it can be seen that the load in Zone 3 was approximately 18.2kW + j0kVAr before the start of the induction motor and increased to approximately 53kW + j75kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 42.8kW + j62kVAr during the warm up phase which lasted about 27 cycles (0.45 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 26.7kW + j7kVAr.

The voltage and frequency at the static switch before the motor start was approximately 282.6V on A-phase, 279.2V on B-phase and 279.4V on C-phase shown in Figure 8c and approximately 60.00Hz shown in Figure 8d. When the motor started, the voltage at the static switch during the inrush decreased to approximately 274.4V on A-phase, 270.9V on B-phase and 271.2V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.90Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 281.6V on A-phase, 278.2V on B-phase and 278.8V on C-phase at an approximate frequency of 60.00Hz.

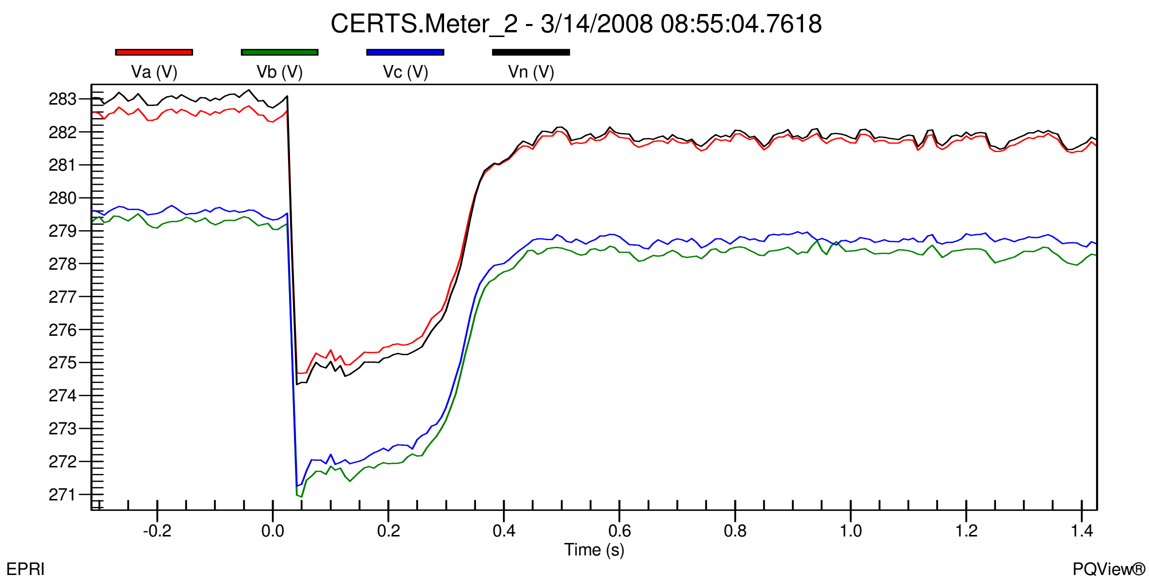

Figure 8c - Static Switch Line-to-Ground Voltages during Motor Start and Utility Connected for Test 10.2.17

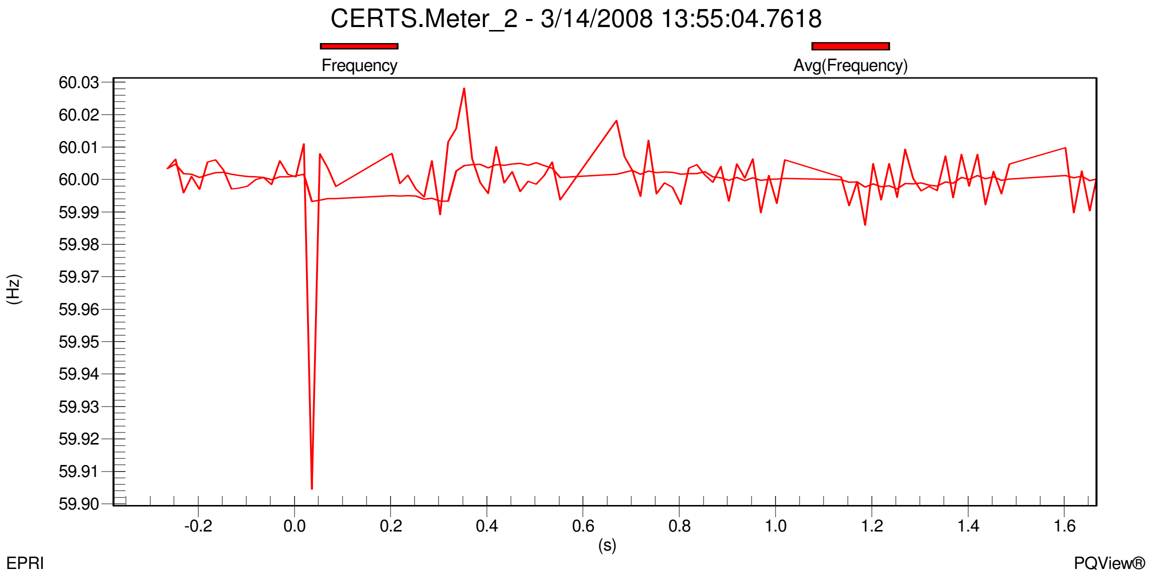

Figure 8d - Static Switch Frequency during Motor Start and Utility Connected for Test 10.2.17

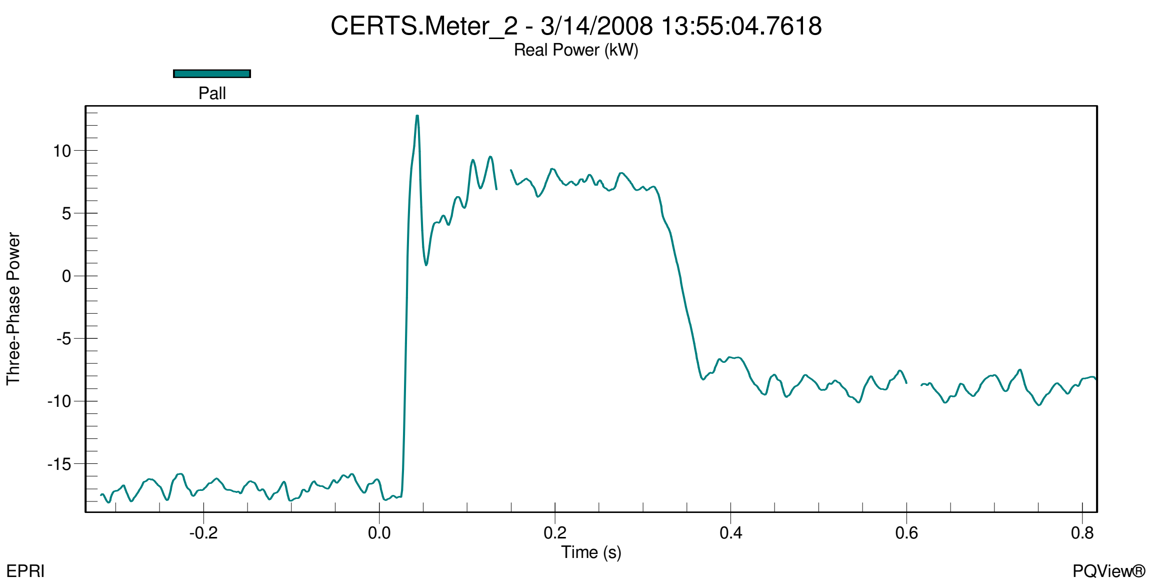

Figure 8e - Static Switch Real Power during Motor Start and Utility Connected for Test 10.2.17

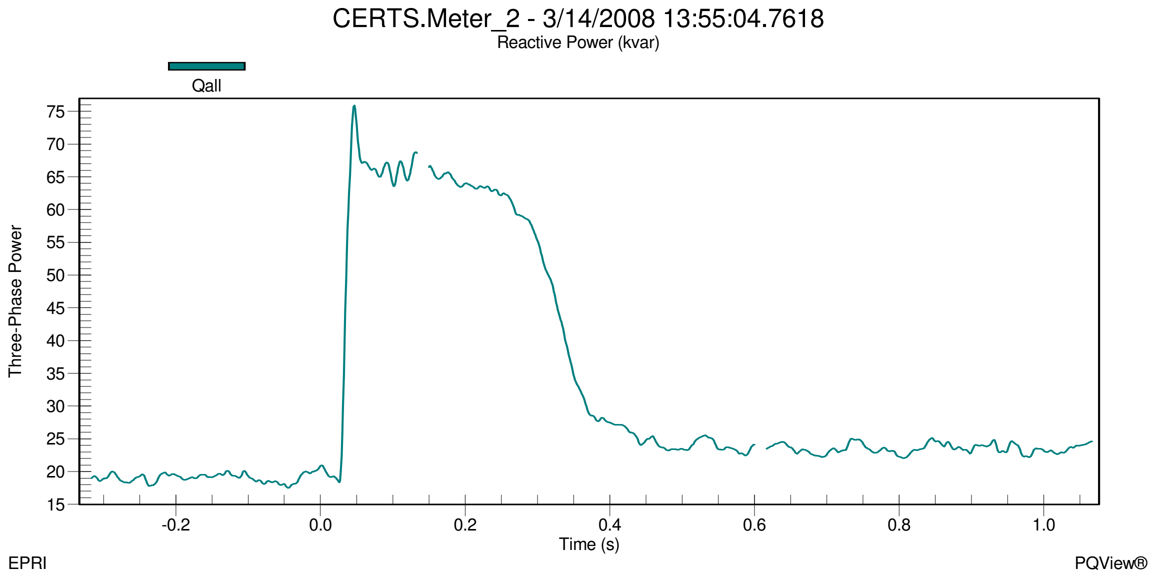

Figure 8f - Static Switch Reactive Power during Motor Start and Utility Connected for Test 10.2.17

Before the motor start Gen-set A1 was producing approximately 38.5kW – j13kVAr. This was enough for the load demands of Zone 3 with real power being exported to Zone 6 of approximately 17kW shown in Figure 8e. The grid was supporting the reactive power of the microgrid with approximately 19.8 shown in Figure 8f. When the motor started the inrush caused the utility to supply approximately 76kVAr and to pick up the load demand in Load Bank 6 along with approximately 13kW of the load in Zone 3. The power being supplied by Gen-set A1 to Load Bank 6 was now supplying the motor inrush which can be seen in Figure 8e as the real power through the static switch becomes positive. Gen-set A1 increased its real and reactive power output level to approximately 44kW + j4.6kVAr. Notice the sign of the VAr output changed from negative to positive for Gen-set A1 in order to support the induction motor load in Zone 3.

When the motor reached steady state, the real and reactive power through the static switch was approximately -9kW + j23kVAr which meant that Gen-set A1 was supplying the power for the induction motor and approximately 9kW of Load Bank 6. Gen-set A1 real power returned to the value before the motor started of approximately 38.5kW and the reactive power increased to approximately -11.4kVAr. Once all the data was verified and recorded into the DAS Database, the motor was shut down and the static switch was directed by the EMS to manually open.

As soon as the static switch opened, Meter 1 recorded real power increased to approximately 36.9kW and reactive power decreased to 1kVAr satisfying the load demand in Load Bank6 which was approximately 36.82kW + j0.787kVAr and not supplying any power beyond the static switch to Load Bank 3. 0kW + j0kVAr was recorded at the static switch, indicating that power was not flowing through the static switch. Load Bank 3 loads was slightly reduced to 23.3kW + j5.9kVAr. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 8g, from approximately 282V on A-phase, 279V on B-phase and 279V on C-phase when connected to the utility grid to 269V on A-phase, 268V on B-phase, and 269V on C-phase at Meter 3 when islanded.

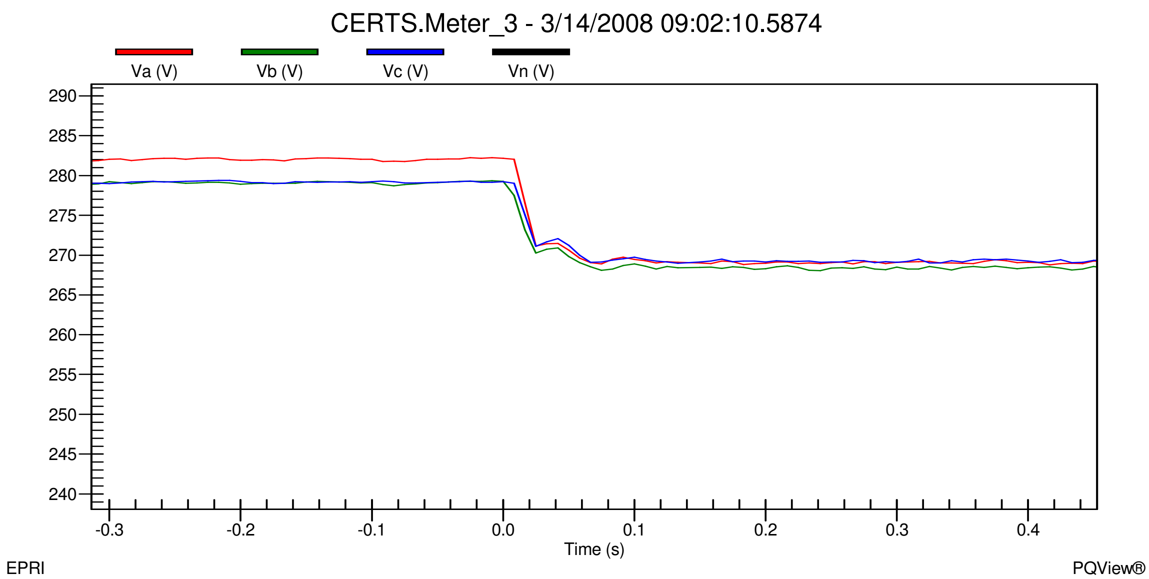

Figure 8g - Meter 3 Line-to-Ground Voltages during Utility Connected to Island mode for Test 10.2.17

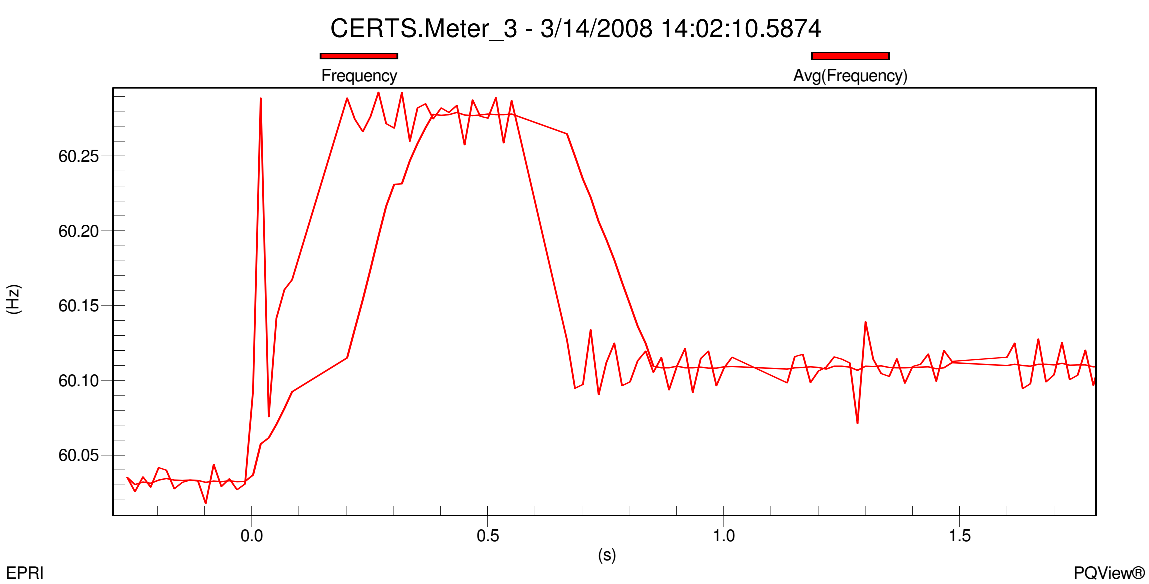

Figure 8h - Meter 3 Frequency during Utility Connected to Island mode for Test 10.2.17

Frequency change in the microgrid, shown in Figure 8h, increased from approximately 60.03Hz when connected to the utility grid to approximately 60.11Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed Gen-set A1 to decrease its output power to satisfy the load demands. Gen-set A1 decreased its output power to approximately 25.5kW and increased its output reactive power to approximately 9kVAr. Meter 3 was approximately -2.3kW – j3.0kVAr indicating that Gen-set A1 was satisfying the load in Load Bank 3 and the power losses in the electrical lines. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the 10Hp induction motor was started in Zone 3.

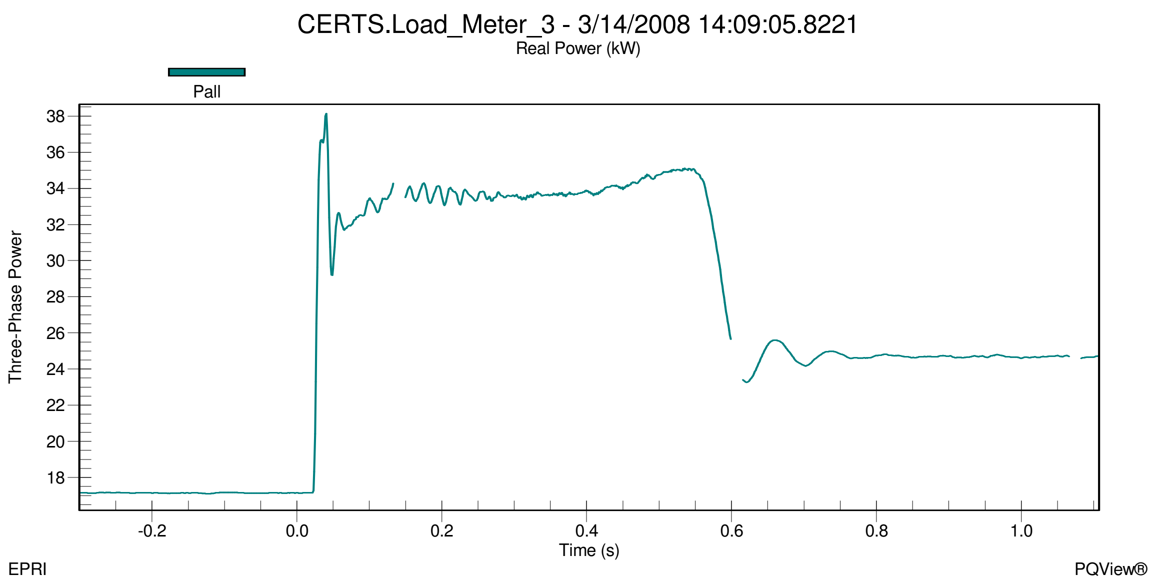

Figure 8i - Load Bank 3 Real Power during Motor Start and Islanded for Test 10.2.17

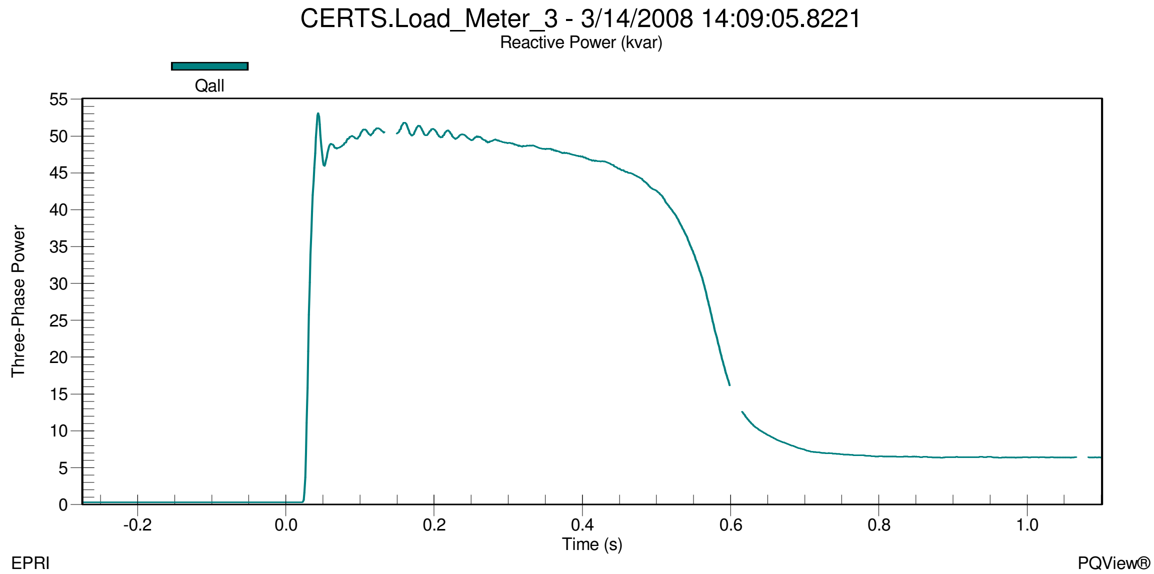

Figure 8j - Load Bank 3 Reactive Power during Motor Start and Islanded for Test 10.2.17

In Figures 8i and 8j it can be seen that the load in Zone 3 was approximately 16.4kW + j0.2kVAr before the start of the induction motor and increased to approximately 38kW + j53kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 33.5kW + j49kVAr during the warm up phase which lasted about 43.8 cycles (0.73 Seconds). When the motor reached steady state the load in Zone 3 was approximately 24.6kW + j6.5kVAr.

The voltage and frequency at Meter 3 before the motor start was approximately 272V on A-phase, 272V on B-phase and 272V on C-phase shown in Figure 8k and approximately 60.18Hz shown in Figure 8l. When the motor started, the voltage at Meter 3 during the inrush decreased to approximately 238.5V on A-phase, 237.5V on B-phase and 238.5V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.75Hz and quickly increased to approximately 60.03Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 269V on A-phase, 268V on B-phase and 269V on C-phase at an approximate frequency of 60.10Hz.

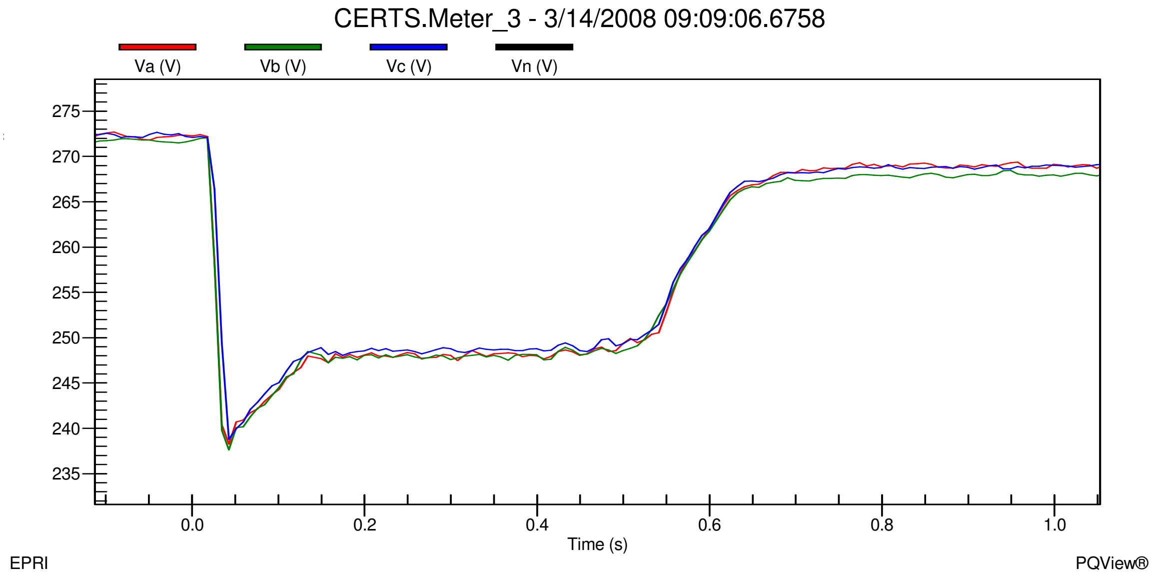

Figure 8k - Meter 3 Line-to-Ground Voltages during Motor Start and Islanded for Test 10.2.17

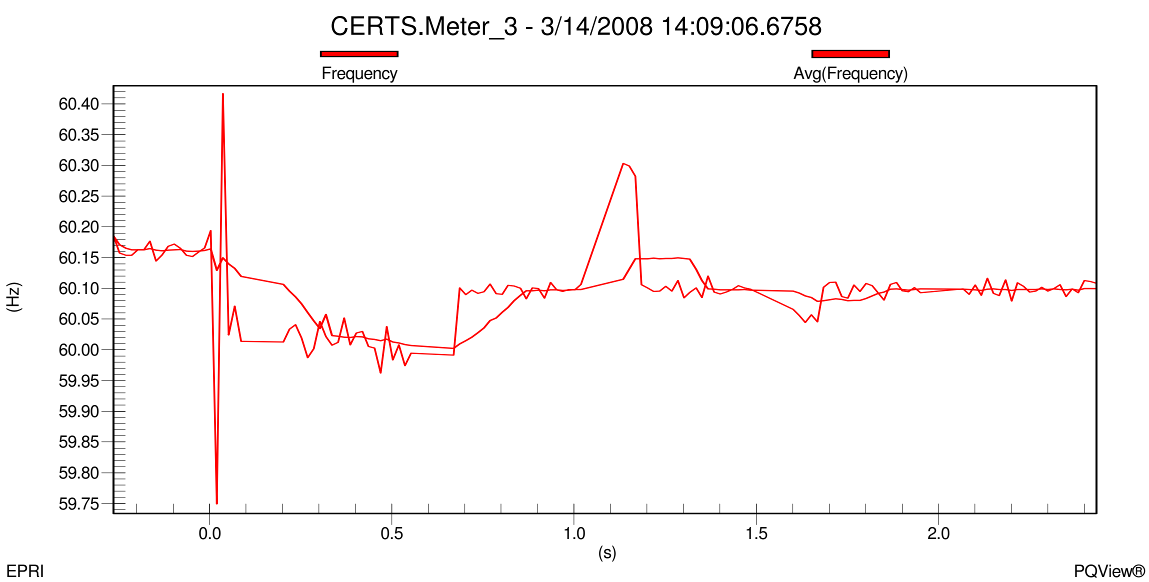

Figure 8l - Meter 3 Frequency during Motor Start and Islanded for Test 10.2.17

Before the motor started, Gen-set A1 was producing approximately 18.9kW + j4kvAr shown in Figures 8m and 8n. The power generated by Gen-set A1 was satisfying the loads in Load Bank 3 and all the electrical losses in the microgrid system. When the motor started the inrush caused the Gen-set to increase its output level to 40kW + j54kVAr. Gen-set A1 decreased its output level when the motor was warming up and eventually dropped to 27kW + j9.8kVAr when the motor reached steady state. Once all the data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually close.

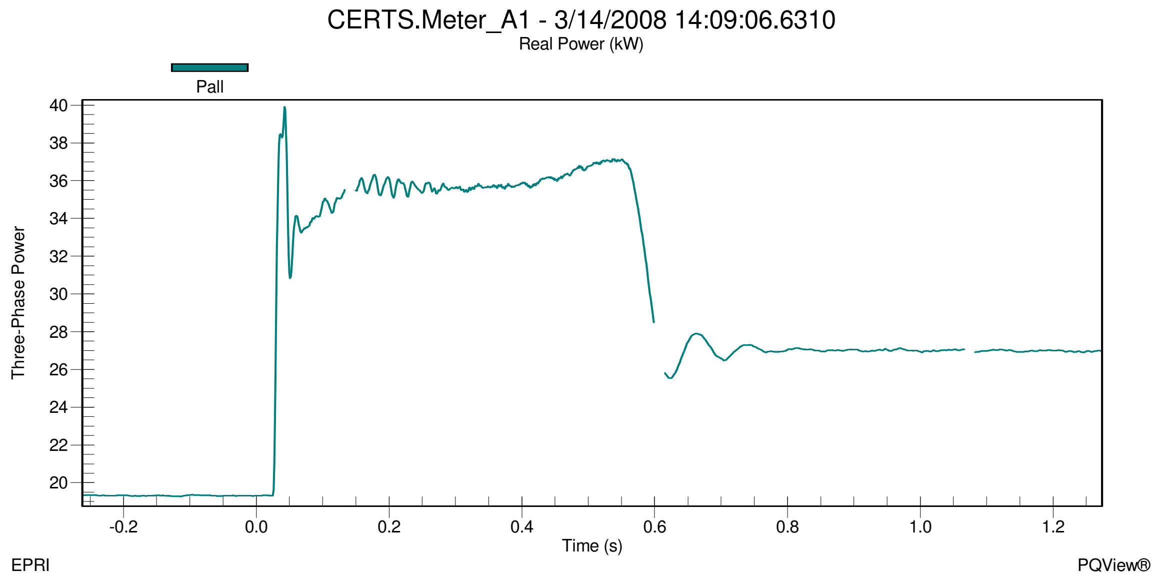

Figure 8m - Gen-set A1 Real Power during Motor Start and Islanded for Test 10.2.17

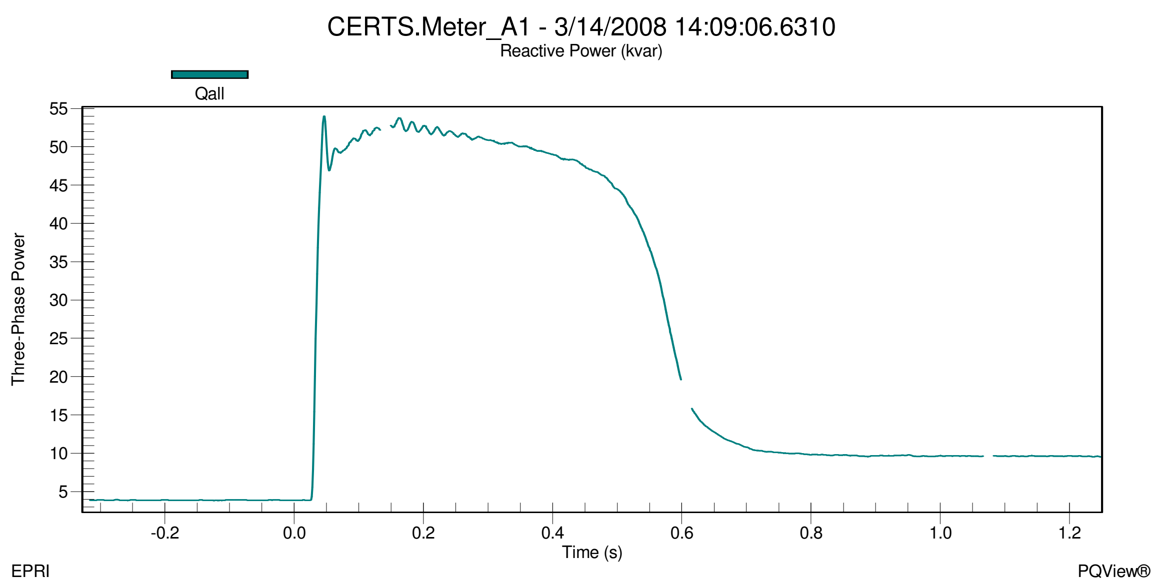

Figure 8n - Gen-set A1 Reactive Power during Motor Start and Islanded for Test 10.2.17

As soon as the static switch closed, Meter 1 recorded real power decreased from approximately 36.8kW to 25kW and reactive power increased from approximately 1kVAr to 23.7kVAr which means that the utility was satisfying a portion of the load demand in Load Bank 6 and all the reactive power in the microgrid. Figures 8o and 8p show the static switch real power decreasing from approximately 0kW to -11kW and reactive power increasing from approximately 0kVAr to 22.2kVAr. At the beginning of the test, the initial power flow through the static switch was -17kW + j19.8kVAr which is not the same recorded at this point in the test because the 10Hp motor load is on in Zone 3. Gen-set A1 has picked up the motor load and is supporting Load Bank6 with approximately 11kW.

Load Bank 3 loads increased slightly to 25kW + j6.4kVAr. This slight increase is a result from a voltage rise in the microgrid, shown in Figure 8q, from approximately 269V on A-phase, 268V on B-phase and 269V on C-phase when islanded to 281.5V on A-phase, 279V on B-phase and 279V on C-phase at Meter 3 when connected to the utility grid.

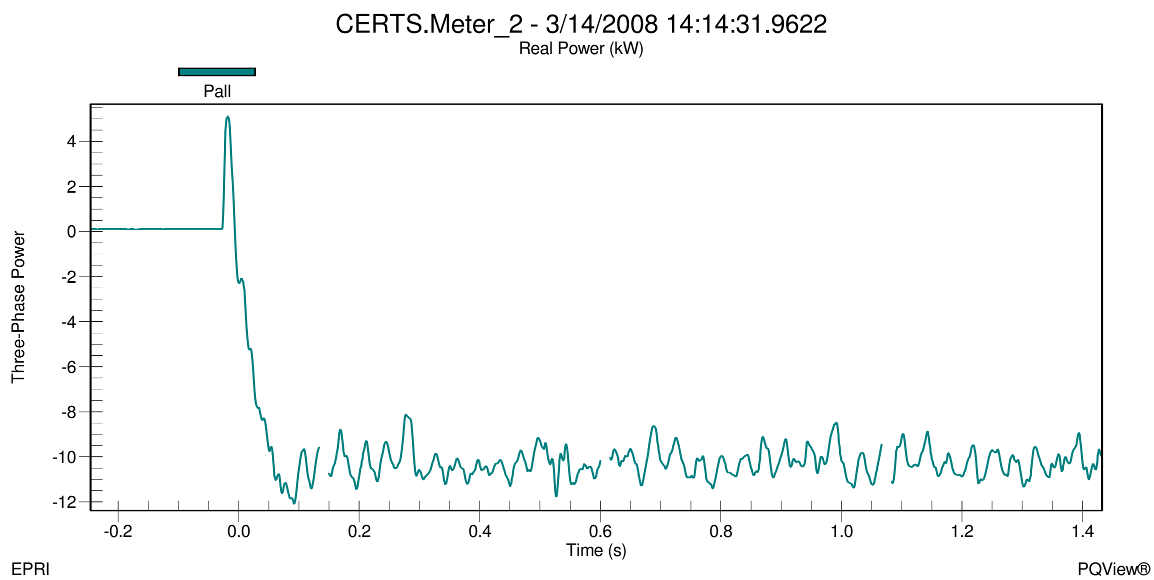

Figure 8o - Static Switch Real Power during Island to Utility Connected mode for Test 10.2.17

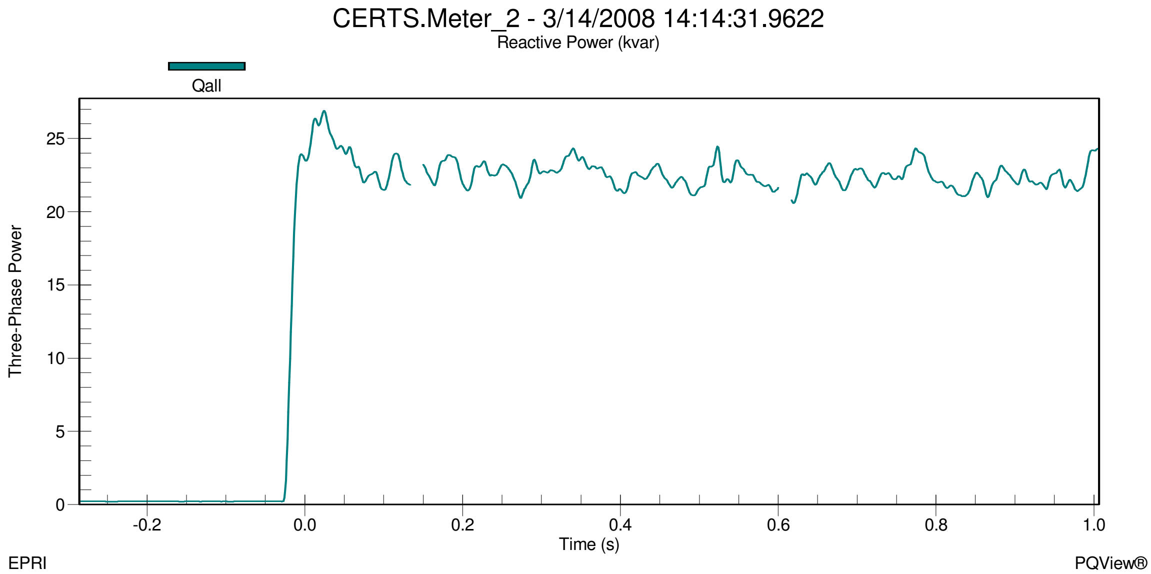

Figure 8p - Static Switch Reactive Power during Island to Utility Connected mode for Test 10.2.17

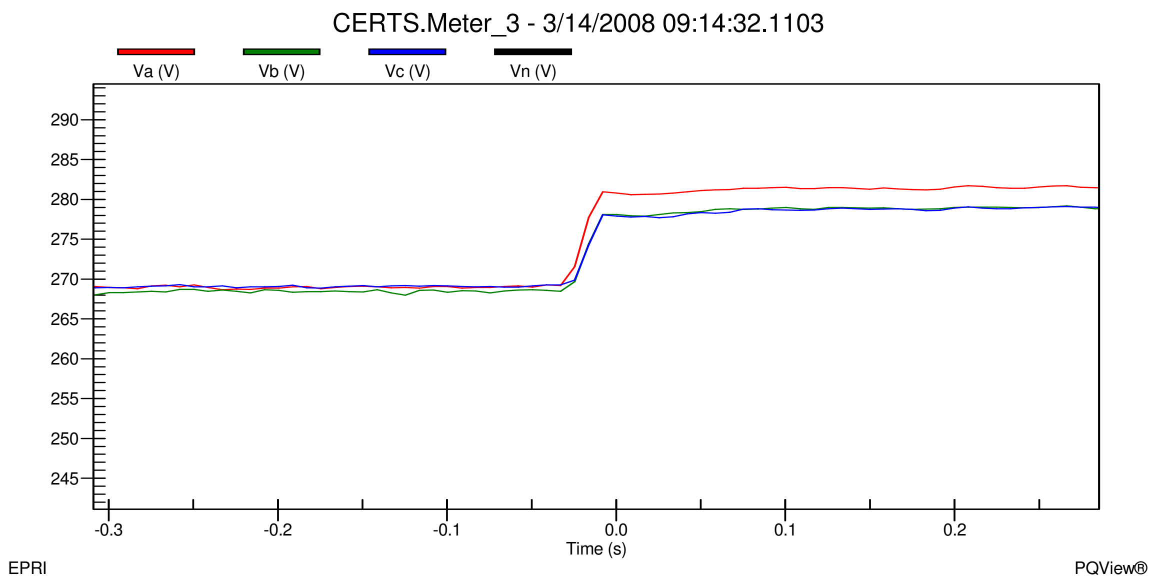

Figure 8q - Meter 3 Line-to-Ground Voltages during Island to Utility Connected mode for Test 10.2.17

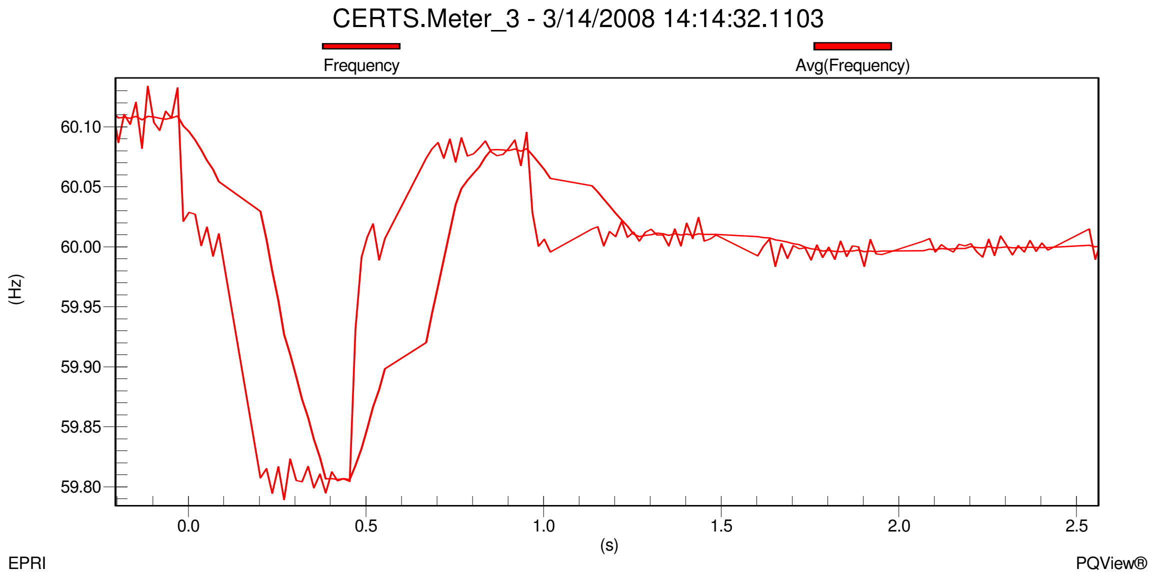

Figure 8r - Meter 3 Frequency during Island to Utility Connected mode for Test 10.2.17

Frequency change in the microgrid, shown in Figure 8r, decreased from approximately 60.11Hz when islanded to approximately 60.00Hz when connected to the utility grid. This change in frequency is due to the frequency no longer being established by Gen-set A1 using the CERTS algorithm but by the utility. Gen-set A1 is in unit power control mode therefore when the static switch closed back into the utility the Gen-set produced real power based on the set-point initialized at the beginning of the test. The output power for Gen-set A1 was relatively close to the value at the beginning of the test with Gen-set A1 producing approximately 38kW – j11.5kVAr. After all the data was verified and recorded into the DAS Database, the motor was turned off and the Gen-sets and Load Banks set-points were changed according to the next test (10.2.18) in Table 1.

For Test 10.2.18 the measured values, after the Gen-sets were warmed up and load banks brought on-line, were approximately 33kW + j22kVAr at Meter 1, -2.5kW + j20kVAr at Meter 2, -6kW + j15kVAr at Meter 3 and 12.5kW + j3kVAr at Meter 4. From the microgrid, 36kW – j12kVAr was produced by Gen-set A1 and 23.5kW – j2kVAr was produced by Gen-set A2. The load banks were 18kW + j0kVAr at LB3, 35.78kW + j0.714kVAr at LB4 and 35.9kW + j0.77kVAr at LB6. These measurements were relatively close to the expected values in Table 1, but not exact due to temperature, phase voltages and electrical losses in conductors. In addition, the 40kW settings for LB4 and LB6 and 20kW setting for LB3 were also below selected set values. At the time of these measurements, the voltage and frequency was 281.8V on A-phase, 279.7V on B-phase and 279.7V on C-phase and 60.02Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 281.9V on A-phase, 279.7V on B-phase and 279.2V on C-phase and 60.00Hz at Meter 3.

The Gen-sets in this test were set up to produce -10kW going through Zone 3 (i.e., Meter 3) which means they produced 10kW more power than Load Banks 3 and 4 needed. Approximately 6kW of excess power was exported out of Zone 3 and 2.5kW of that power went through the static switch to Load Bank 6 and the remaining 3.5kW was due to power losses in the conductors. Since Load Bank 6 was approximately 35.9kW + j0.77kVAr, the utility had to supply approximately 33kW to satisfy the load. Reactive power had to be imported in from the utility of approximately 22kVAr because Gen-sets A1 and A2 needed approximately 14lkVAr between the two and the reactive power of Load Bank 4. Once all the data was verified and recorded into the DAS Database, the 10Hp induction motor was started in Zone 3.

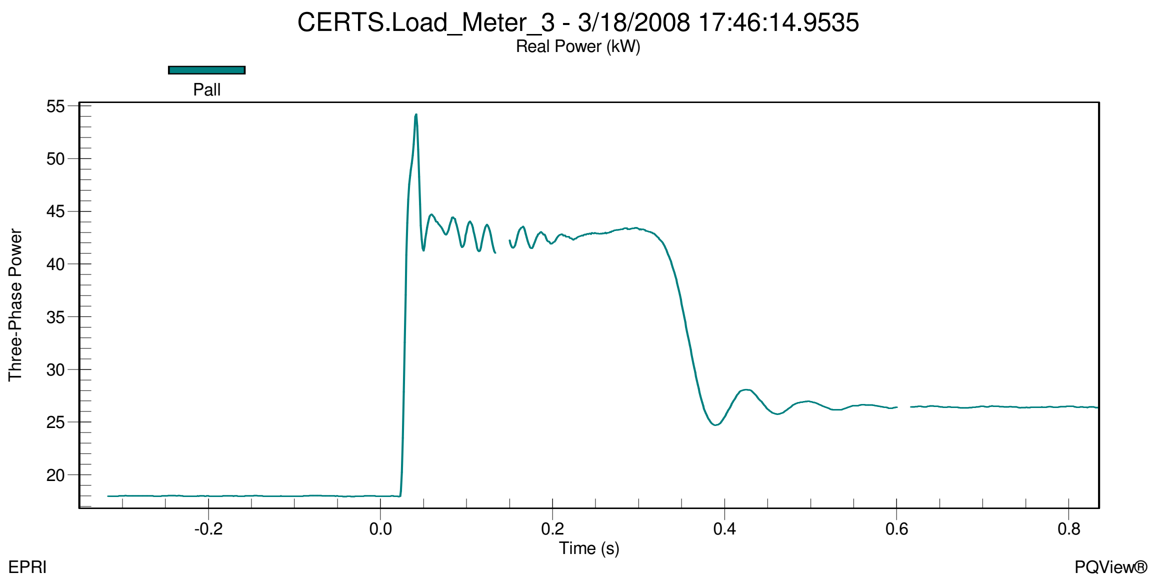

Figure 9a - Load Bank 3 Real Power during Motor Start and Utility Connected for Test 10.2.18

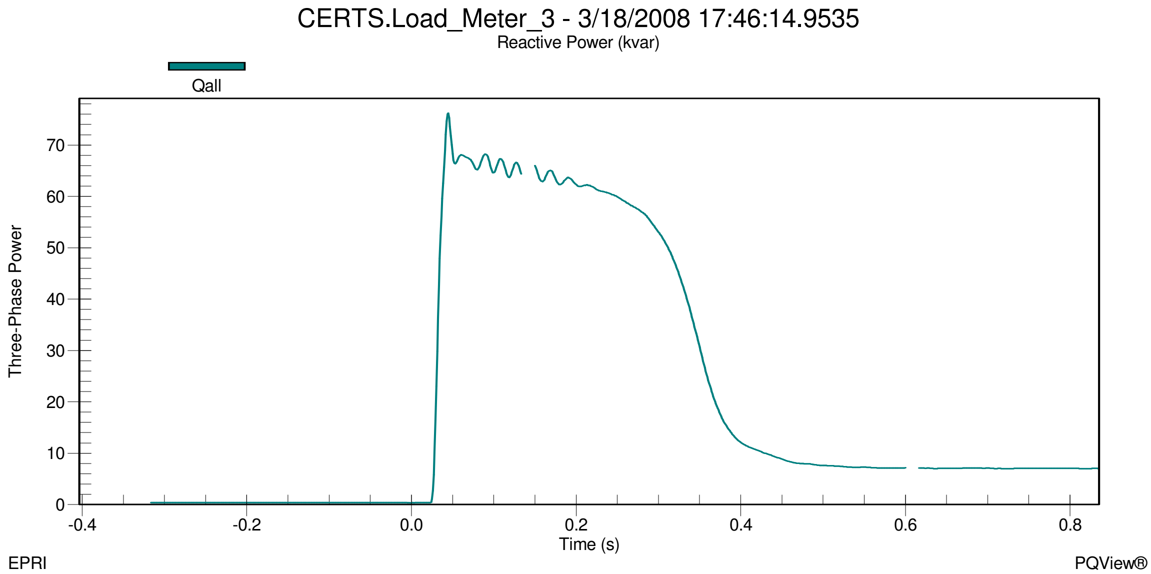

Figure 9b - Load Bank 3 Reactive Power during Motor Start and Utility Connected for Test 10.2.18

In Figures 9a and 9b it can be seen that the load in Zone 3 was approximately 18kW + j0kVAr before the start of the induction motor and increased to approximately 54.2kW + j76kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 42.8kW + j63kVAr during the warm up phase which lasted about 28.2 cycles (0.47 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 26.5kW + j7kVar.

The voltage and frequency at the static switch before the motor start was approximately 281.8V on A-phase, 279.7V on B-phase and 279.7V on C-phase shown in Figure 9c and approximately 60.02Hz shown in Figure 9d. When the motor started, the voltage at the static switch during the inrush decreased to approximately 274.5V on A-phase, 271.5V on B-phase and 271.5V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.94Hz and quickly increased to approximately 60.02Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 280.8V on A-phase, 278.8V on B-phase and 278.8V on C-phase at an approximate frequency 60.02Hz.

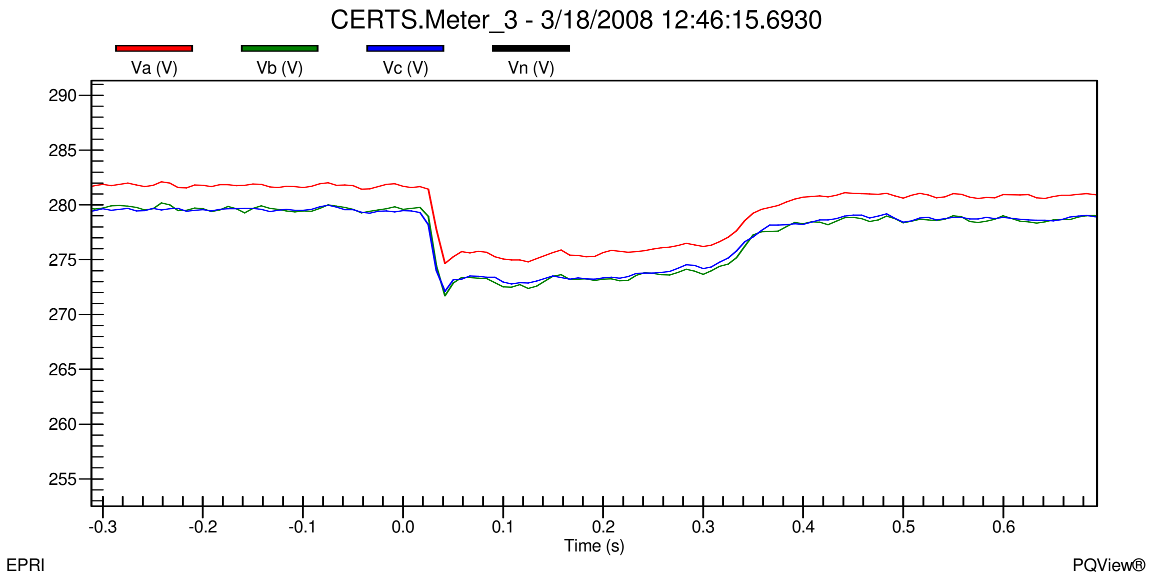

Figure 9c - Static Switch Line-to-Ground Voltage during Motor Start and Utility Connected for Test 10.2.18

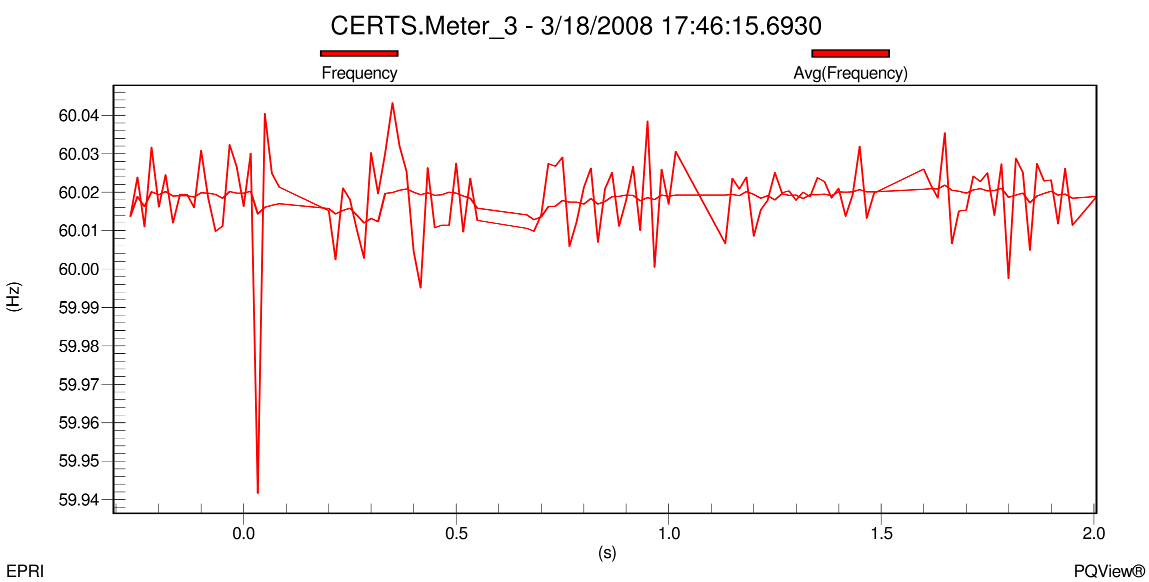

Figure 9d - Static Switch Frequency during Motor Start and Utility Connected for Test 10.2.18

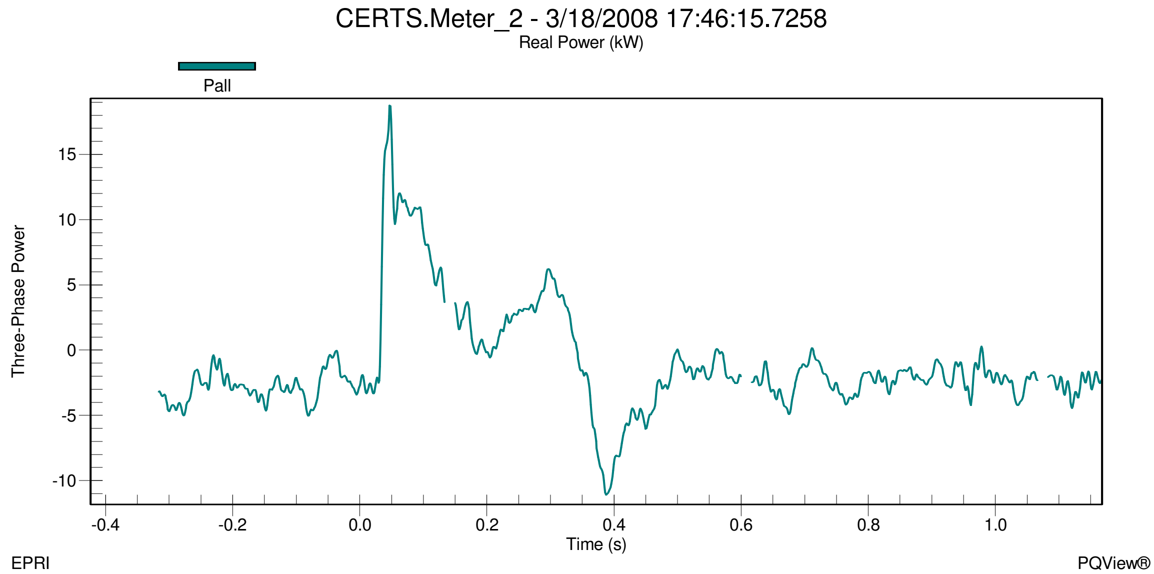

Figure 9e - Static Switch Real Power during Motor Start and Utility Connected for Test 10.2.18

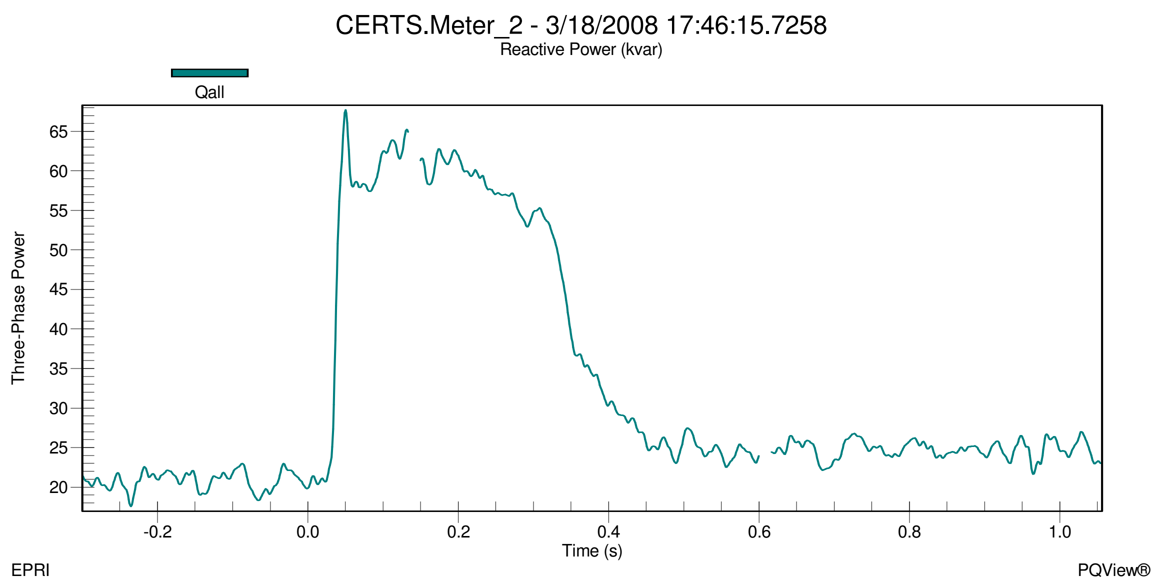

Figure 9f - Static Switch Reactive Power during Motor Start and Utility Connected for Test 10.2.18

Before the motor started Gen-sets A1 and A2 were producing approximately 36kW – j12kVAr and 23.5kW – j2kVAr, respectively. This was enough power for the load demands of Load Banks 3 and 4 with real power being exported to Zone 6 of approximately 2.5kW shown in Figure 9e. The grid was supporting the reactive power of the microgrid with approximately 20kVAr shown in Figure 9f. When the motor started the inrush caused the utility to supply approximately 68kVAr and to pick up the load demand of Load Bank 6 and approximately 18.8kW of the microgrid loads. The power that was being supplied by Gen-set A1 to Load Bank 6 was now supplying the motor inrush which can be seen in Figure 9e as the real power through the static switch becomes positive. Gen-sets A1 and A2 increased their real and reactive power output levels to approximately 59kW – j0.6kVAr and 31.8kW + j18kVAr, respectively. Notice the signs of the VAr output changed from negative to positive for both Gen-sets in order to support the induction motor load in Zone 3.

When the motor reached steady state, the real and reactive power through the static switch was approximately -2.5kW + j24kVAr which meant that Gen-sets A1 and A2 were supplying the power for the induction motor and approximately 2.5kW of Load Bank 6. The real power in Gen-set A1 increased from its initial value at the beginning of the test to approximately 44kW and the real power for Gen-set A2 returned to the value before the motor started which was approximately 23.5kW. Reactive power in Gen-set A1 and A2 increased from its initial value at the beginning of the test to approximately -9kVAr and -0.5kVAr, respectively. Once all the data was verified and recorded into the DAS Database, the motor was shut down and the static switch was directed by the EMS to manually open.

As soon as the static switch opened, Meter 1 recorded real power increased to approximately 37kW and reactive power decreased to 1.2kVAr satisfying the load demand in Load Bank 6 which was approximately 36.78kW + j0.785kVAr and not supplying any power beyond the static switch to Load Banks 3 and 4. 0kW + j0kVAr was recorded at the static switch, indicating that power was not flowing through the static switch. Load Banks 3 and 4 loads reduced slightly to 17.4kW + j0.3285kVAr and 34.45kW + j0.686kVAr, respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 9g, from approximately 281.9V on A-phase, 279.8V on B-phase and 279.8V on C-phase when connected to the utility grid to 275V on A-phase, 275V on B-phase and 275V on C-phase at Meter 3 when islanded.

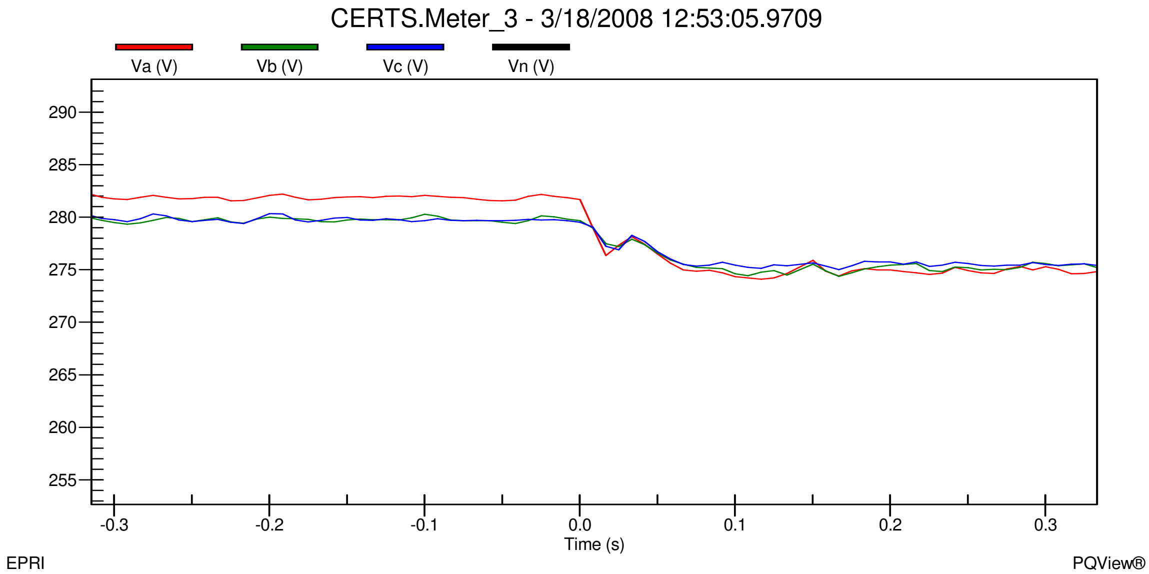

Figure 9g - Meter 3 Line-to-Ground Voltages during Utility Connected to Island mode for Test 10.2.18

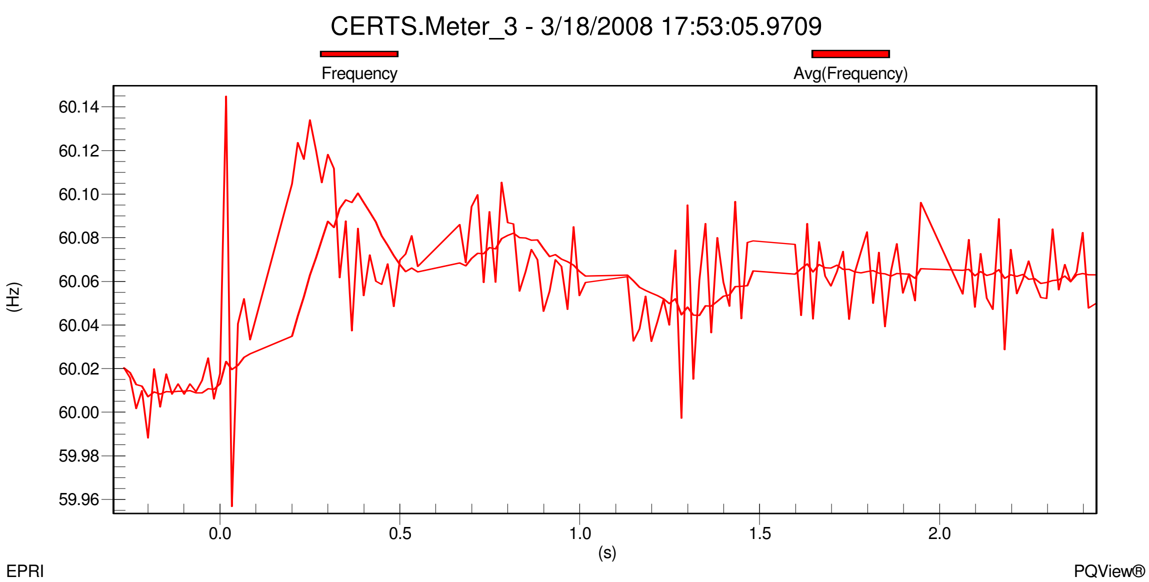

Figure 9h - Meter 3 Frequency during Utility Connected to Island mode for Test 10.2.18

Frequency change in the microgrid, shown in Figure 9h, increased from approximately 60.01Hz when connected to the utility grid to approximately 60.06Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed Gen-set A2 to decrease its output real power to approximately 17.5kW. Gen-set A1 remained relatively at the same level which was approximately 37kW. Reactive power in Gen-sets A1 and A2 increased to approximately -3kVAr and 8kVAr, respectively. Meter 3 was approximately -2.03kW -j2.05kAr indicating that the Gen-sets were satisfying the loads in the microgrid and the power losses in the electrical lines. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the 10Hp induction motor was started in Zone 3.

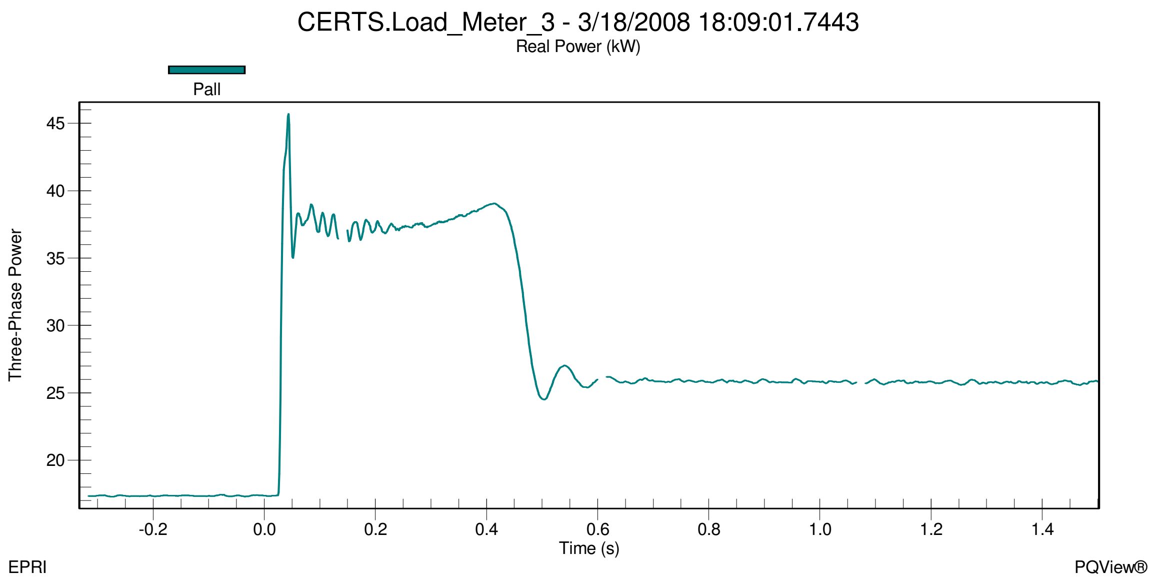

Figure 9i - Load Bank 3 Real Power during Motor Start and Islanded for Test 10.2.18

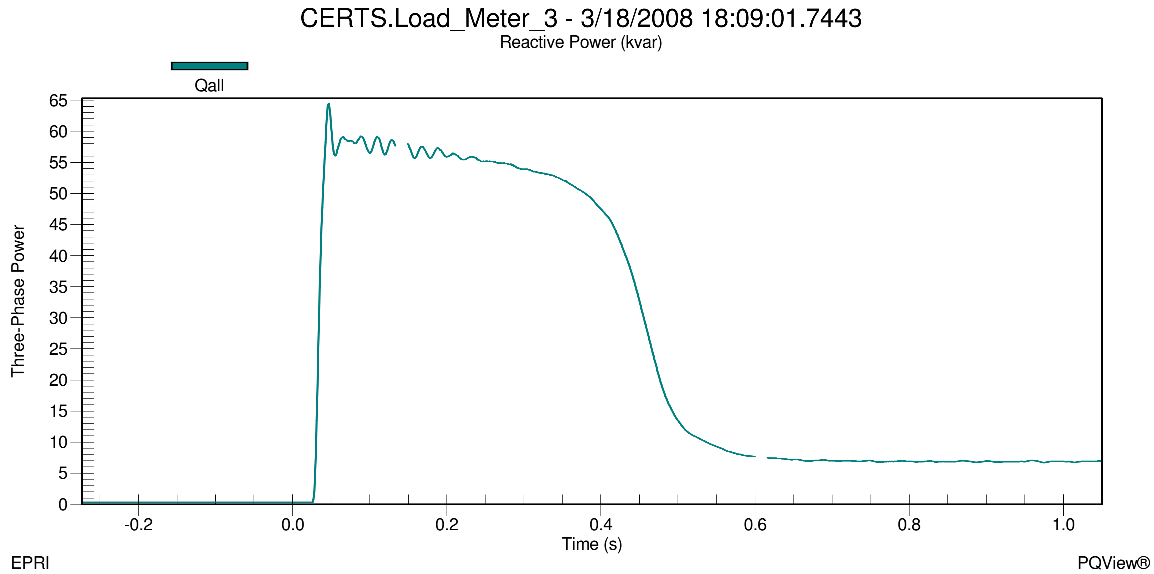

Figure 9j - Load Bank 3 Reactive Power during Motor Start and Islanded for Test 10.2.18

In Figures 9i and 9j it can be seen that the load in Zone 3 was approximately 17.5kW + j0kVAr before the start of the induction motor and increased to approximately 46kW + j65kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 37.8kW + j55kVAr during the warm up phase which lasted about 37.8 cycles (0.63 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 25.8kW + j7kVAr.

The voltage and frequency at Meter 3 before the motor start was approximately 275V on A-phase, 275V on B-phase and 275V on C-phase shown in Figure 9k and approximately 60.07Hz shown in Figure 9l. When the motor started, the voltage at Meter 3 during the inrush decreased to approximately 254.5V on A-phase, 255.9V on B-phase and 255.9V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.97Hz and quickly increased to approximately 60.03Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 273V on A-phase, 273V on B-phase and 273V on C-phase at an approximate frequency of 60.06Hz.

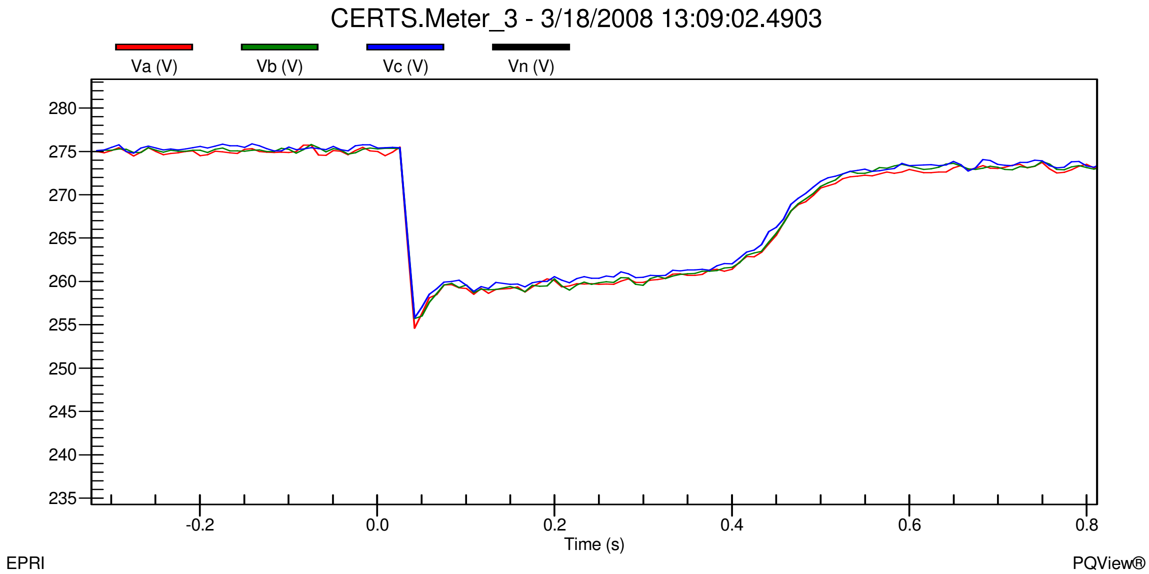

Figure 9k - Meter 3 Line-to-Ground Voltages during Motor Start and Islanded for Test 10.2.18

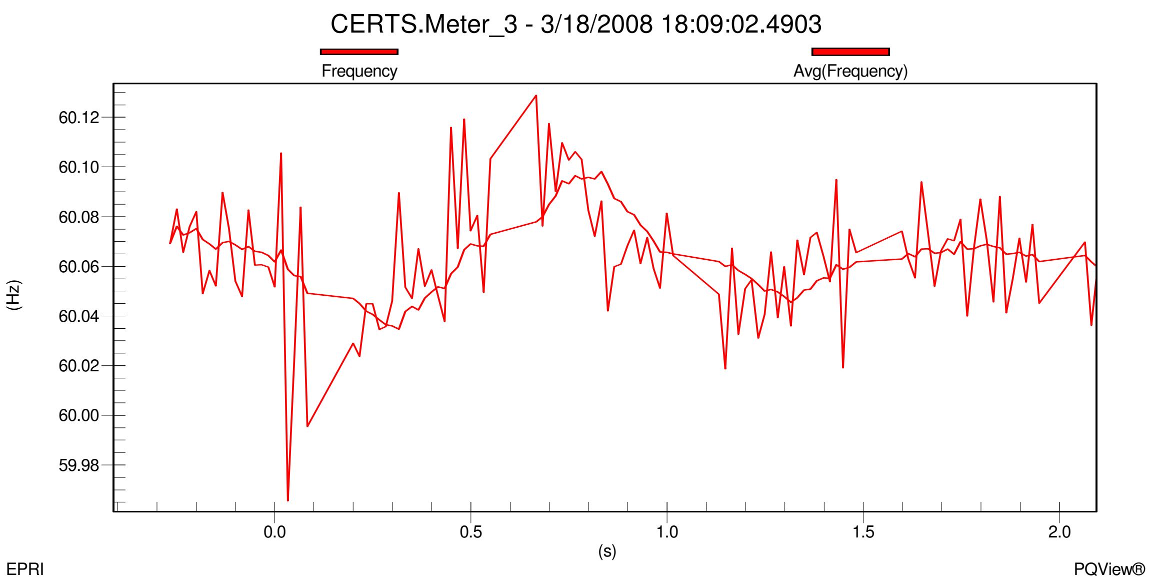

Figure 9l - Meter 3 Frequency during Motor Start and Islanded for Test 10.2.18

Before the motor started Gen-sets A1 and A2 were producing approximately 37kW – j3kVAr and 17.5kW + j8kVAr, respectively shown in Figures 9m – 9p. The power generated by both Gen-sets was satisfying the loads in Load Banks 3 and 4 and all the electrical losses in the microgrid system. When the motor started the inrush caused the Gen-sets to increase their output power levels to 47.5kW + j30kVAr for Gen-set A1 and 30kW + j37kVAr for Gen-set A2. The increase in real and reactive power due to the motor start inrush was shared by both Gen-sets and Gen-set A2 picked up most of the real power. Gen-set A1 increased its output real power during the warm up phase to approximately 57kW and decreased its reactive power. Gen-set A2 decreased real and reactive power output during the warm up phase. The Gen-sets eventually dropped their output levels to 45.4kW – j0.2kVAr for Gen-set A1 and 16.5kW + 11.1kVAr for Gen-set A2 when the motor reached steady state. Once all the data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually close.

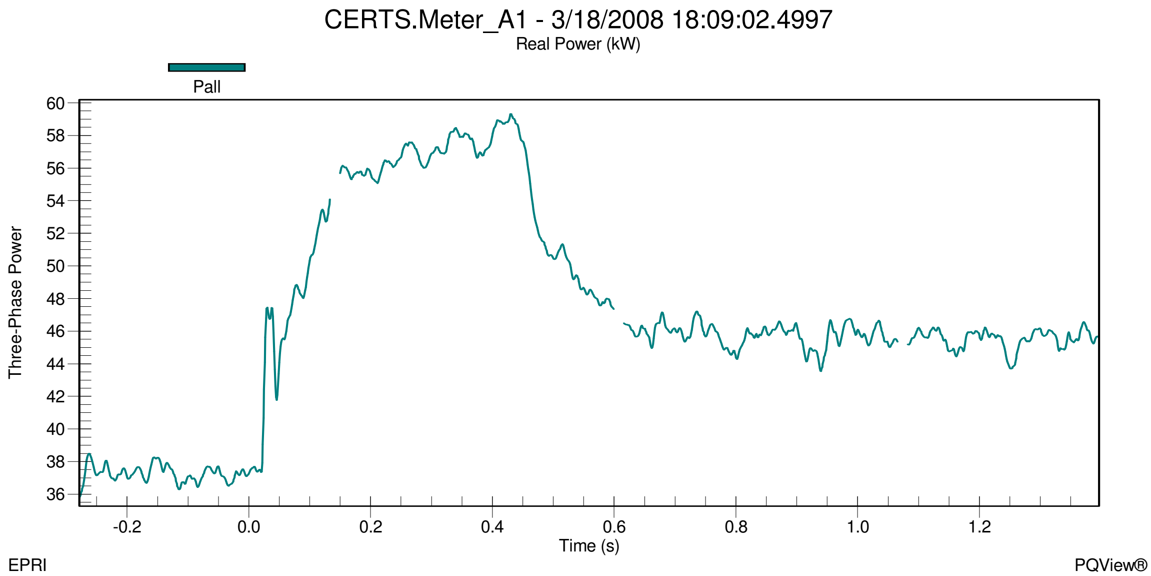

Figure 9m - Gen-set A1 Real Power during Motor Start and Islanded for Test 10.2.18

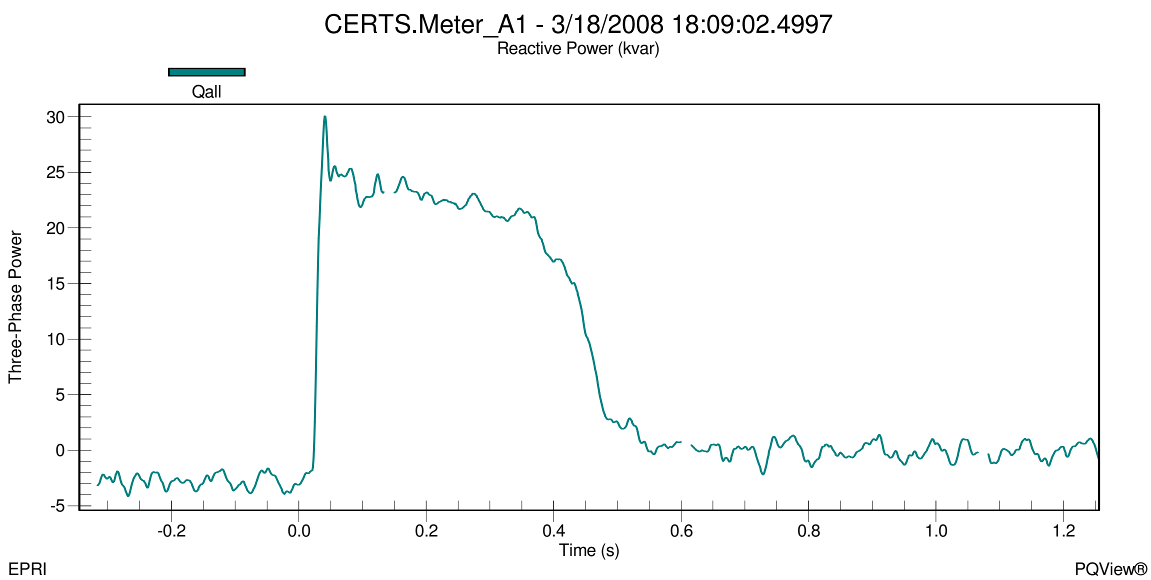

Figure 9n - Gen-set A1 Reactive Power during Motor Start and Islanded for Test 10.2.18

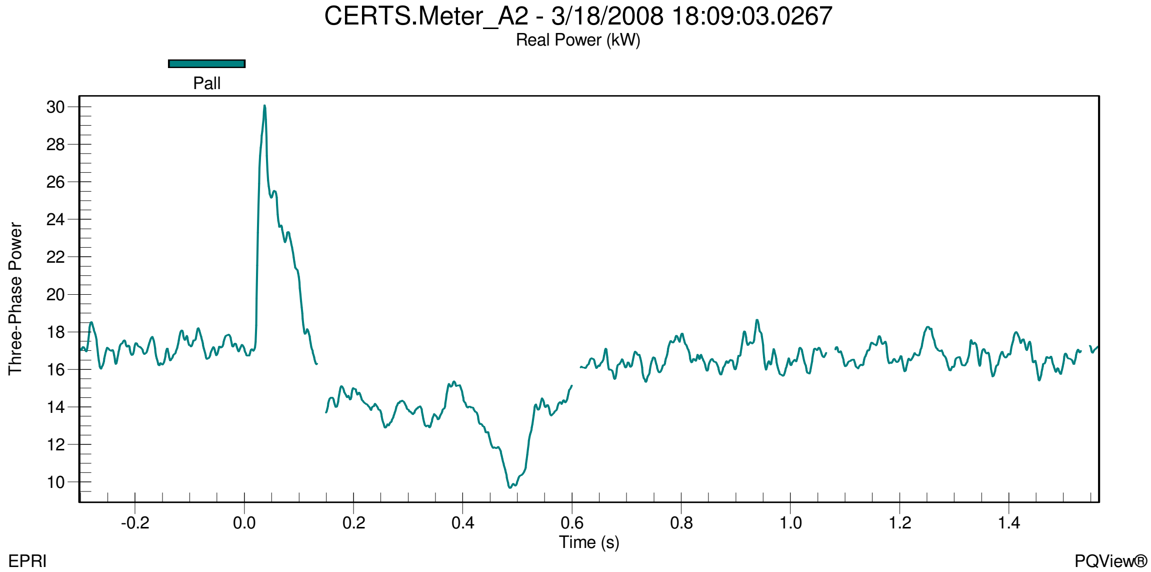

Figure 9o - Gen-set A2 Real Power during Motor Start and Islanded for Test 10.2.18

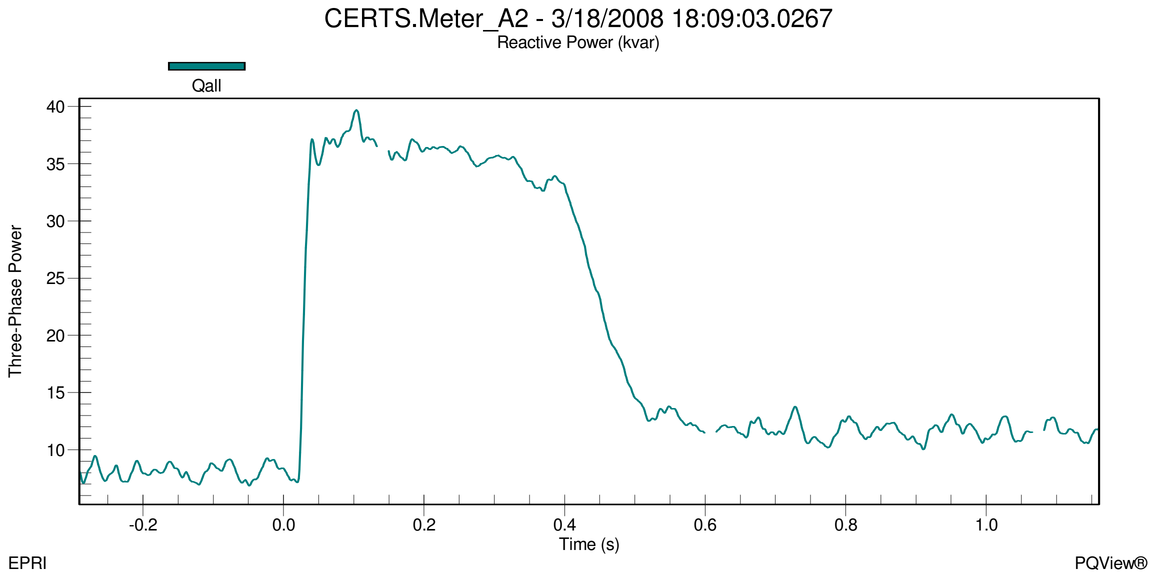

Figure 9p - Gen-set A2 Reactive Power during Motor Start and Islanded for Test 10.2.18

As soon as the static switch closed, Meter 1 recorded real power decreased from approximately 37kW to 30kW and reactive power increased from approximately 1.5kVAr to 29kVAr which means that the utility was satisfying a portion of the load demand in Load Bank 6 and all the reactive power in the microgrid. Figures 9q and 9r show the static switch real power decreasing from approximately 0kW to -5kW and reactive power increasing from approximately 0kVAr to 27.2kVAr. At the beginning of the test, the initial power flow through the static switch was -2.5kW + j20kVAr which is not the same recorded at this point in the test because the 10 Hp motor load is on in Zone 3. The Gen-sets have picked up the motor load and supporting Load Bank 6 with approximately 5kW.

Load Banks 3 and 4 loads increased slightly to 25.1kW + j6.49kVAr and 35.8kW + j0.714kVAr, respectively. This slight load increase is a result from a voltage rise in the microgrid, shown in Figure 9s, from approximately 273.2V on A-phase, 273.2V on B-phase and 273.2V on C-phase when islanded to 282V on A-phase, 279.5V on B-phase and 279.5V on C-phase at Meter 3 when connected to the utility grid.

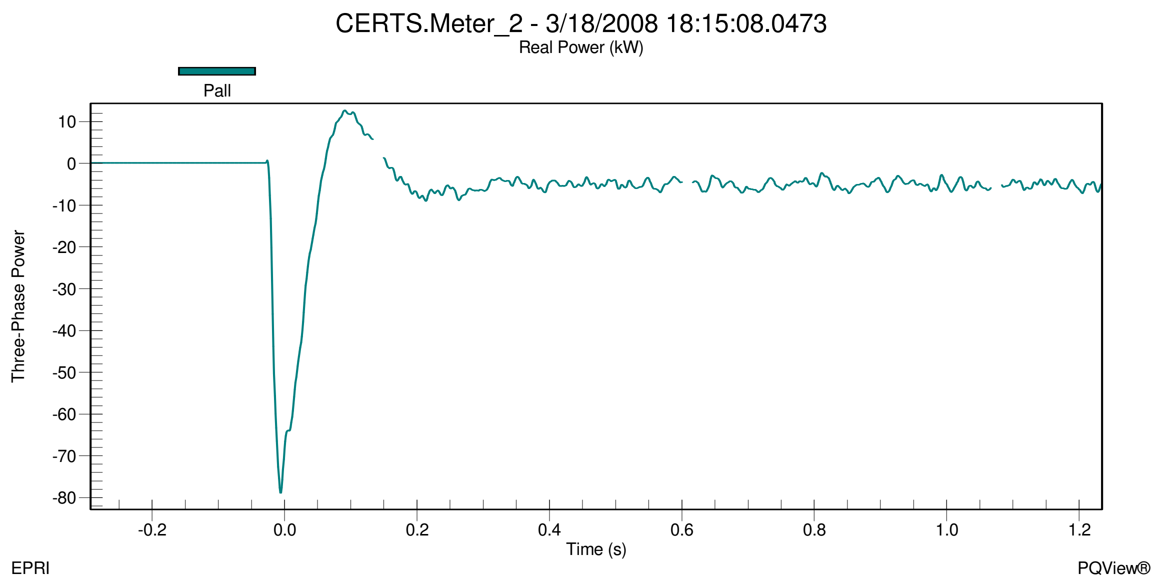

Figure 9q - Static Switch Real Power during Island to Utility Connected mode for Test 10.2.18

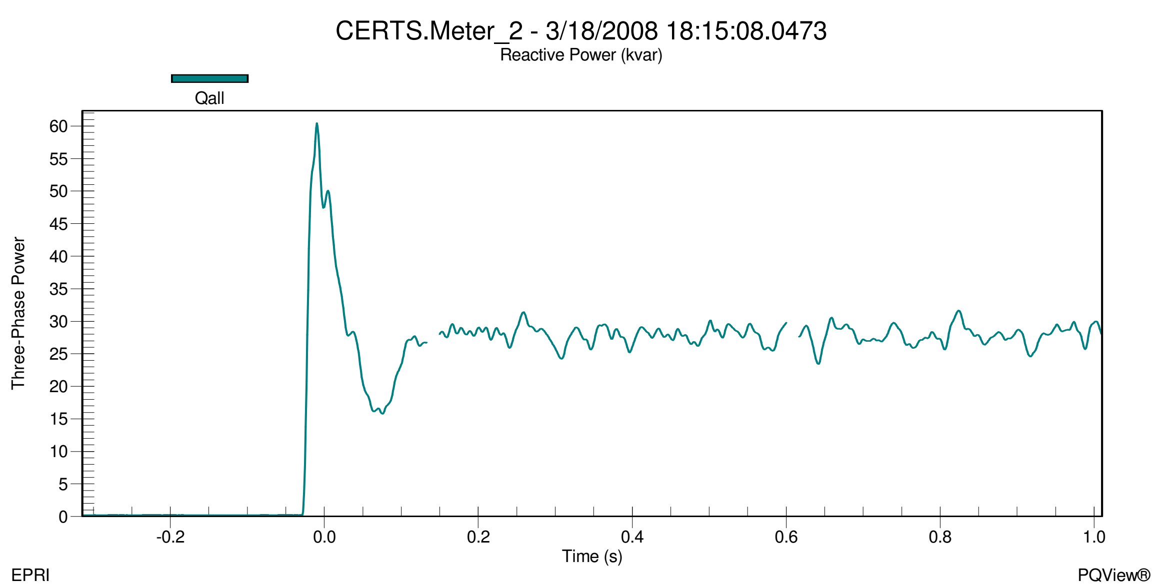

Figure 9r - Static Switch Reactive Power during Island to Utility Connected mode for Test 10.2.18

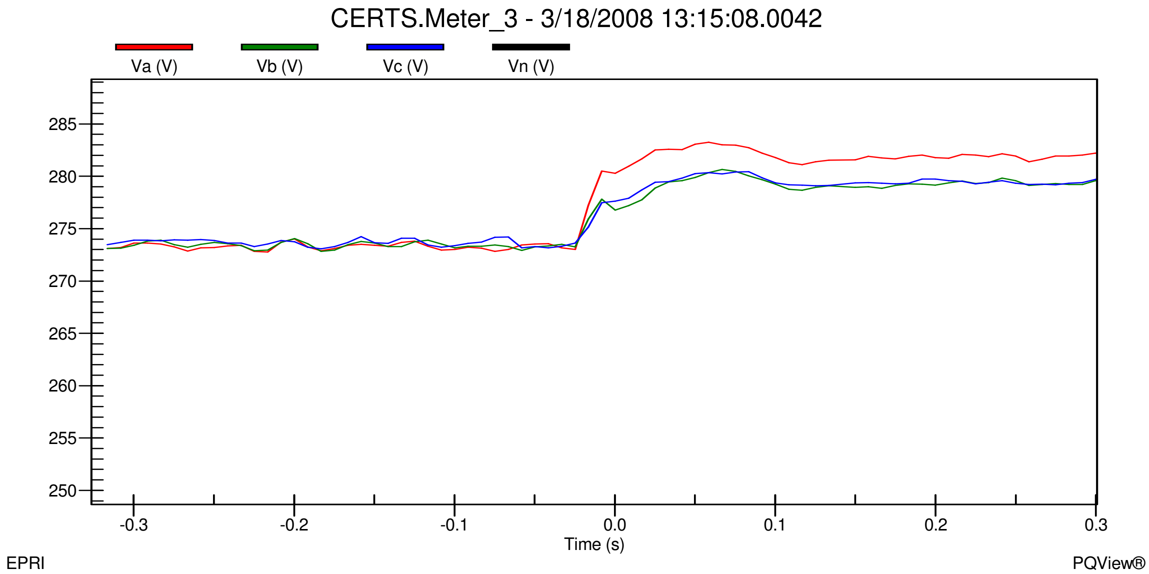

Figure 9s - Meter 3 Line-to-Ground Voltages during Island to Utility Connected mode for Test 10.2.18

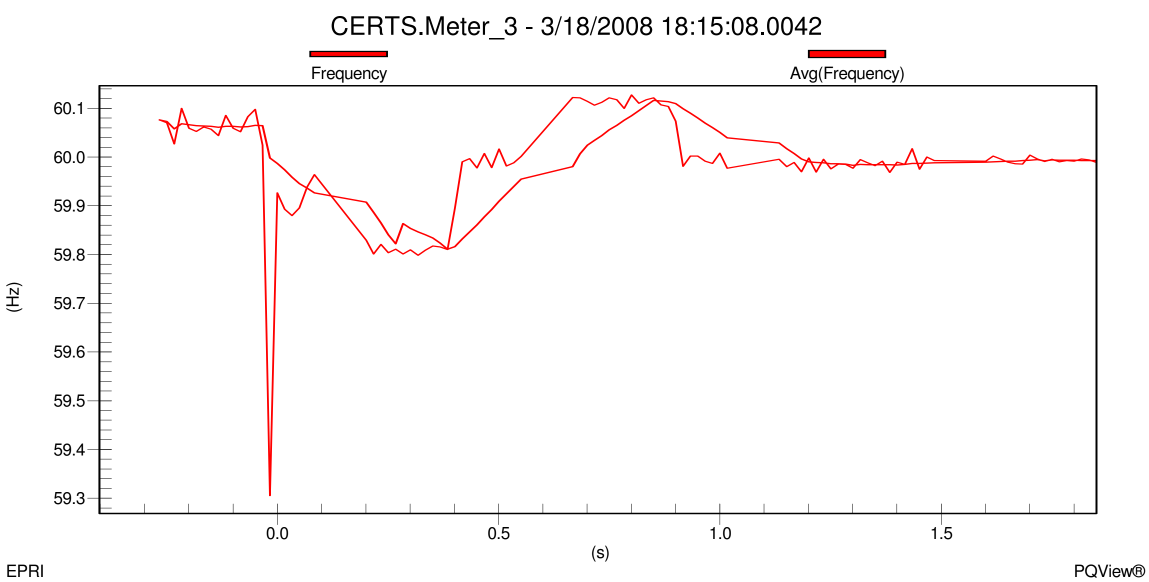

Figure 9t - Meter 3 Frequency during Island to Utility Connected mode for Test 10.2.18

Frequency change in the microgrid, shown in Figure 9t, decreased from approximately 60.06Hz when islanded to approximately 59.99Hz when connected to the utility grid. This change in frequency is due to the frequency no longer being established by the Gen-sets using the CERTS algorithm but by the utility. Gen-sets A1 and A2 are in zone power control mode therefore when the static switch closed back into the utility the Gen-sets produced real power based on set-points for the power flow through Zones 3 and 4 initialized at the beginning of the test. The real power in both Gen-sets increased from their initial values at the beginning of the test to approximately 42kW for Gen-set

A1 and 26kW for Gen-set A2. This increase is because the Gen-sets have picked up the real power of the induction motor in Zone 3. Reactive powers for both Gen-sets were relatively close to the values at the beginning of the test with approximately -12.5kVAr for Gen-set A1 and -3kVAr for Gen-set A2. After all the data was verified and recorded into the DAS Database, the motor was turned off and the Gen-sets and Load Banks set-points were changed according to the next test (10.2.20) in Table 1.

For Test 10.2.20 the measured values, after Gen-set A1 was warmed up and load banks brought on-line, were approximately 22kW + j19kVAr at Meter 1, -15kW + j18kVAr at Meter 2 and -17kW + j8kVAr at Meter 3. From the microgrid, 35.8kW – j12kVAr was produced by Gen-set A1. The load banks were 18kW + j0kVAr at LB3 and 35.8kW + j0.775kVAr at LB6. These measurements were relatively close to the expected values in Table 1, but not exact due to temperature, phase voltages and electrical losses in conductors. In addition, the 40kW setting for LB6 and 20kW setting for LB3 were also below selected set values. At the time of these measurements, the voltage and frequency was 282.2V on A-phase, 278.8V on B-phase and 278.8V on C-phase and 60.00Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 282.5V on A-phase, 279.5V on B-phase and 279.5V on C-phase and 60.00Hz at Meter 3.

Gen-set A1 in this test was set up to produce -20kW going through Zone 3 (i.e., Meter 3) which means it produced 20kW more power than Load Bank 3 needed. Approximately 17kW of excess power was exported out of Zone 3 and 15kW of that power went through the static switch to Load Bank 6 and the remaining 2kW was due to power losses in the conductors. Since Load Bank 6 was approximately 35.8kW + j0.775kVAr, the utility had to supply approximately 22kW to satisfy the load. Reactive power had to be imported in from the utility of approximately 19kVAr because Gen-set A1 needed approximately 12kVAr and losses in the conductors.

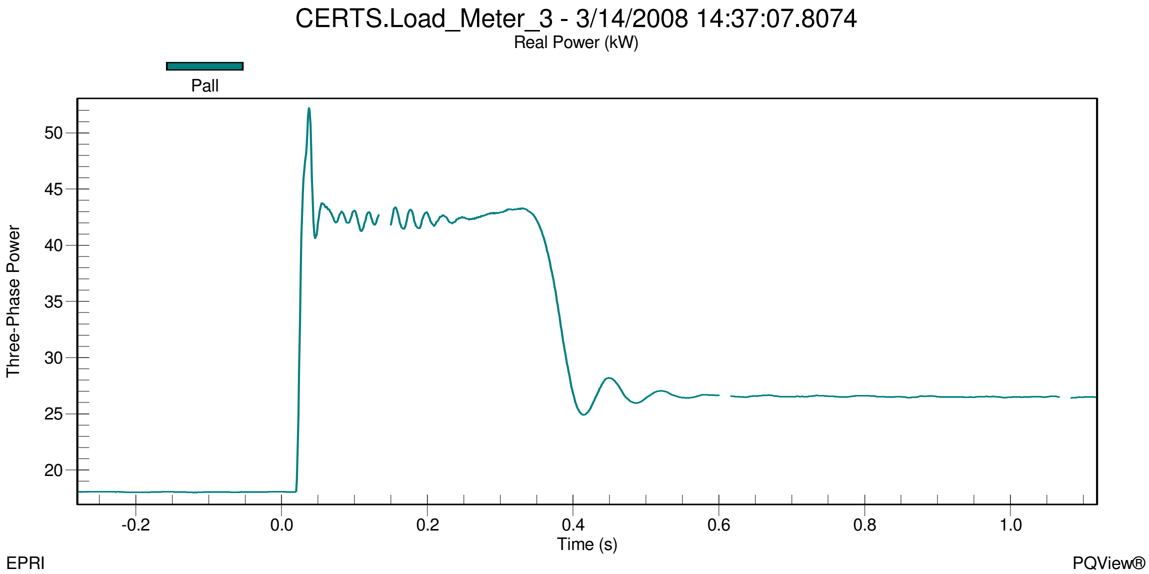

Figure 10a - Load Bank 3 Real Power during Motor Start and Utility Connected for Test 10.2.20

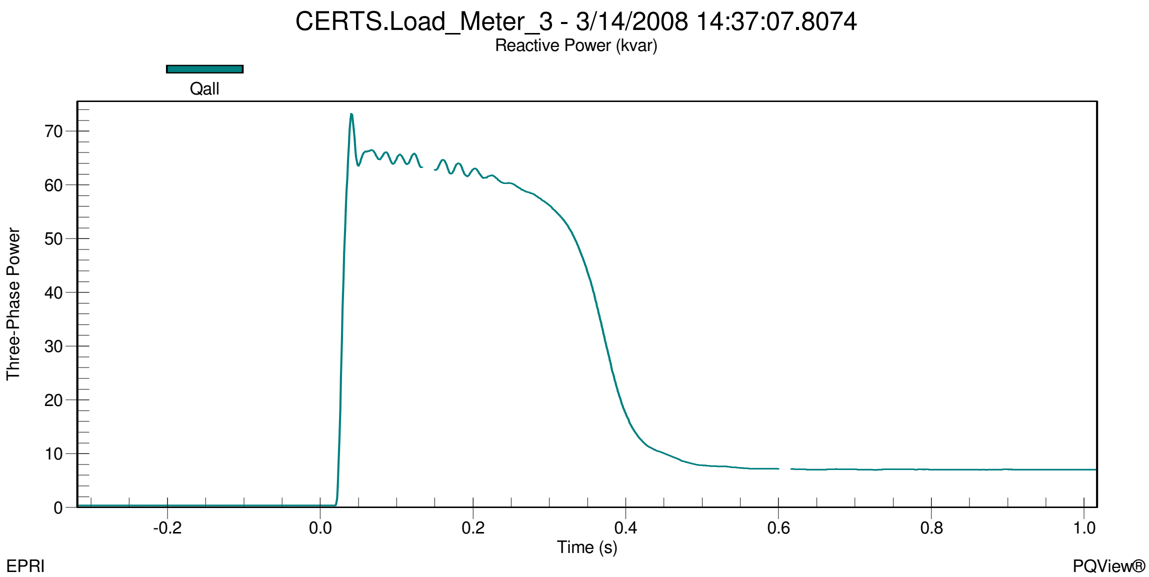

Figure 10b - Load Bank 3 Reactive Power during Motor Start and Utility Connected for Test 10.2.20

In Figures 10a and 10b it can be seen that the load in Zone 3 was approximately 18kW + j0kVAr before the start of the induction motor and increased to approximately 52.2kW + j73.1kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 42.5kW + j62kVAr during the warm up phase which lasted about 33 cycles (0.55 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 26.5kW + j7kVAr.

The voltage and frequency at the static switch before the motor start was approximately 282.2V on A-phase, 278.8V on B-phase and 278.8V on C-phase shown in Figure 10c and approximately 60.00Hz shown in Figure 10d. When the motor started, the voltage at the static switch during the inrush decreased to approximately 274.3V on A-phase, 270.6V on B-phase and 270.8V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.90Hz and quickly increased to approximately 60.00Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 281.6V on A-phase, 278.2V on B-phase and 278.2V on C-phase at an approximate frequency 60.00Hz.

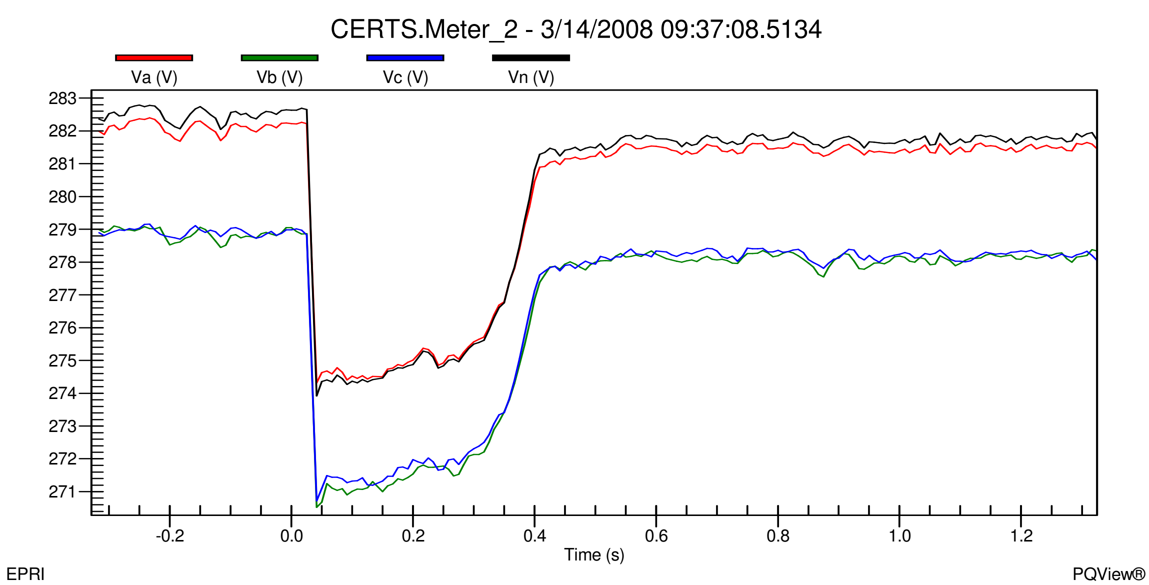

Figure 10c - Static Switch Line-to-Ground Voltage during Motor Start and Utility Connected for Test 10.2.20

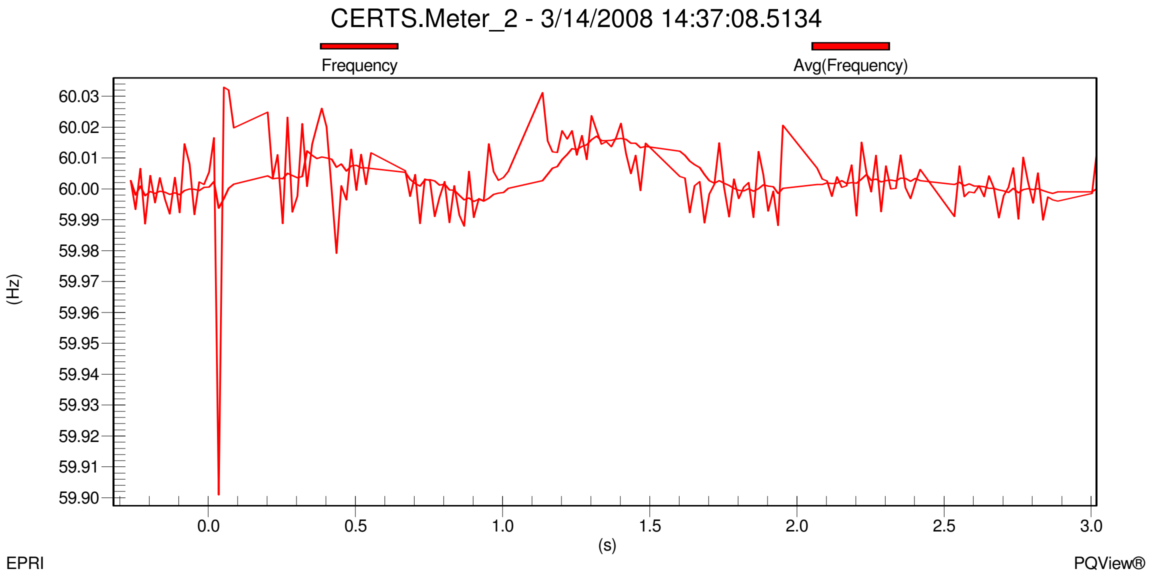

Figure 10d - Static Switch Frequency during Motor Start and Utility Connected for Test 10.2.20

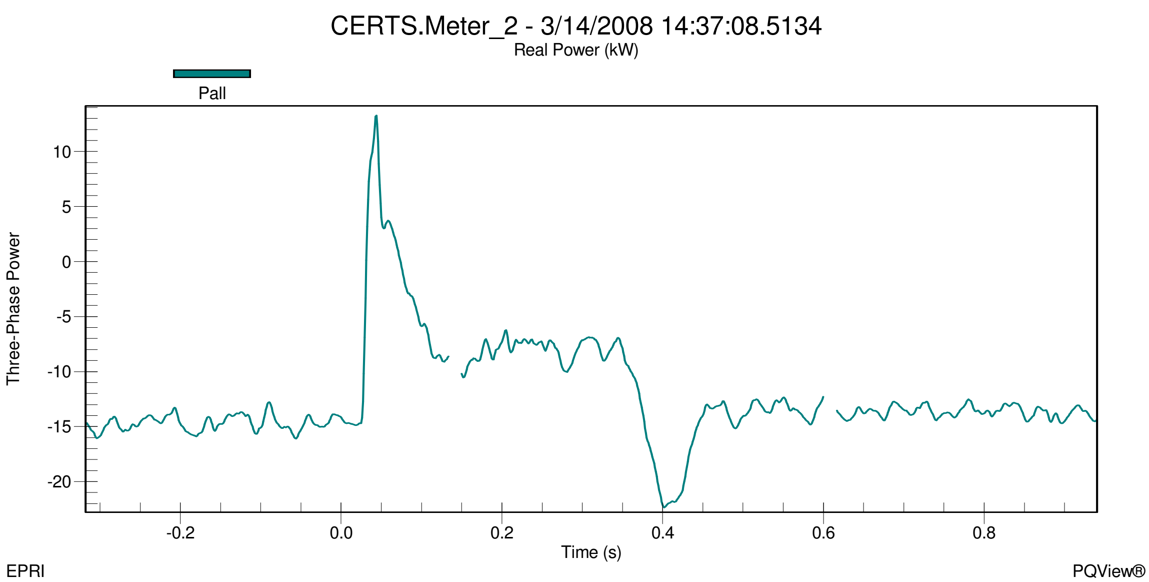

Figure 10e - Static Switch Real Power during Motor Start and Utility Connected for Test 10.2.20

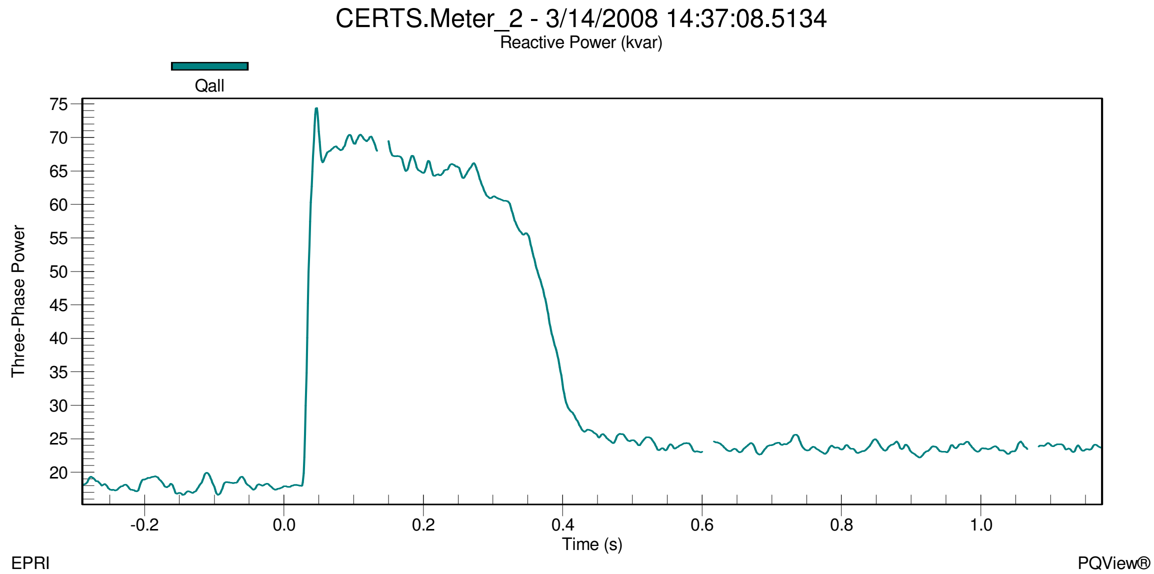

Figure 10f - Static Switch Reactive Power during Motor Start and Utility Connected for Test 10.2.20

Before the motor started Gen-set A1 was producing approximately 35.8kW – j12kVAr. This was enough power for the load demands of Load Bank 3 with real power being exported to Zone 6 of approximately 15kW shown in Figure 10e. The grid was supporting the reactive power of the microgrid with approximately 19kVAr shown in Figure 10f. When the motor started the inrush caused the utility to supply approximately 74.5kVAr and to pick up the load demand of Load Bank 6 and approximately 13.3kW of the load demand in Zone 3. The power that was being supplied by Gen-set A1 to Load Bank 6 was now supplying the motor inrush which can be seen in Figure 9e as the real power through the static switch becomes positive. Gen-set A1 increased its real and reactive power output levels to approximately 55.1kW + j2.9kVAr. Notice the signs of the VAr output changed from negative to positive for Gen-set A1 in order to support the induction motor load in Zone 3.

When the motor reached steady state, the real and reactive power through the static switch was approximately -14kW + j23.5kVAr which meant that Gen-set A1 was supplying the power for the induction motor and approximately 14kW of Load Bank 6. The real power in Gen-set A1 increased from its initial value at the beginning of the test to approximately 43.2kW and the reactive power went relatively back to the initial value before the motor started of approximately -11kVAr. Once all the data was verified and recorded into the DAS Database, the motor was shut down and the static switch was directed by the EMS to manually open.

As soon as the static switch opened, Meter 1 recorded real power increased to approximately 36.9kW and reactive power decreased to 1kVAr satisfying the load demand in Load Bank 6 which was approximately 36.5kW + j0.781kVAr and not supplying any power beyond the static switch to Load Bank 3. 0kW + j0kVAr was recorded at the static switch, indicating that power was not flowing through the static switch. Load Bank 3 loads reduced slightly to 17.05kW + j0kVAr. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 10g, from approximately 282.5V on A-phase, 279.5V on B-phase and 279.5V on C-phase when connected to the utility to 272V on A-phase, 272V on B-phase and 272V on C-phase at Meter 3 when islanded.

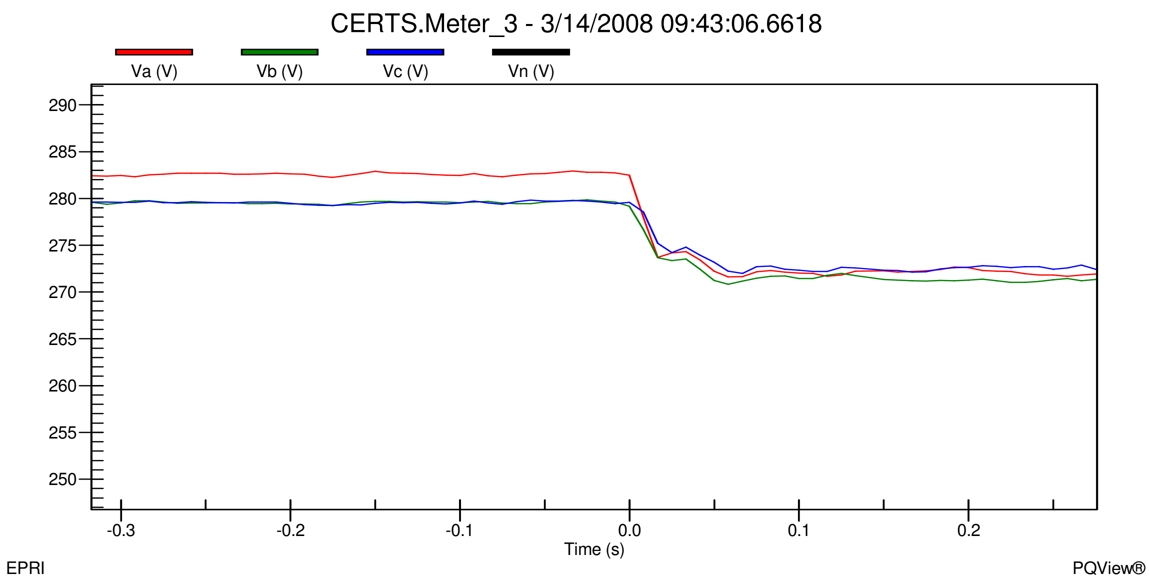

Figure 10g - Meter 3 Line-to-Ground Voltages during Utility Connected to Island mode for Test 10.2.20

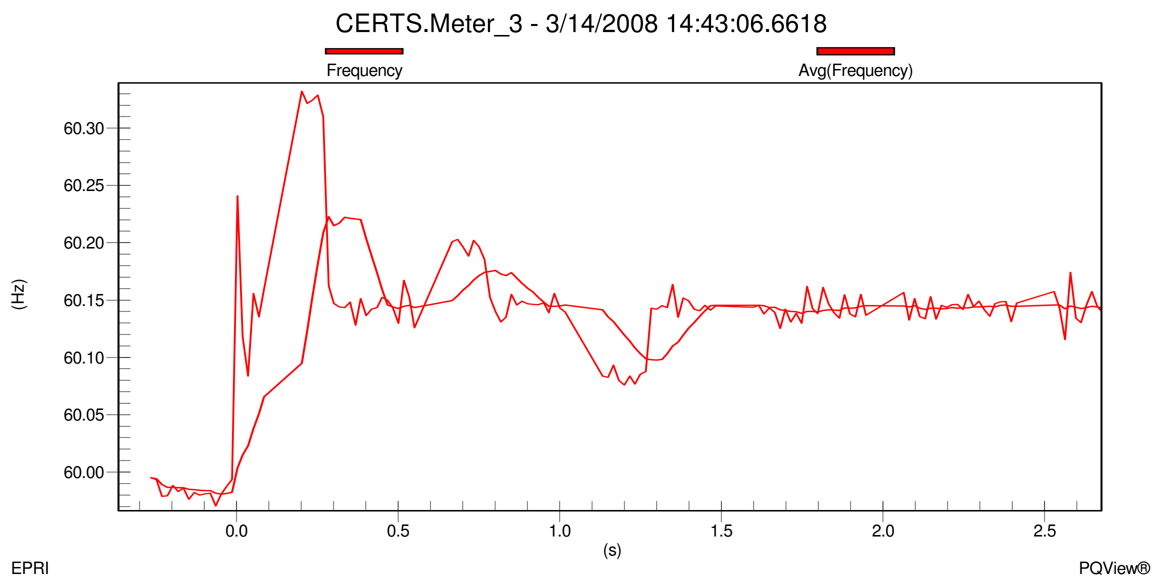

Figure 10h - Meter 3 Frequency during Utility Connected to Island mode for Test 10.2.20

Frequency change in the microgrid, shown in Figure 10h, increased from approximately 59.99Hz when connected to the utility grid to approximately 60.15Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed Gen-set A1 to decrease its output real power to approximately 18.8kW. Reactive power in Gen-set A1 increased to approximately 4kVAr. Meter 3 was approximately -2.5kW – 3.2kVAr indicating that Gen-set A1 was satisfying the load in Load Bank 3 and the power losses in the electrical lines. All data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the 10Hp induction motor was started in Zone 3.

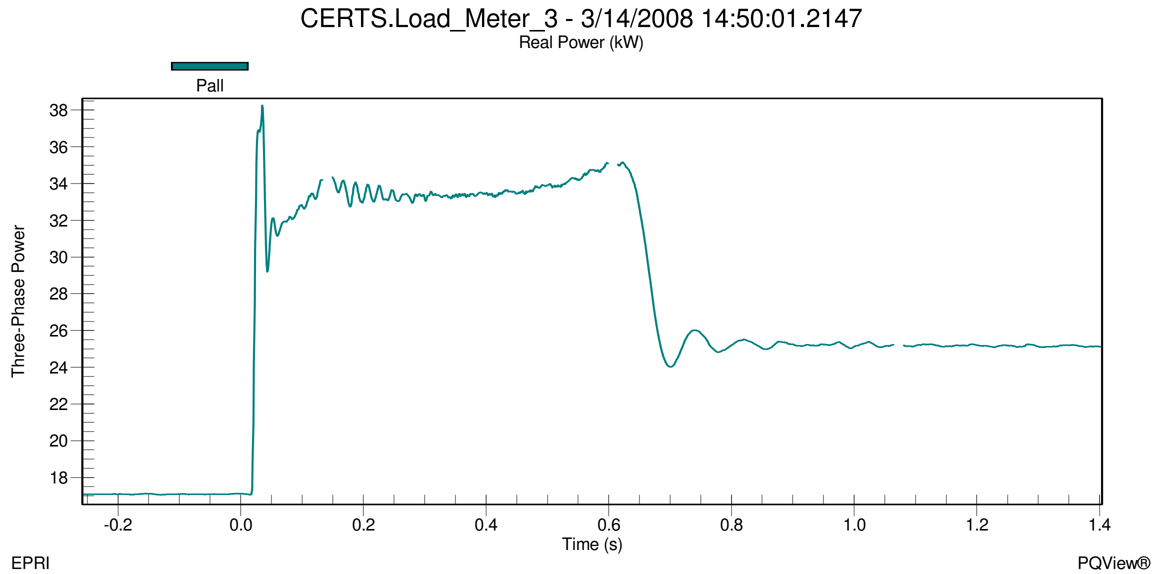

Figure 10i - Load Bank 3 Real Power during Motor Start and Islanded for Test 10.2.20

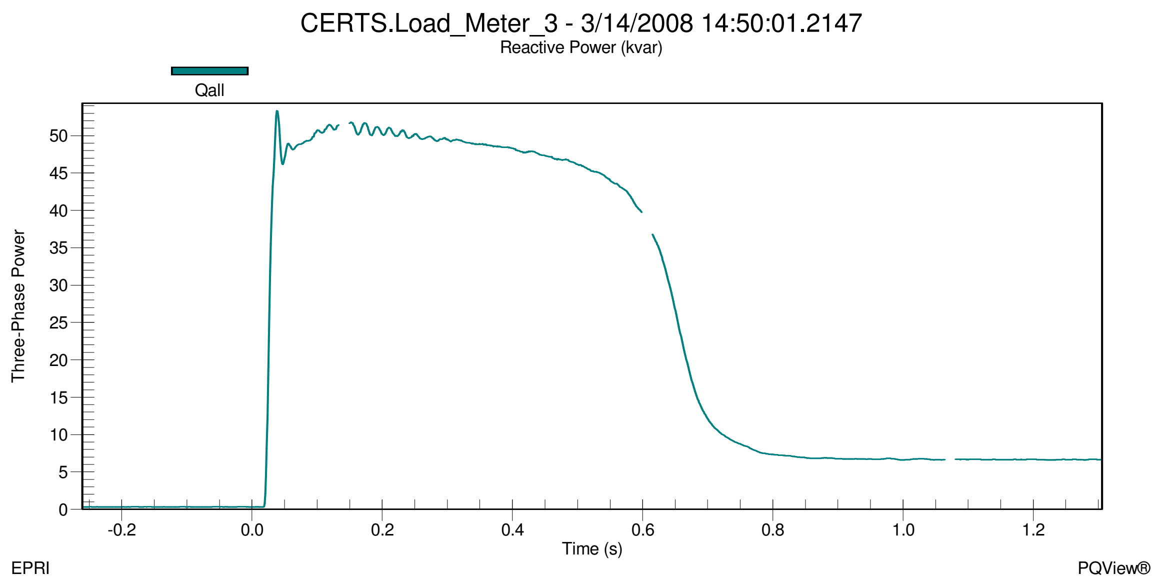

Figure 10j - Load Bank 3 Reactive Power during Motor Start and Islanded for Test 10.2.20

In Figures 10i and 10j it can be seen that the load in Zone 3 was approximately 16kW + j0.3kVAr before the start of the induction motor and increased to approximately 38.3kW + j53.2kVAr during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 34kW + j48.3kVAr during the warm up phase which lasted about 49.2 cycles (0.82 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 25.2kW + j7kVAr.

The voltage and frequency at Meter 3 before the motor start was approximately 272V on A-phase, 272V on B-phase and 272V on C-phase shown in Figure 10k and approximately 60.17HZ shown in Figure 10l. When the motor started, the voltage at Meter 3 during the inrush decreased to approximately 235.5V on A-phase, 235.5V on B-phase and 235.5V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.99Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 269V on A-phase, 269V on B-phase and 269V on C-phase at an approximate frequency of 60.15Hz.

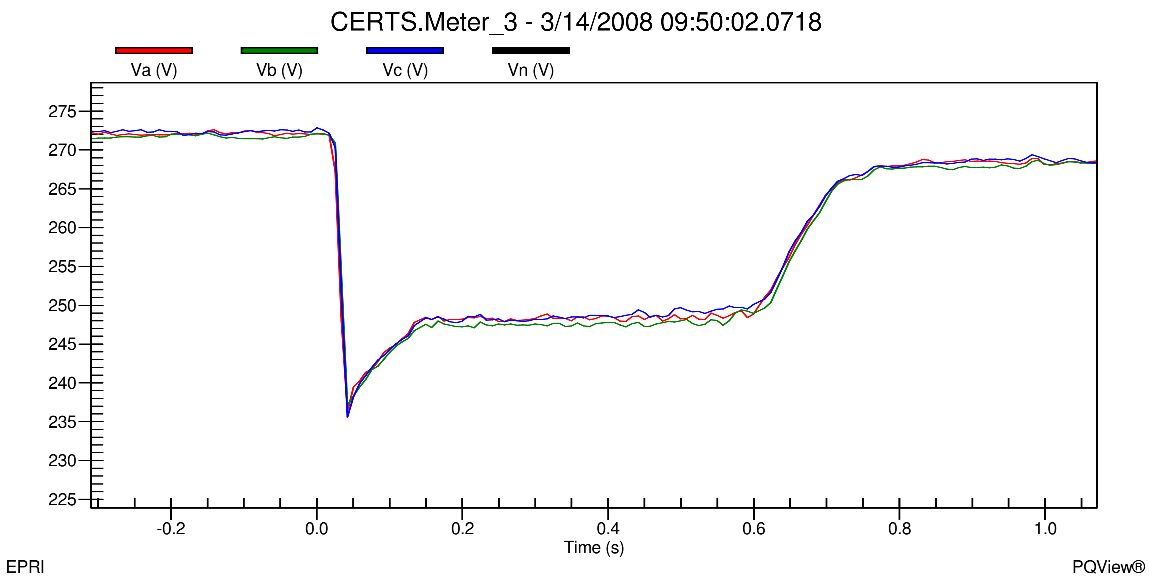

Figure 10k - Meter 3 Line-to-Ground Voltages during Motor Start and Islanded for Test 10.2.20

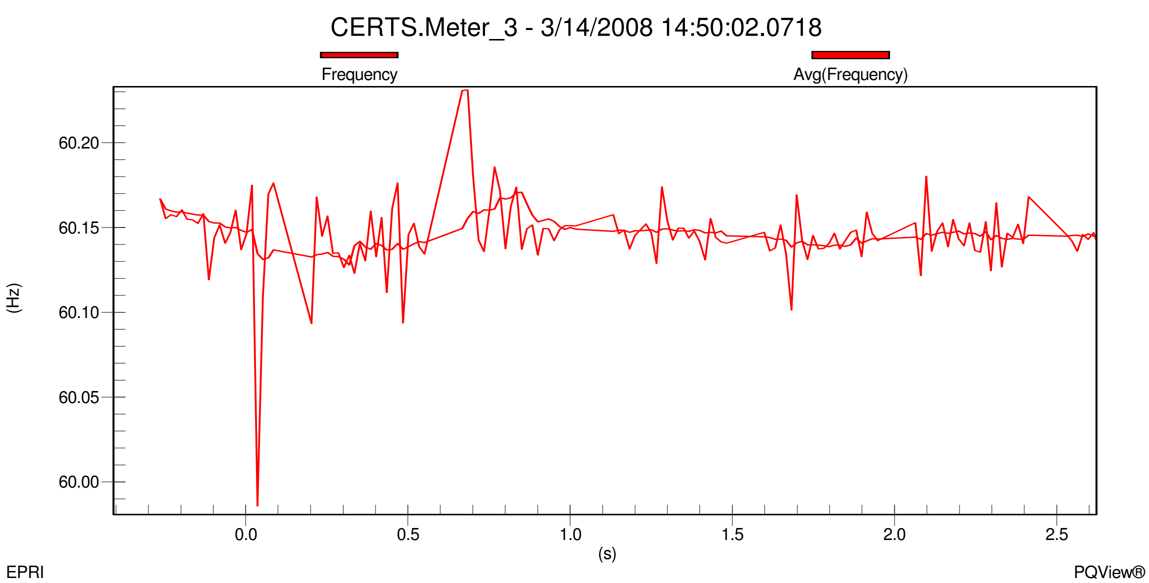

Figure 10l - Meter 3 Frequency during Motor Start and Islanded for Test 10.2.20

Before the motor started, Gen-set A1 was producing approximately 18.8kW + j4kVAr shown in Figures 10m and 10n. The power generated by Gen-set A1 was satisfying the loads in Load Bank 3 and all the electrical losses in the microgrid system. When the motor started the inrush caused Gen-set A1 to increase its output power level to 40kW + j54.5kVAr. Gen-set A1 decreased its output level while the motor was warming up and eventually dropped to 27.5kW + j10kVAr when the motor reached steady state. Once all the data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually close.

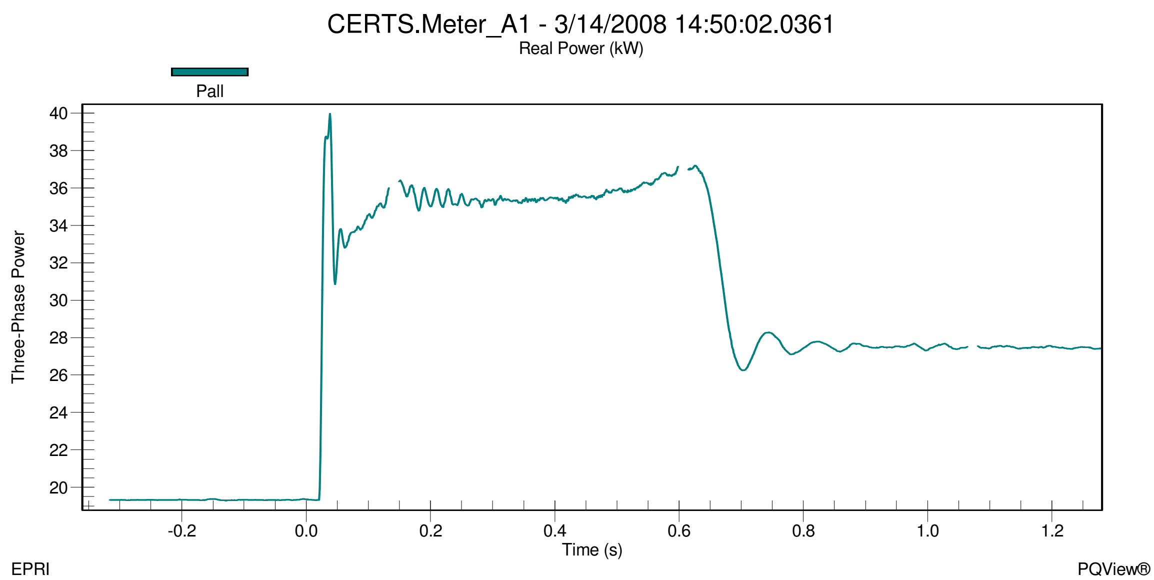

Figure 10m - Gen-set A1 Real Power during Motor Start and Islanded for Test 10.2.20

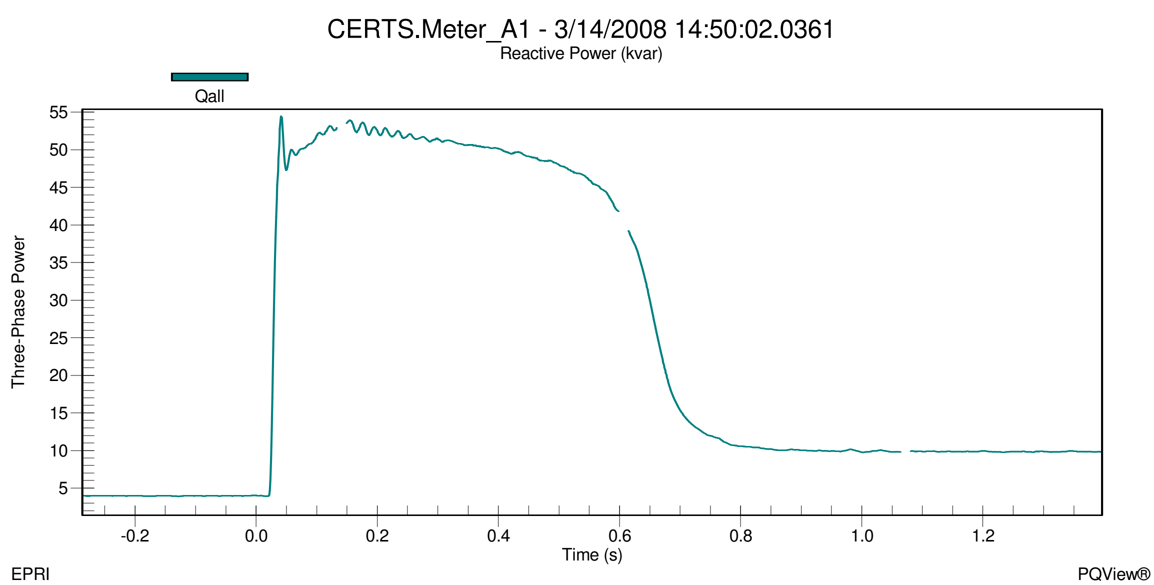

Figure 10n - Gen-set A1 Reactive Power during Motor Start and Islanded for Test 10.2.20

As soon as the static switch closed, Meter 1 recorded real power decreased from approximately 36.8kW to 26.7kW and reactive power increased from approximately 1kVAr to 25kVAr which means that the utility was satisfying a portion of the load demand in Load Bank6 and all the reactive power in the microgrid. Figures 10o and 10p show the static switch real power decreasing from approximately 0kW to -10.6kW and reactive power increasing from approximately 0kVAr to 24kVAr. At the beginning of the test, the initial power flow through the static switch was -15kW + j18kVAr which is not the same recorded at this point in the test because the 10Hp motor load is on in Zone 3. Gen-set A1 has picked up the motor load and supporting Load Bank 6 with approximately 10.6kW.

Load Bank 3 increased slightly to 24.9kW + j6.4kAVr. This slight load increase is a result from a voltage rise in the microgrid, shown in Figure 10q, from approximately 269V on A-phase, 269V on B-phase and 269V on C-phase when islanded to 282V on A-phase, 279.3V on B-phase and 279.3V on C-phase at Meter 3 when connected to the utility grid.

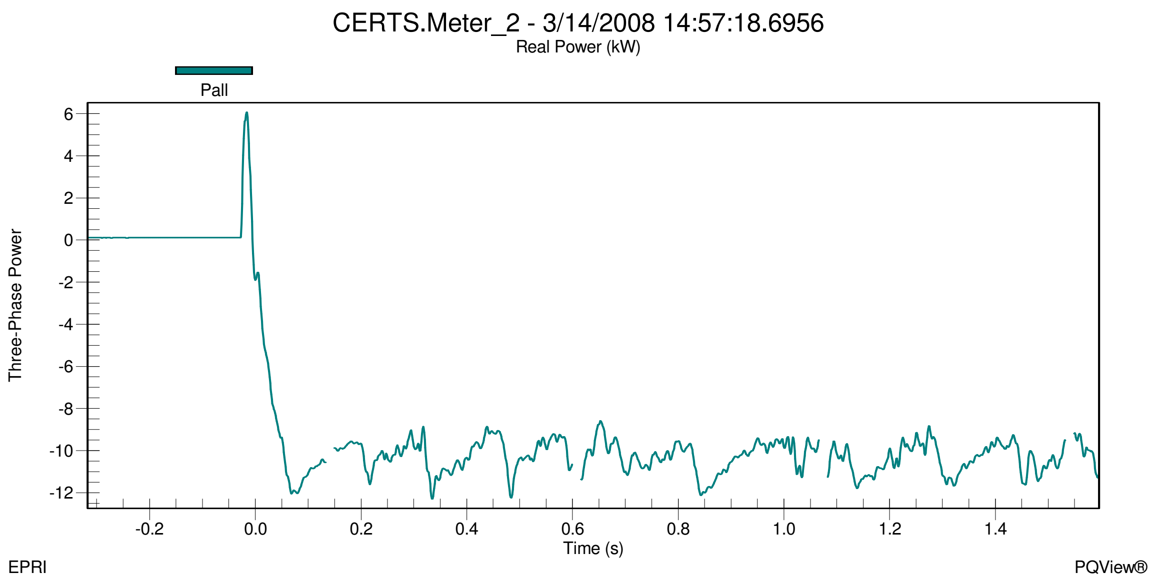

Figure 10o - Static Switch Real Power during Island to Utility Connected mode for Test 10.2.20

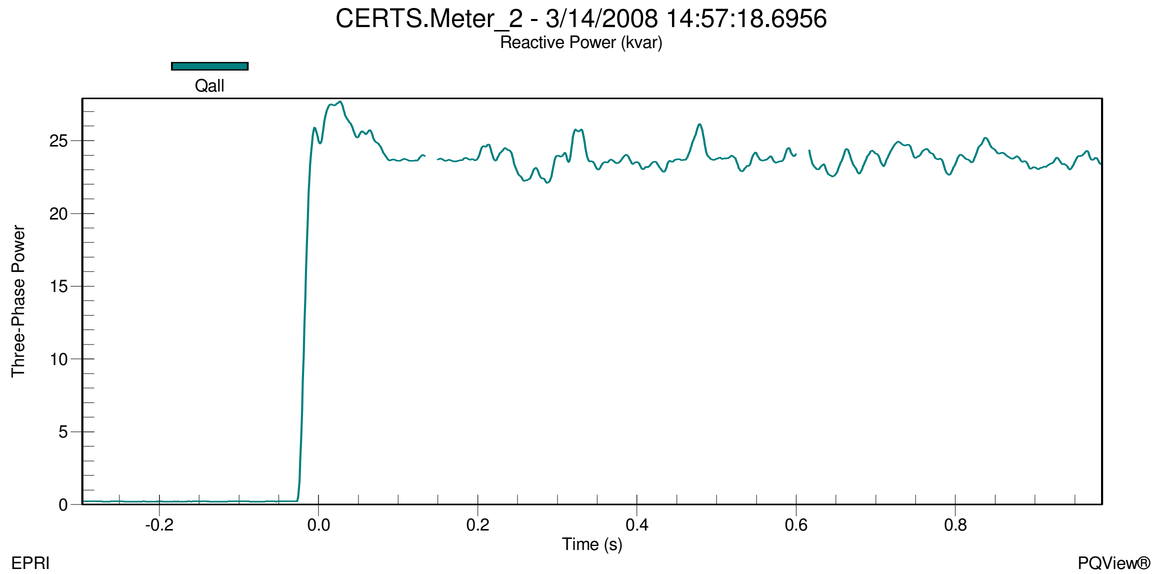

Figure 10p - Static Switch Reactive Power during Island to Utility Connected mode for Test 10.2.20

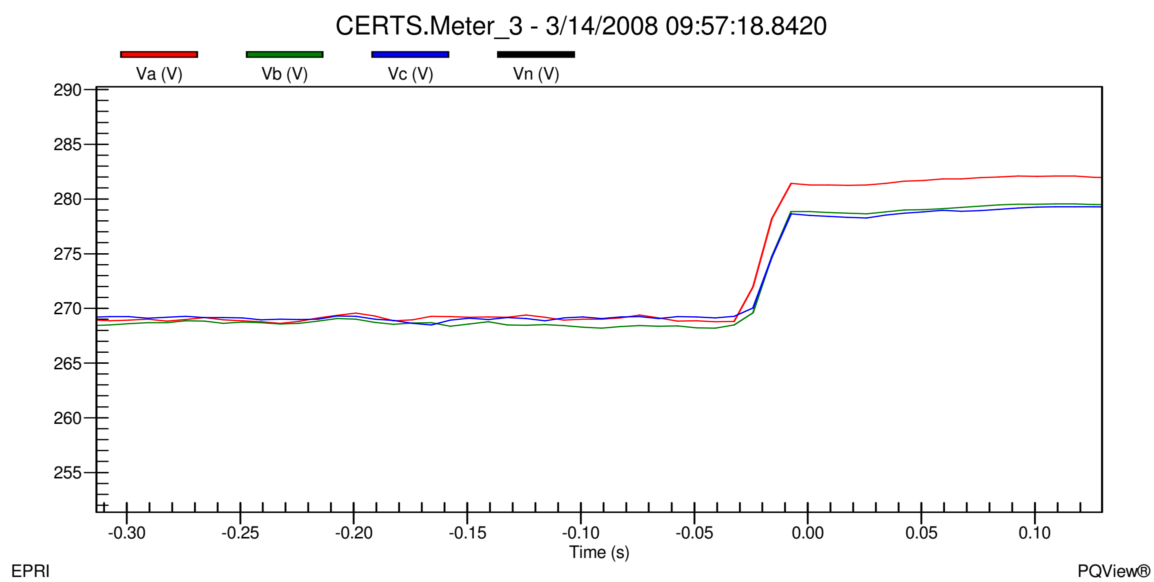

Figure 10q - Meter 3 Line-to-Ground Voltages during Island to Utility Connected mode for Test 10.2.20

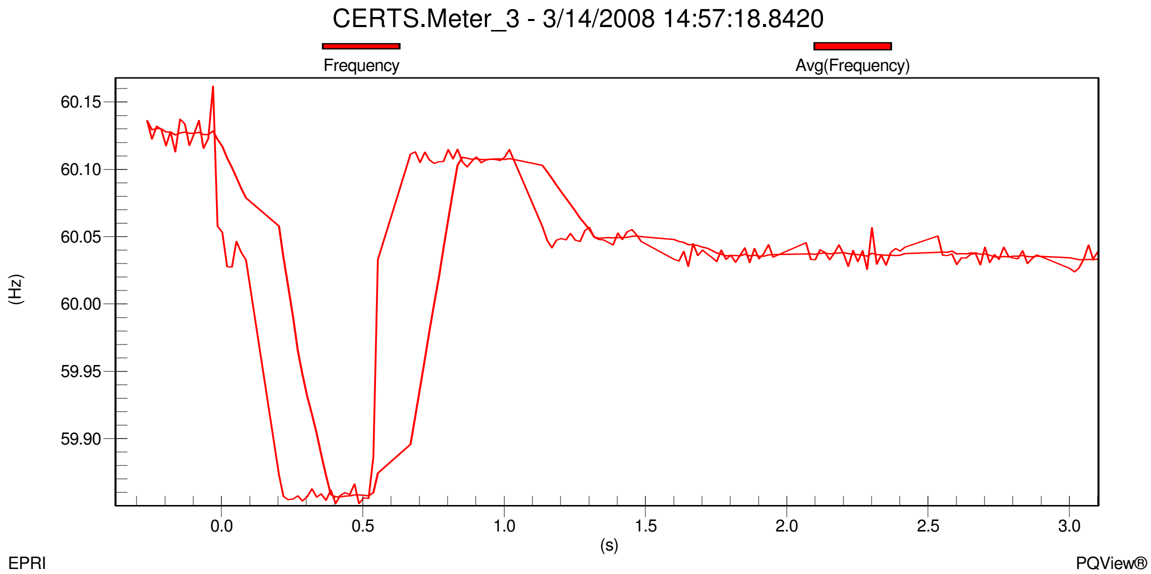

Figure 10r - Meter 3 Frequency during Island to Utility Connected mode for Test 10.2.20

Frequency change in the microgrid, shown in Figure 10r, decreased from approximately 60.13Hz when islanded to approximately 60.03Hz when connected to the utility grid. This change in frequency is due to the frequency no longer being established by the Gen-set using the CERTS algorithm but by the utility. Gen-set A1 is in zone power control mode therefore when the static switch closed back into the utility Gen-set A1 produced real power based on set-points for the power flow through Zone 3 initialized at the beginning of the test. The real power increased from its initial value at the beginning o f the test to approximately 38.4kW for Gen-set A1. This increase is because Gen-set A1 has picked up the real power of the induction motor in Zone 3. Reactive power for Gen-set A1 was relatively close to the value at the beginning of the test with approximately -11.2kVAr. After all the data was verified and recorded into the DAS Database, the motor, Gen-set A1, and Load Banks 3 and 6 were turned off.

6.1.2 Motor Start Tests, Weak Grid, Unbalanced Load with 0.9 Power Factor

Performance Goal:

Verify and document power flow, Micro-grid frequency changes and protection design with different Gen-set settings during motor starts when utility connected and then repeat motor start test during an islanded mode of operation.

Six tests were completed in this section with each test event and settings listed in Table 1. During each test Gen-sets A1 and A2 were both set for either unit or zone power control mode of operation. Each of the six tests varied the output power command set-point in each Gen-set, along with varying the load settings in load banks LB3, LB4 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	Meter 1	Meter 2	Meter 3	Meter 4	LB 3	LB 4	LB 6
10.3.12	Unit +40kW	Unit +30kW	+30kW	-10kW	-10kW	+10kW	20kW	A=10kW B=15kW C=15kW	A=10kW B=20kW C=10kW
10.3.14	Unit +40kW	0kW	+10kW	-30kW	-30kW	0kW	10kW	0kW	A=10kW B=20kW C=10kW
10.3.15	Unit +40kW	Unit +30kW	+70kW	+30kW	+30kW	+20kW	50kW	A=10kW B=20kW C=20kW	A=10kW B=20kW C=10kW
10.3.17	Unit +40kW	0kW	+20kW	-20kW	-20kW	0kW	20kW	0kW	A=10kW B=20kW C=10kW
10.3.18	Zone -10kW	Zone +10kW	+30kW	-10kW	-10kW	+10kW	20kW	A=10kW B=15kW C=15kW	A=10kW B=20kW C=10kW
10.3.20	Zone -20kW	0kW	+20kW	-20kW	-20kW	0kW	20kW	0kW	A=10kW B=20kW C=10kW

Table 2 -Unbalance Load, Weak Grid, Before Motor Start settings of Gen-sets and Load Banks

The test procedures for these six tests were exactly the same as in the tests performed in Section 6.1.1 (Tests 10.2.12 – 10.2.20).

For Test 10.3.12 the measured values, after the Gen-sets were warmed up and load banks brought on-line are provided in Table 3.

Meter	Gen-set A1	Gen – set A2	Meter 1	Meter 2	Meter 3	Meter 4	LB 3	LB 4	LB 6
3 Phase kW	37.5	28.5	30	-7.8	-10.5	8.5	18.2	36.7	36.9
1 Phase kW	A=11 B=15.5 C=10.5	A=8 B=12 C=8.5	A=8 B=11 C=11	A=-2 B=-7 C=1.2	A=-3 B=-8 C=0.05	A=2 B=1.5 C=5	A=6 B=6.2 C=6	A=9.7 B=13.5 C=13.5	A=9.7 B=17.6 C=9.6
3 Phase kVAr	-12	-4	24.5	22.4	17.9	5	0.3	0.615	0.638
1 Phase kVAr	A=-4.5 B=-4 C=-3.5	A=-2 B=-1 C=-1	A=9 B=8 C=7.5	A=8.7 B=7 C=6.7	A=7.5 B=5.2 C=5.2	A=2.4 B=1.2 C=1.4	A=0.1 B=0.1 C=0.1	A=0.13 B=0.28 C=0.205	A=0.122 B=0.394 C=0.122

Table 3 - Measured Values after Start Up for Test 10.3.12

These measurements were relatively close to the expected values in Table 2, but not exact due to temperature, phase voltages and electrical losses in conductors. In addition, the 40kW settings for LB3 and LB4 and the 20kW setting for LB3 were also below selected set values. At the time of the measurements, the voltage and frequency was 282.7V on A-phase, 279V on B-phase and 279.6V on C-phase and 60.02Hz at the static switch (i.e., Meter 2) when connected to the utility grid; and 282.7V on A-phase, 279.5V on B-phase and 279.5V on C-phase and 60.02Hz at Meter 3.

The Gen-sets in this test were set up to produce more power than Load Banks 3 and 4 needed which approximately 7.8kW of excess power was exported through the static with to Load Bank 6. Since Load Bank 6 was approximately 36.9kW (A= 9.7kW B=17.6kW C=9.6kW) + j0.638kVAr (A=0.122kVAr B=0.394kVAr C=0.122kVAr), the utility had to supply approximately 30kW (A=8kW B=11kW C=11kW) to satisfy the load. Reactive power had to be imported in from the utility of approximately 24.5kVAr (A=9kVAr B=8kVAr C=7.5kVAr) because of Gen-set A1 and A2 needed approximately 16kVAr between both and the reactive power absorbed in the electrical lines. Once all the data was verified and recorded into the DAS Database, the 10Hp induction motor was started in Zone 3.

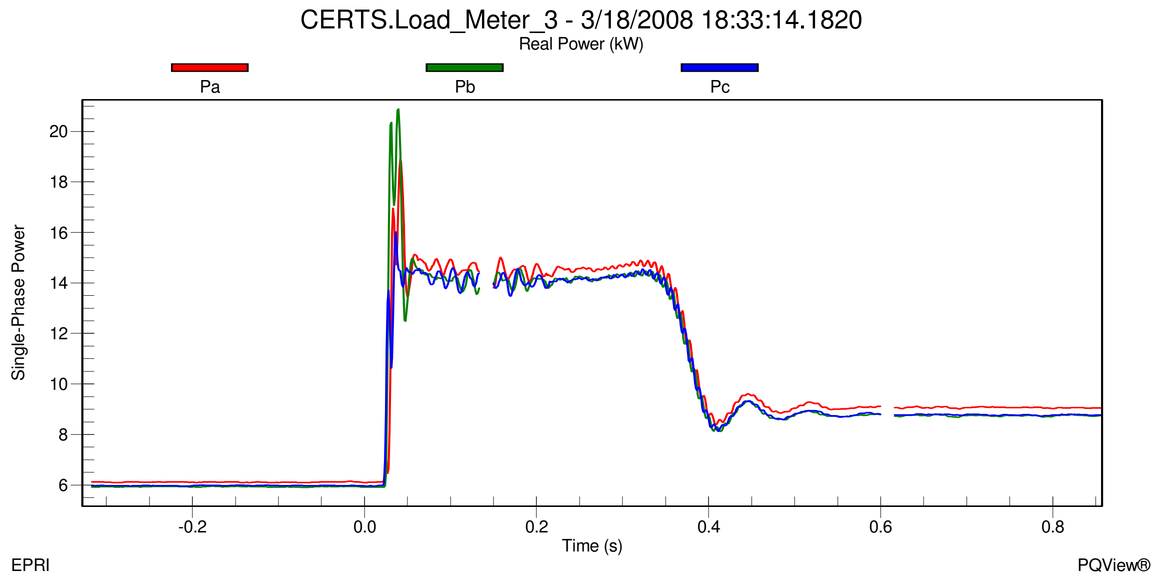

Figure 11a - Load Bank 3 Real Single-Phase Power during Motor Start and Utility Connected for Test 10.3.12

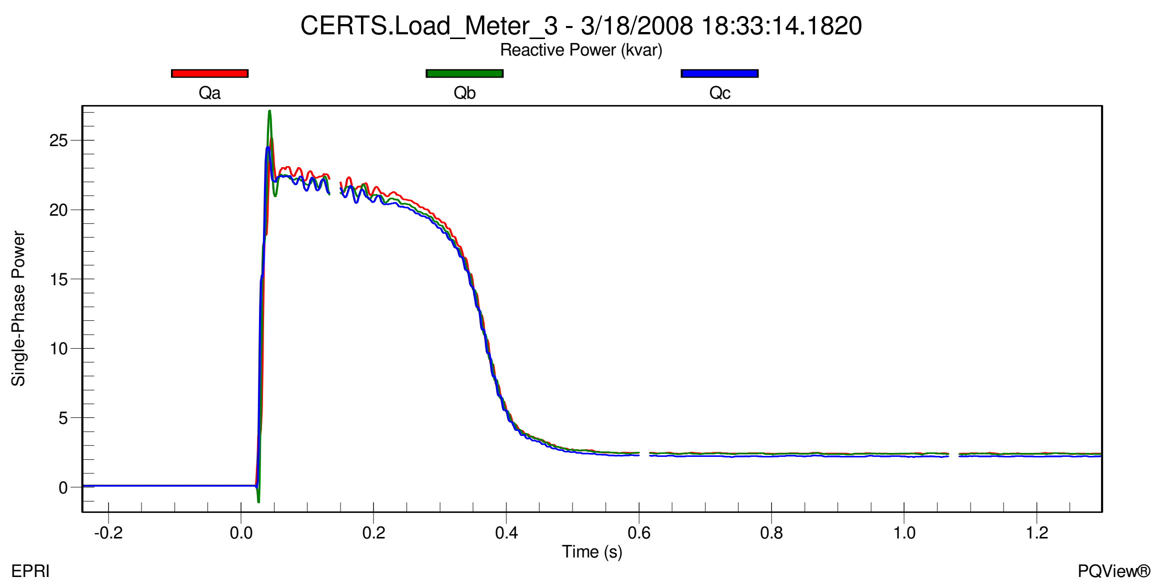

Figure 11b - Load Bank 3 Reactive Single-Phase Power during Motor Start and Utility Connected for Test 10.3.12

In Figures 11a and 11b it can be seen that the load in Zone 3 was approximately 18.2kW (A=6kW B=6.2kW C=6kW) + j0.3kVAr (A=0.1kVAr B=0.1kVAr C=0.1kVAr) before the start of the induction motor and increased to approximately 55.6kW (A=19kW B=20.9kW C=15.7kW) + j76.1kVAr (A=24.5kVAr B=27.1kVAr C=24.5kVAr) during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately

43.1kW (A=14.7kW B=14.2kW C=14.2kW) + j63.5kVAr (A=21.5kVAr B=21kVAr C=21kAVr) during the warm up phase which lasted about 33 cycles (0.55 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 26.5kW (A=9.1kW B=8.7kW C=8.7kW) + j6.6kVAr (A=2.2kVAr B=2.2kVAr C=2.2kVAr).

The voltage and frequency at the static switch before the motor start was approximately 282.7V on A-phase 279V, on B-phase and 279.6V on C-phase shown in Figure 11c and approximately 60.02Hz shown in Figure 11d. When the motor started, the voltage at the static switch during the inrush decreased to approximately 276.3V on A-phase, 272.4V on B-phase and 273V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.96Hz and quickly increased to approximately 60.00Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 282.1V on A-phase, 278.2V on B-phase and 278.9V on C-phase at an approximate frequency of 60.01Hz.

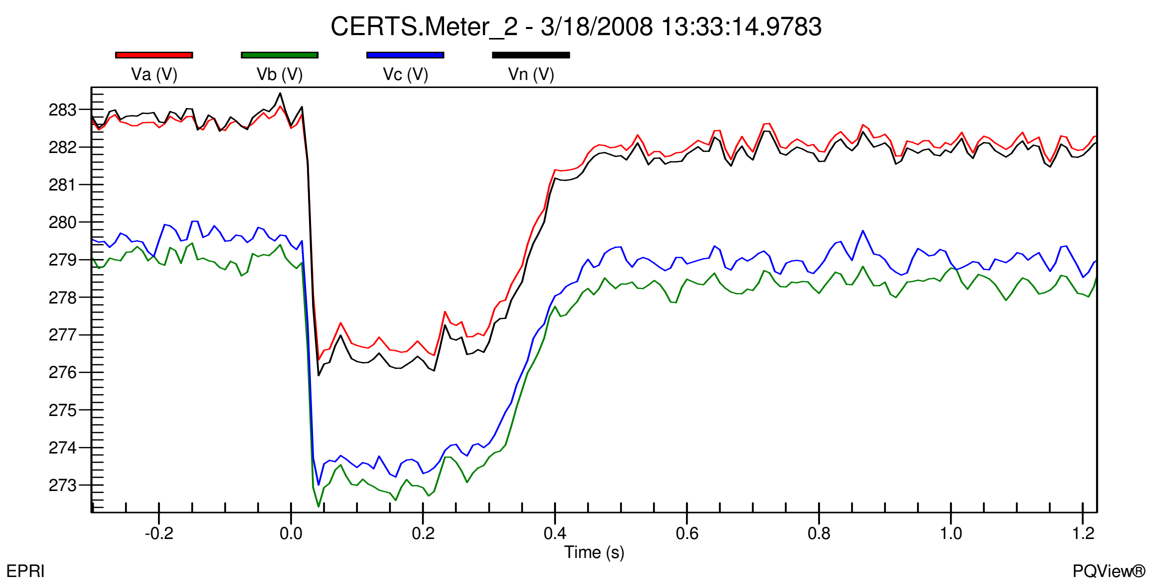

Figure 11c - Static Switch Line-to-Ground Voltages during Motor Start and Utility Connected for Test 10.3.12

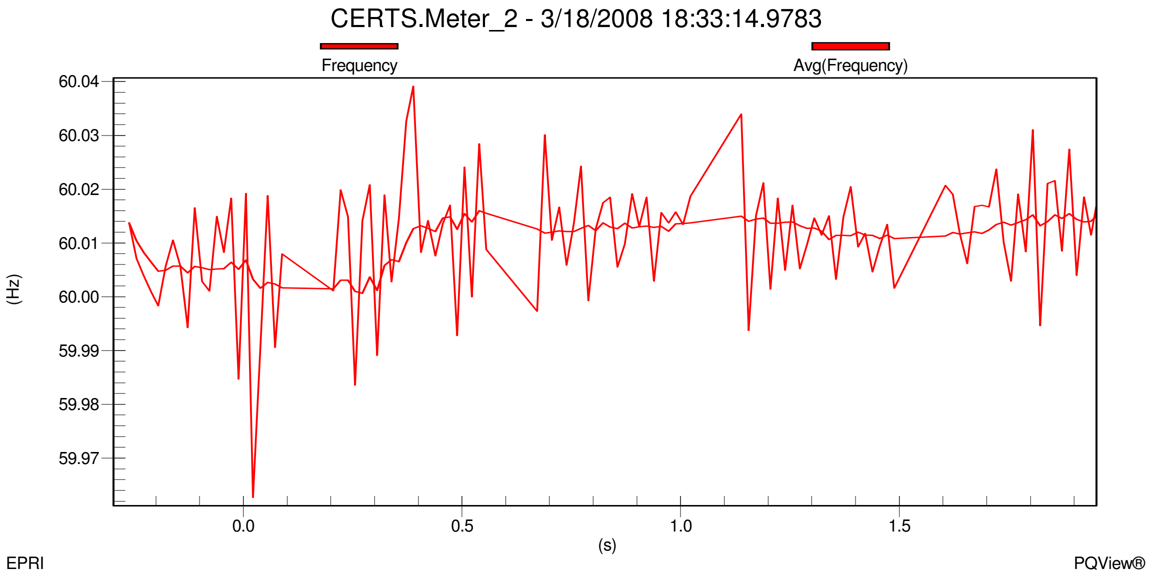

Figure 11d - Static Switch Frequency during Motor Start and Utility Connected for Test 10.3.12

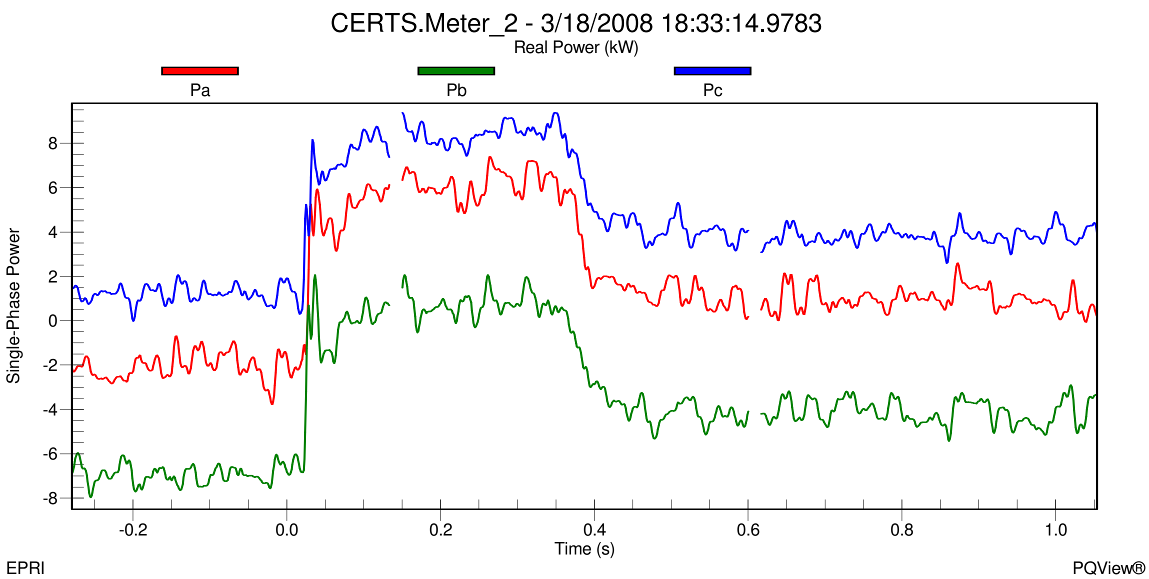

Figure 11e - Static Switch Real Single-Phase Power during Motor Start and Utility Connected for Test 10.3.12

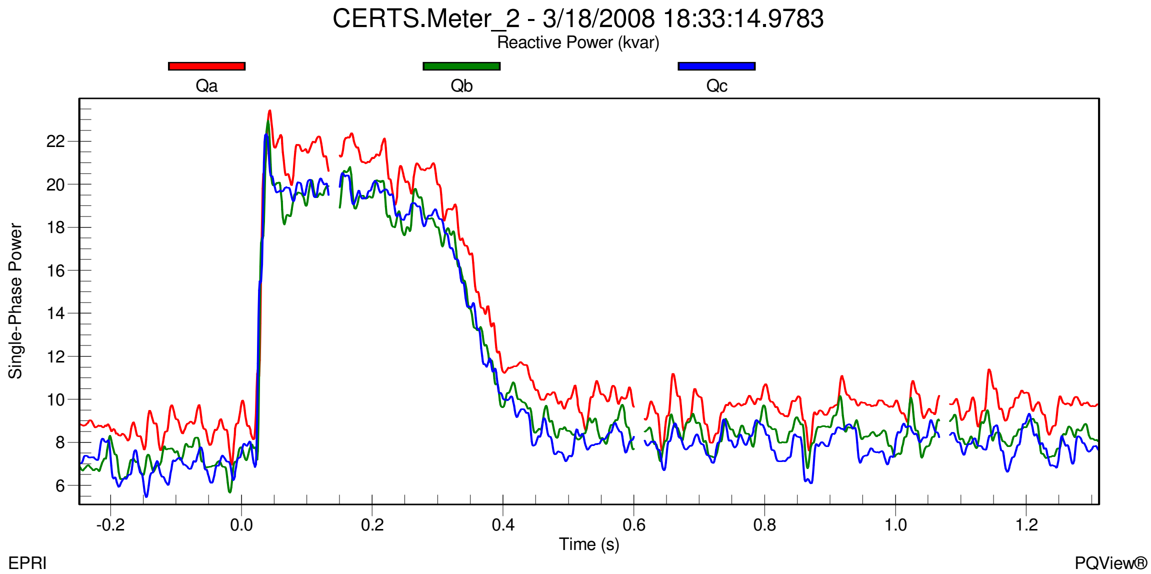

Figure 11f - Static Switch Reactive Single-Phase Power during Motor Start and Utility Connected for Test 10.3.12

Before the motor started Gen-sets A1 and A2 were producing approximately 37.5kW (A=11kW B=15.5kW C=10.5kW) – j12kVAr (A=-4.5kVAr B=-4kVAr C=-3.5kVAr) and 28.5kW (A=8kW B=12kW C=8.5kW) – j4kVAr (A=-2kVAr B=-1kVAr C=-1kVAr), respectively. This was enough power for the load demands of Zones 3 and 4 with real power being exported to Zone 6 of approximately 7.8kW shown in Figure 11e. The grid was supporting the reactive power of the microgrid with approximately 22.4kVAr (A=8.7kVAr B=7kVAr C=6.7kVAr) shown in Figure 11f. When the motor started the inrush caused the utility to supply approximately 68.4kVAr (A=23.5kVAr B=22.6kVAr C=22.3kVAr) and to pick up the load demands of Load Bank 6 along with approximately 15.3kW (A=5.3kW B=1.8kW C=8.2kW) of the microgrid critical loads. The power being supplied by Gen-sets A1 and A2 to Load Bank 6 was now supplying a portion of the motor inrush which can be seen in Figure 11e as the real power becomes positive. Gen-sets A1 and A2 increased their real and reactive power output levels to approximately 43kW (A=13kW B=18kW C=12kW) + j0.3kVAr (A=-1kVAr B=0.9kVAr C=0.4kVAr) and 36.5kW (A=10.1kW B=15.8kW C=10.6kW) + j12kVAr (A=3.7kVAr B=4.6kVAr C=3.7kVAr), respectively. Notice the signs of the VAr output changed from negative to positive for both Gen-sets in order to support the induction motor load in Zone 3.

When the motor reached steady state, the real and reactive power through the static switch was approximately 0.4kW (A=0.9kW B=-4.3kW C=3.8kW) + j25.8kVAr (A=9.7kVAr B=8.4kVAr C=7.7kVAr) which meant that Gen-sets A1 and A2 were supplying enough power for the induction motor and Load Banks 3 and 4 but needed approximately 0.4kW (A=0.9kW B=4.3kW C=3.8kW) from the utility grid for the power losses in the conductors. Gen-sets A1 and A2 real power returned to the values before the motor started of approximately 37.5kW (A=11kW B=15.5kW C=10.5kW) and 28.5kW (A=8kW B=12kW C=8.5kW), respectively, and the reactive power increased to approximately -10.8kVAr (A=-4kVAr B=-3.3kVAr C=-3.5kVAr) in Gen-set A1 and -1kVAr (A=-1.4kVAr B=0.2kVAr C=0.2kVAr) in Gen-set A2. Once all the data was verified and recorded into the DAS Database, the motor was shut down and the static switch was directed by the EMS to manually open.

As soon as the static switch opened, Meter 1 recorded real power increased to approximately 38.1kW (A=10.1kW B=18.1kW C=9.9kW) and reactive power decreased to -0.5kVAr (A=-0.3kVAr B=0.1kVAr C=-0.3kVAr) satisfying the load demand in Load Bank 6 which was approximately 37.9kW (A=10.1kW B=9.8kW C=18kW) + j0.655kVAr (A=0.123kVAr B=0.405kVAr C=0.127kVAr) and not supplying any power beyond the static switch to Load Banks 3 and 4. 0kW (A=0kW B=0kW C=0kW) + j0kVAr (A=0kVAr B=0kVAr C=0kVAr) was recorded at the static switch indicating that power was not flowing through the static switch. Load banks 3 and 4 loads reduced slightly to 17.35kW (A=5.76kW B=5.84kW C=5.75kW) + j0.321kVAr (A=0.105kVAr B=0.123kVAr C=0.093kVAr) and 35.4kW (A=9.3kW B=13.1kW C=13kW) + j0.59kVAr (A=0.115kVAr B=0.275kVAr C=0.2kVAr), respectively. This load reduction resulted from a voltage drop in the microgrid, shown in Figure 11g, from approximately 283V on A-phase, 280V on B-phase and 280V on C-phase when connected to the utility grid to 275V on A-phase, 276V on B-phase and 274V on C-phase at Meter 3 when islanded.

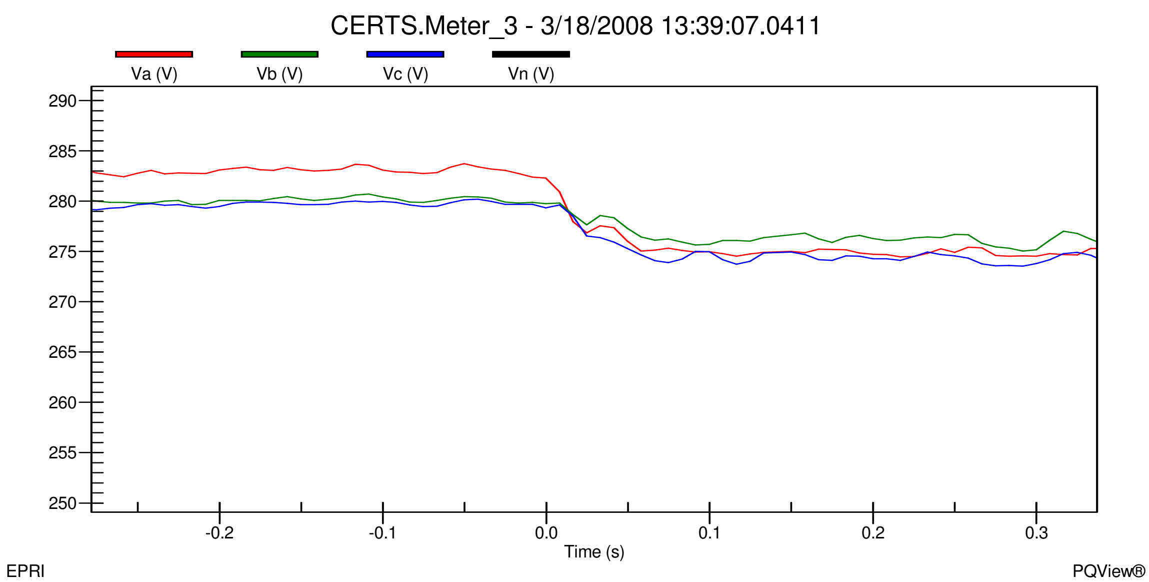

Figure 11g - Meter 3 Line-to-Ground Voltages during Utility Connected to Island mode for Test 10.3.12

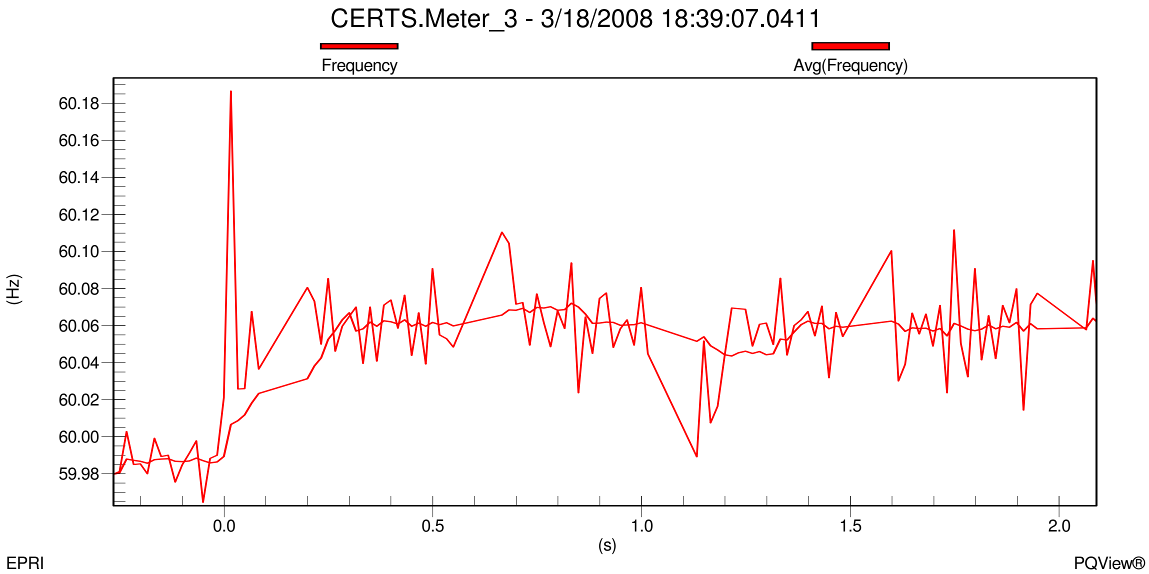

Figure 11h - Meter 3 Frequency during Utility Connected to Island mode for Test 10.3.12

Frequency change in the microgrid, shown in Figure 11h, increased from approximately 59.99Hz when connected to the utility grid to approximately 60.06Hz when islanded. This change in frequency was part of the CERTS algorithm which allowed the Gen-sets to decrease their output power to satisfy the load demands. Gen-set A1 and A2 decreased their output real power to approximately 31.4kW (A=9kW B=11.4kW C=11kW) and 22.7kW (A=6.8kW B=2kW C=8.5kW), respectively and increased their output reactive power to approximately -2.2kVAr (A=-0.8kVAr B=-1kVAr C=-0.4kVAr) and 7.5kVAr (A=2.5kVAr B=2.5kVAr C=2.5kVAr), respectively. Meter 3 was approximately –1.1kW (A=-0.1kW B=-0.5kW C=-0.5kW) - j4.2kVAr (A=-1.5kVAr B=-1.1kVAr C=-1.6kVAr) indicating that the Gen-sets were satisfying the loads in the microgrid and the power losses in the electrical lines. All the data was verified and recorded into the DAS Database. The microgrid ran for a couple of minutes in this electrical state before the 10Hp induction motor was started in Zone 3.

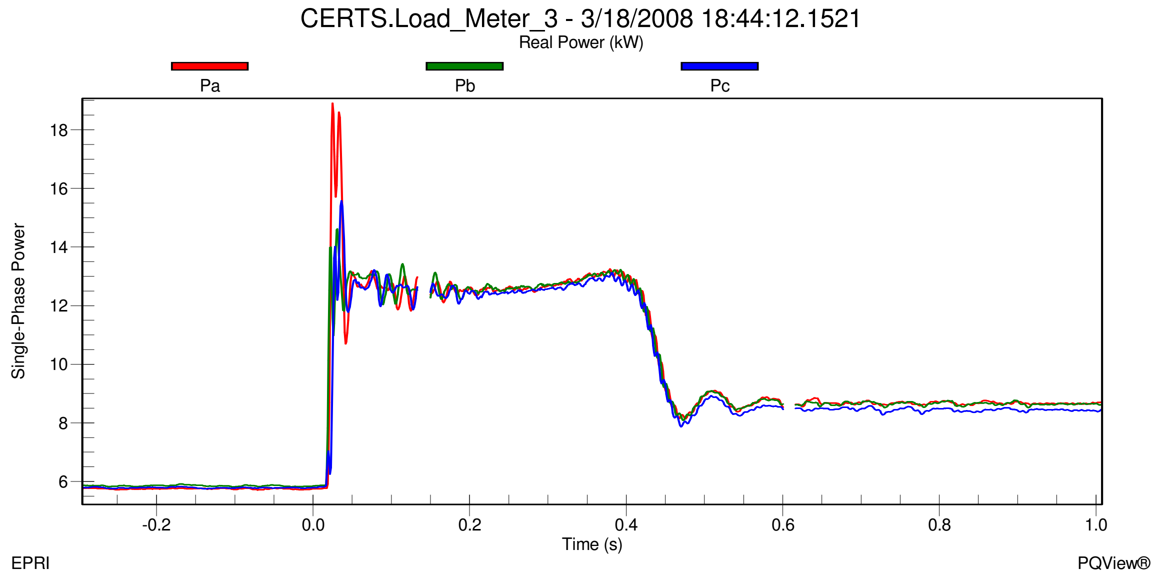

Figure 11i - Load Bank3 Real Single-Phase Power during Motor Start and Islanded for Test 10.3.12

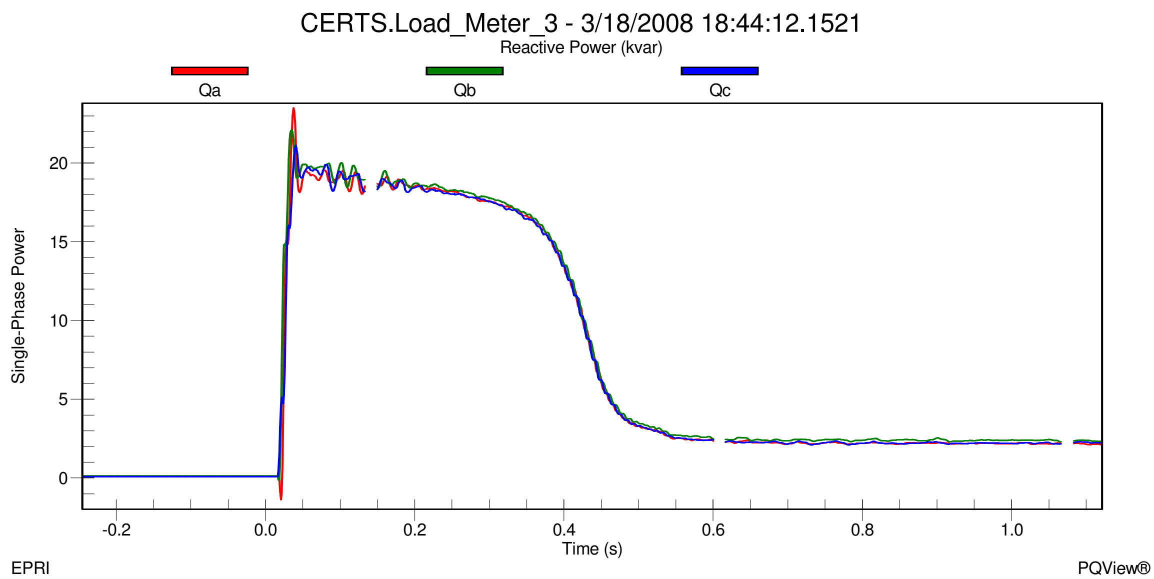

Figure 11j - Load Bank 3 Reactive Single-Phase Power during Motor Start and Islanded for Test 10.3.12

In Figures 11i and 11j it can be seen that the load in Zone 3 was approximately 17.4kW (A=5.8kW B=5.8kW C=5.8kW) + j0.15kVAr (A=0.05kVAr B=0.05kVAr C=0.05kVAr) before the start of the induction motor and increased to approximately 47kW (A=19kW B=14kW C=14kW) + j66.8kVAr (A=23.7kVAr B=22kVAr C=21.1kVAr) during the inrush phase of the motor start. After about 1.5 cycles, the motor settled down to approximately 37.8kW (A=12.6kW B=12.6kW C=12.6kW) + j56.1kVAr (A=18.7kVAr B=18.7kVAr C=18.7kVAr) during the warm up phase which lasted about 36 cycles (0.6 Seconds). When the motor reached steady state, the load in Zone 3 was approximately 25.8kW (A=8.7kW B=8.4kW C=8.7kW) + j6.9kVAr (A=2.3kVAr B=2.3kVAr C=2.3kVAr).

The voltage and frequency at Meter 3 before the motor start was approximately 275V on A-phase, 275.5V on B-phase and 274V on C-phase shown in Figure 11k and approximately 60.05Hz shown in Figure 11l. When the motor started, the voltage at Meter 3 during the inrush decreased to approximately 255V on A-phase, 254.3V on B-phase and 254.3V on C-phase for about 1.5 cycles. Frequency dropped during the inrush to approximately 59.81Hz and quickly increased to approximately 60.00Hz. Voltage increased as the motor was warming up and eventually settled at a steady state voltage at approximately 273.2V on A-phase, 273.2V on B-phase and 272.7V on C-phase at an approximate frequency of 60.02Hz.

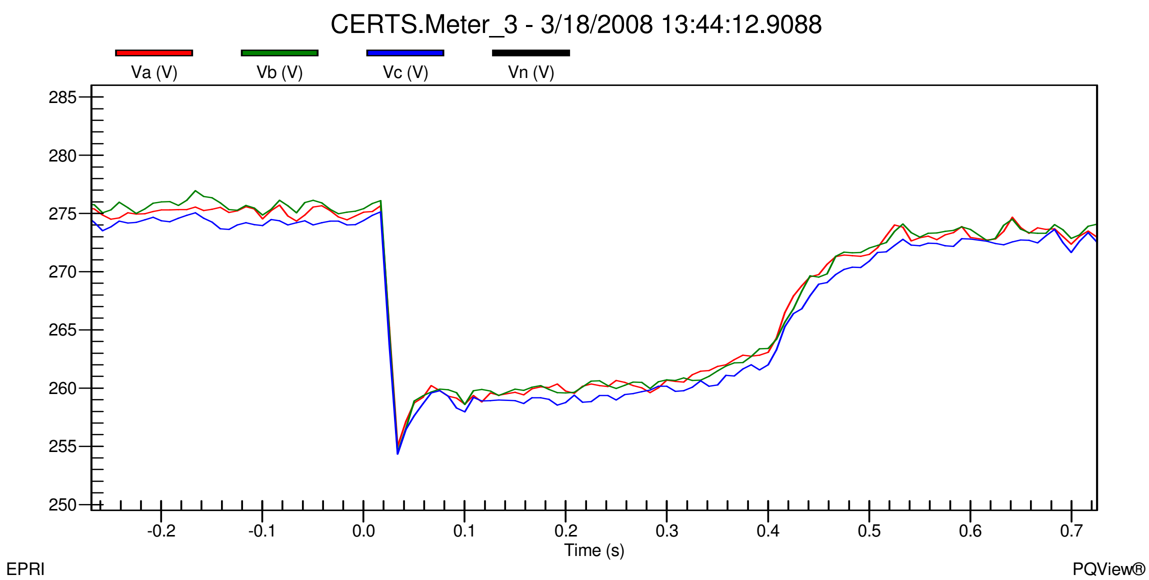

Figure 11k - Meter 3 Line-to-Ground Voltages during Motor Start and Islanded for Test 10.3.12

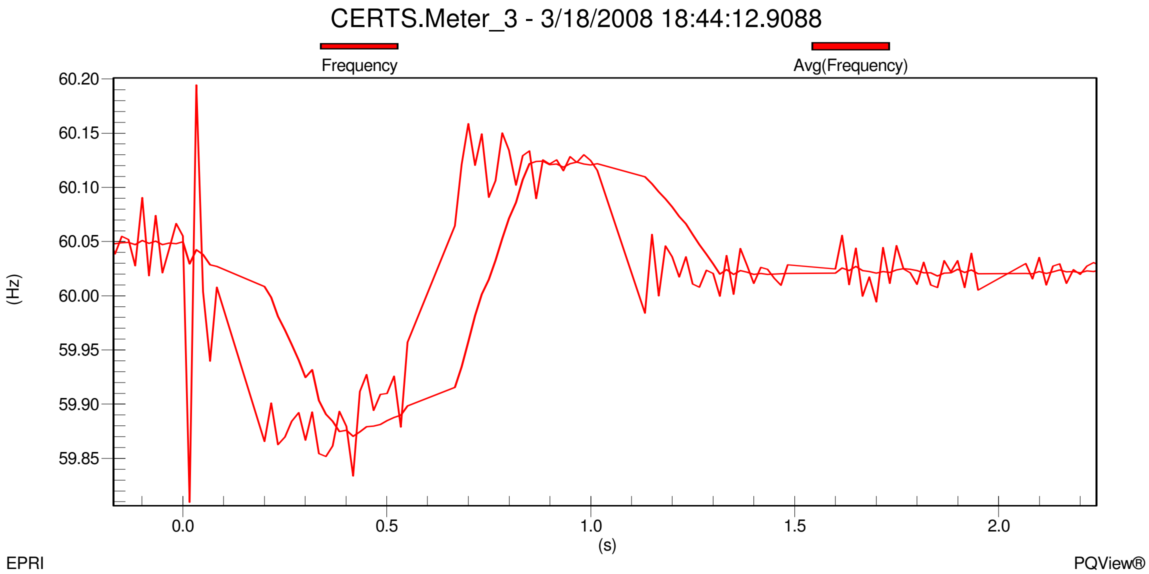

Figure 11l - Meter 3 Frequency during Motor Start and Islanded for Test 10.3.12

Before the motor started Gen-sets A1 and A2 were producing approximately 32kW (A=9.5kW B=11.7kW C=10.8kW) – j2kVAr (A=-1kVAr B=-0.8kVAr C=-0.2kVAr) and 23.5kW (A=6.5kW B=8.5kW C=8.5kW) + j7.1kVAr (A=2.3kVAr B=2.5kVAr C=2.3kVAr), respectively shown in Figures 11m – 11p. The power generated by both Gen-sets was satisfying the loads in Load Banks 3 and 4 and all the electrical losses in the microgrid system. When the motor started the inrush caused the Gen-sets to increase their output levels to 46.1kW (A=16.2kW B=15.8kW C=14.1kW) + j27.6kVAr (A=7.5kVAr B=11kVAr C=9.1kVAr) for Gen-set A1 and 35.4kW (A=10.7kW B=11.5kW C=13.2kW) + j37.8kVAr (A=13.5kVAr B=11.3kVAr C=13kVAr) for Gen-set A2. The Gen-sets decreased their output levels while the motor was warming up and eventually dropped to 35.5kW (A=11kW B=12.6kW C=11.9kW) + j1.3kVAr (A=0kVAr B=0.5kVAr C=0.8kVAr) for Gen-set A1 and 27.5kW (A=7.7kW B=9.9kW C=9.9kW) + j10.3kVAr (A=3.4kVAr B=3.5kVAr C=3.4kVAr) for Gen-set A2 when the motor reached steady state. Once all the data was verified and recorded into the DAS Database, the static switch was directed by the EMS to manually close.

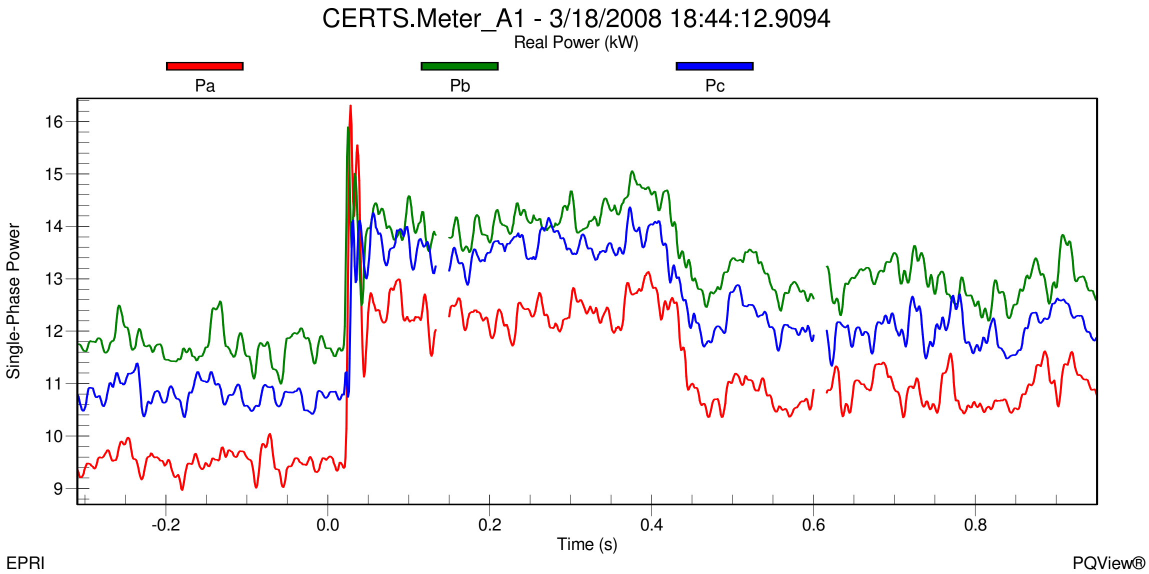

Figure 11m - Gen-set A1 Real Single-Phase Power during Motor Start and Islanded for Test 10.3.12

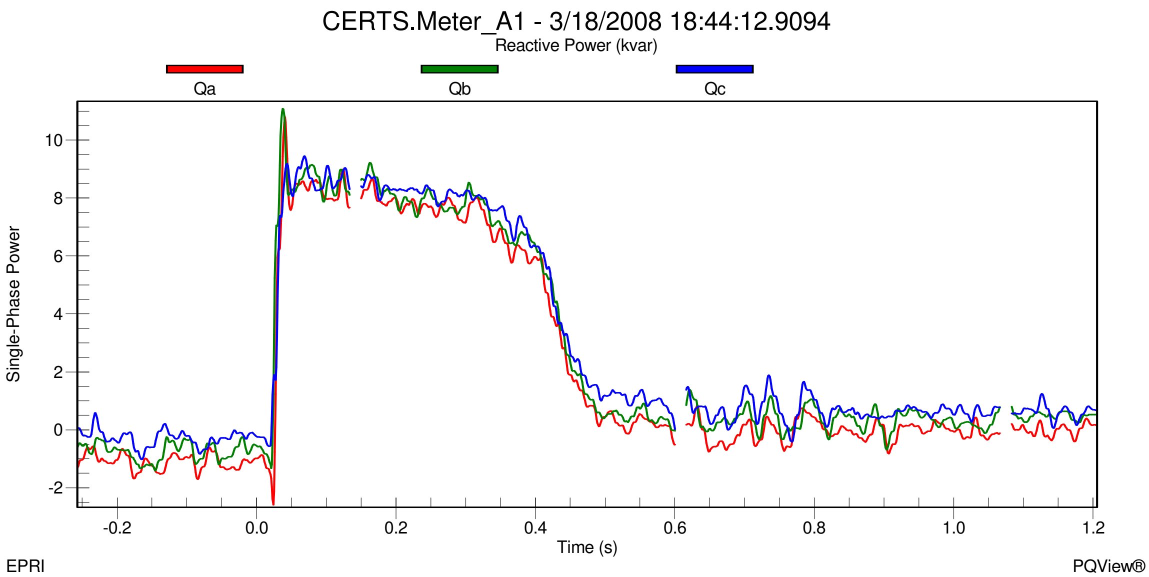

Figure 11n - Gen-set A1 Reactive Single-Phase Power during Motor Start and Islanded for Test 10.3.12

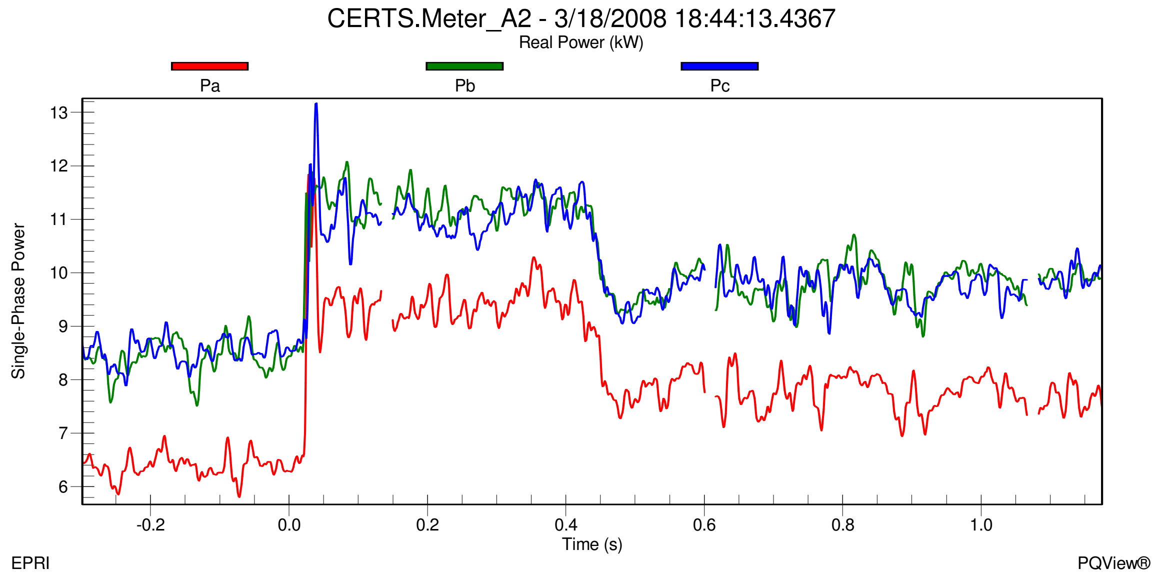

Figure 11o - Gen-set A2 Real Single-Phase Power during Motor Start and Islanded for Test 10.3.12

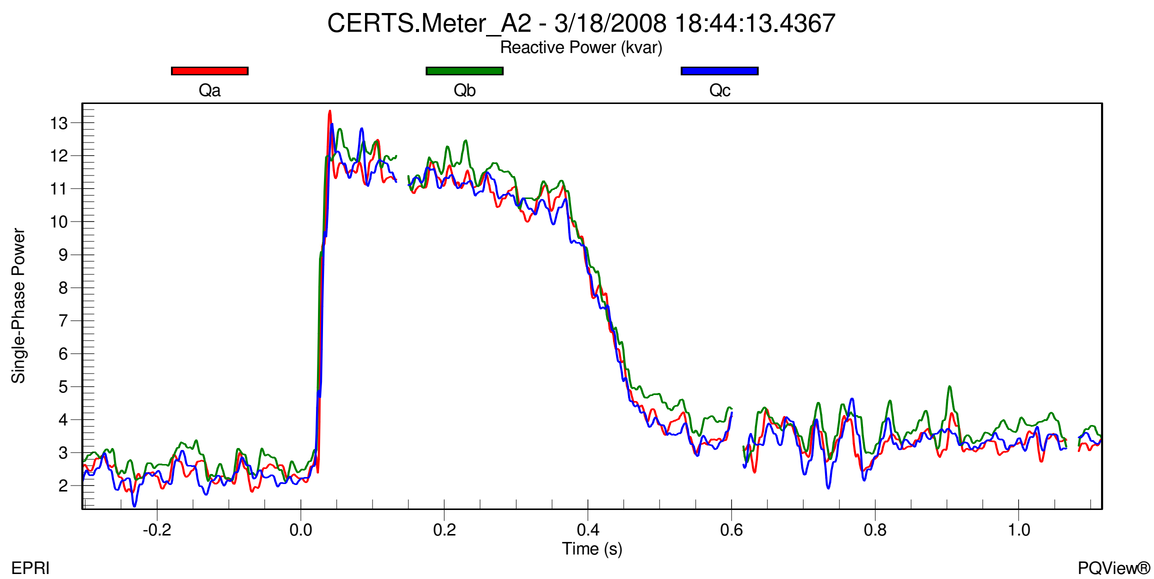

Figure 11p - Gen-set A2 Reactive Single-Phase Power during Motor Start and Islanded for Test 10.3.12

As soon as the static switch closed, Meter 1 recorded real power decreased from approximately 37.7kW (A=10kW B=18kW C=9.7kW) to 33.2kW (A=9.2kW B=12kW C=12kW) and reactive power increased from approximately 0.9kVAr (A=0.2kVAr B=0.5kVAr C=0.2kVAr) to 24kVAr (A=8.7kVAr B=8kVAr C=7.3kVAr) which means that the utility was satisfying a portion of the load demand in Load Bank 6 and all the reactive power in the microgrid. Figures 11q and 11r show the static switch decreasing in real power from approximately 0kW (A=0kW B=0kW C=0kW) to -3.7kW (A=-0.5kW B=-5.6kW C=2.4kW) and increasing in reactive power from approximately 0kVAr

(A=0kVAr B=0kVAr C=0kVAr) to 23.3kVAr (A=8.6kVAr B=7.6kVAr C=7.3kVAr). At the beginning of the test, the initial power flow through the static switch was -7.8kW (A=-2kW B=-7kW C=1.2kW) + j22.4kVAr (A=8.7kVAr B=7kVAr C=6.7kVAr) which is not the same recorded at this point in the test because the 10Hp motor load is on in Zone 3. The Gen-sets have picked up the motor load and supporting Load Bank 6 with approximately 3.7kW.

Load Banks 3 and 4 loads increased slightly to 24.8kW (A=8.45kW B=8.2kW C=8.15kW) + j6.34kVAr (A=2.17kVAr B=2.17kVAr C=2kVAr) and 36.4kW (A=9.7kW B=13.4kW C=13.3kW) + j0.61kVAr (A=0.12kVAr B=0.28kVAr C=0.21kVAr), respectively. This slight load increase is a result from a voltage rise in the microgrid, shown in Figure 11s, from approximately 273.6V on A-phase, 273.6V on B-phase and 272.5V on C-phase when islanded to 281V on A-phase, 278.1V on B-phase and 277.9V on C-phase at Meter 3 when connected to the utility grid.

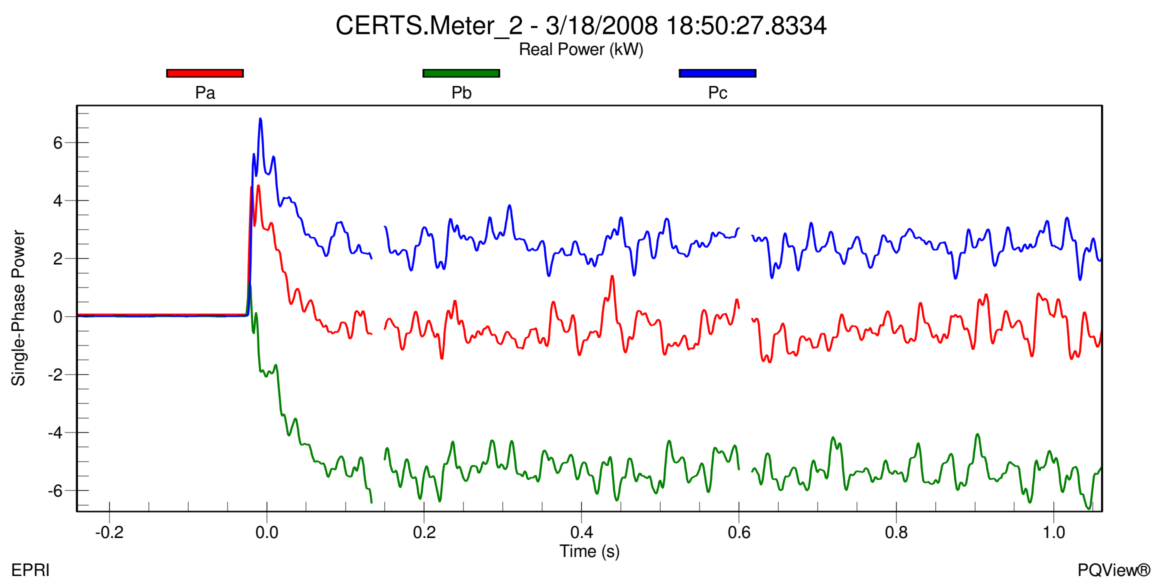

Figure 11q - Static Switch Real Single-Phase Power during Island to Utility Connected mode for Test 10.3.12

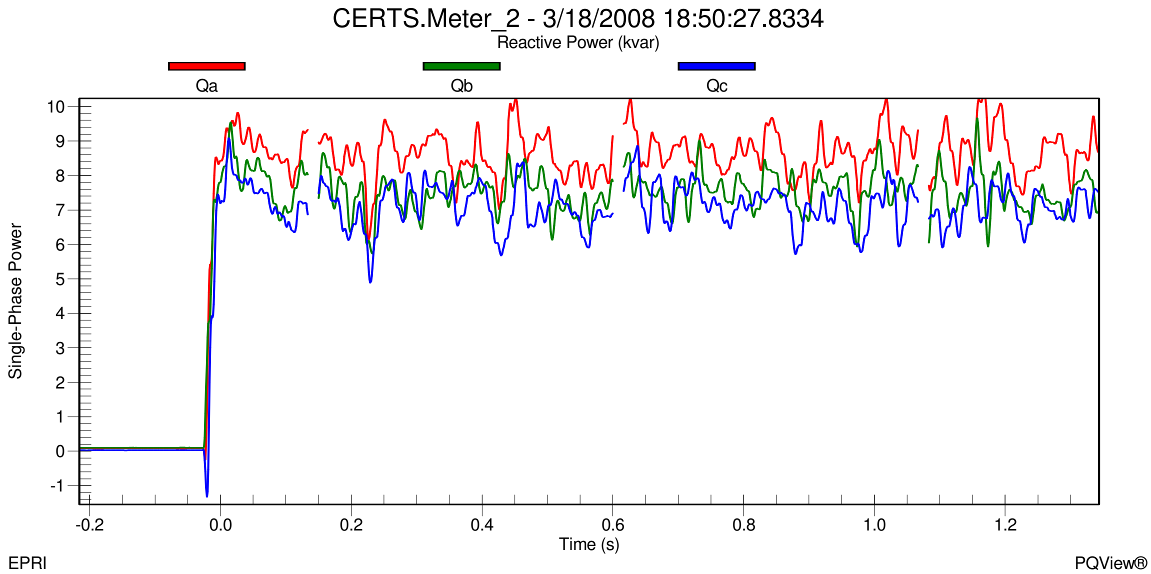

Figure 11r - Static Switch Reactive Single-Phase Power during Island to Utility Connected mode for Test 10.3.12

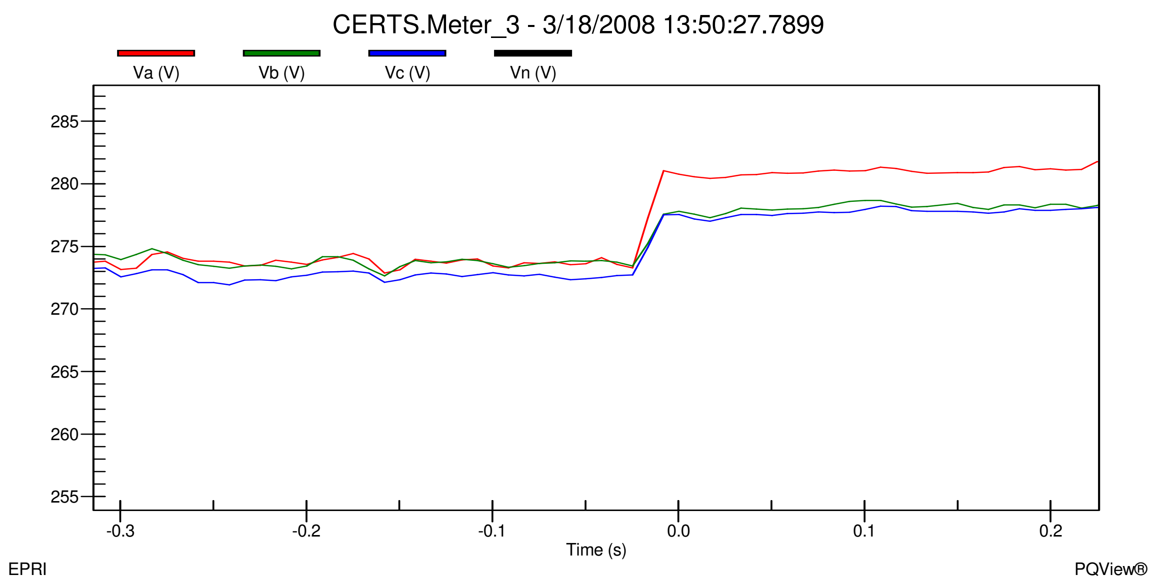

Figure 11s - Meter 3 Line-to-Ground Voltage during Island to Utility Connected mode for Test 10.3.12