Arnold Schwarzenegger
Governor

CERTS MICROGRID LABORATORY TEST BED

Test Plan Section 7.0 Validate Protection Settings and Initial Fault Testing

APPENDIX J

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CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

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CERTS MICROGRID TEST REPORT

SECTION 7.0

"Validate Protection Settings and Initial Fault Testing"

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1.0 INTRODUCTION

A series of tests were performed on the CERTS Microgrid by American Electric Power at the Walnut test site in Groveport, Ohio with support from Lawrence Berkeley National laboratory, Sandia National Laboratory, TECOGEN, The Switch (originally Youtility), Distributed-Energy (originally Northern Power) and University of Wisconsin. These tests were designed to demonstrate the CERTS Microgrid concepts of control and protection while connected to the utility electrical system and isolated (i.e., referred to as "islanded" from it. This paper describes the tests that were performed in Section 7.0 "Validate Protection Settings & Initial Fault Testing" 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.

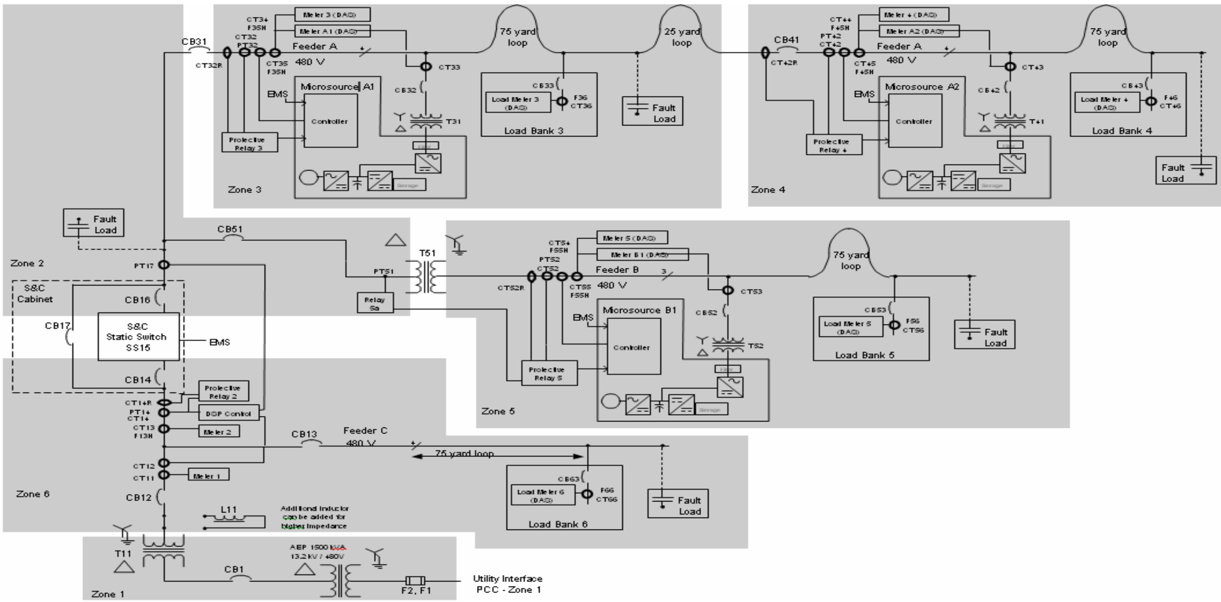

Figure 2 - One Line Diagram of CERTS Microgrid Test Bed

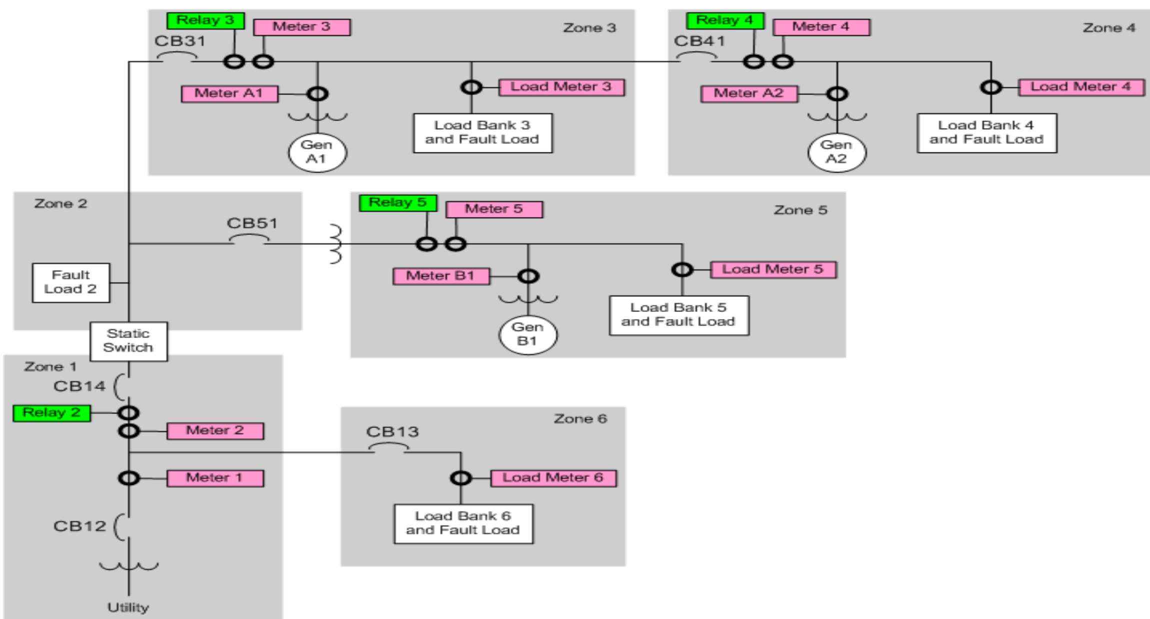

Figure 3 - Simplified diagram of Test Bed showing Meter and Relay locations

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.

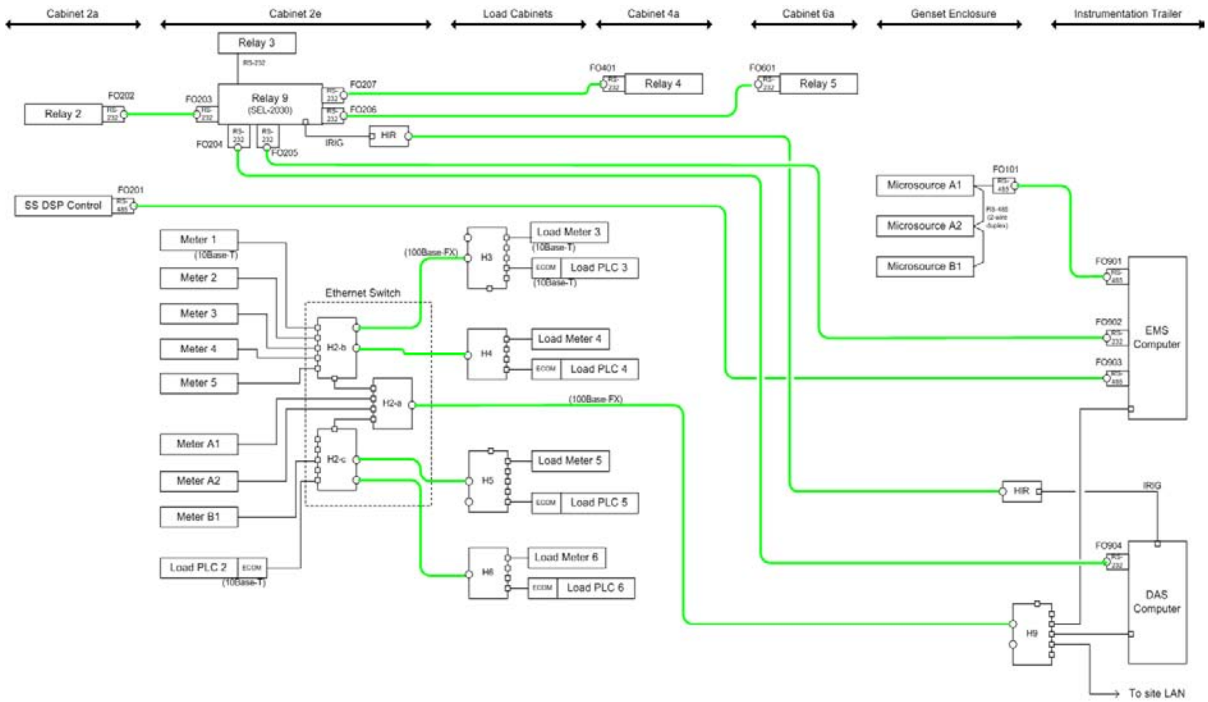

Figure 4 - Diagram of DAS & EMS Data networks

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 PROPOSED TEST PLAN

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

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

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

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

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

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

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

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

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

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

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

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

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

5.0 <u>TESTS PERFORMED IN SECTION 7.0</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 7 was the next set of tests that were developed to demonstrate the CERTS Microgrid protection scheme while connected to the grid and islanded under different overload fault conditions. During each overload fault test event, waveforms of phase currents and line-to-neutral voltages were recorded in DAS at all meter locations and at all relay locations (i.e., Relays 2, 3, 4, & 5). In addition, the relay element that caused the "TRIP" was recorded with trip times for each relay relative to when the fault condition was applied. Tests performed in this section included inductor L11 in the circuit, reflecting weak utility grid conditions.

Test 7.1 induced a three-phase-to-ground balanced overload fault condition in Zone 4 to verify the I^2t protection and a single line-to-ground fault condition in Zone 4 to verify zero-sequence, negative-sequence or residual over-current protection. Zone 3 and Zone 5 were tested similar to Zone 4 by introducing a three-phase-to-ground balanced overload fault and a single line-to-ground fault conditions in the zones, verifying the protection scheme in Test 7.2 (Zone 3) and Test 7.3 (Zone 5). During the 7.1, 7.2 and 7.3 tests, all three Gen-sets were off-line and the CERTS Microgrid was connected to the utility. Test 7.4 tested a three-phase-to-ground balanced overload fault condition in Zone 4 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify I^2t protection, plus to confirm a reverse power event after the zone breaker "opens".

Test 7.5 through Test 7.10 involved applying a single line-to-ground overload fault condition in each Zone, located beyond the static switch, while connected to the utility grid. Each one of the six tests differs from one another by which Gen-sets are on-line during the fault, which phase is faulted, and in which zone the fault is applied. These tests were designed to verify zero-sequence, negative-sequence or residual over-current protection settings. Test 7.5 verified the protection in Zone 3 by applying a single line-to-ground overload fault condition with Gen-sets A1 operating in parallel with the utility grid. Test 7.6 tested a single line-to-ground overload fault condition in Zone 3 with Gen-sets A1 and A2 operating in parallel with the utility grid. Test 7.7 tested a single line-to-ground overload fault condition in Zone 5 with Gen-set B1 operating in parallel with the utility grid. Test 7.8 tested a single line-to-ground overload fault condition in Zone 5 with Gen-sets A1 and B1 operating in parallel with the utility grid. Test 7.9 tested a single line-to-ground overload fault condition in Zone 4 with Gen-sets

A1 and A2 operating in parallel with the utility grid. Test 7.10 tested a single line-to-ground overload fault condition in Zone 2 with Gen-sets A1 and B1 operating in parallel with the utility grid.

Tests 7.11 and 7.12 both applied a single line-to-ground overload fault condition in Zone 6 while connected to the utility. Test 7.11 involved only Gen-set A1 operating in parallel with the grid; and Test 7.12 involved Gen-sets A1 and B1 operating in-parallel with the grid. Both tests were designed to verify the I^2t protection of the breaker in Zone 6.

The four tests, 7.13 – 7.16, applied a line-to-line overload fault condition in one of the five zones beyond the static switch with a combination of two Gen-sets, operating in parallel with the utility grid. These tests were designed to test negative-sequence, I^2t protection or residual over-current protection settings. Test 7.13 tested a phase-to-phase overload fault condition in Zone 3 with Gen-sets A1 and A2 operating in parallel with the utility grid. Test 7.14 tested a phase-to-phase overload fault condition in Zone 4 with Gen-sets A1 and A2 operating in parallel with the utility grid. Test 7.15 tested a phase-to-phase overload fault condition in Zone 2 with Gen-sets A1 and B1 operating in-parallel with the utility grid. Test 7.16 tested a phase-to-phase overload fault condition in Zone 5 with Gen-sets A1 and B1 operating in parallel with the utility grid.

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

6.1 <u>SECTION 7 – VALIDATE PROTECTION SETTINGS & INITIAL FAULT TESTING</u>

6.1.1 <u>Zone 4 Circuit Breaker Settings and Utility Connected</u>

Performance Goal:

Initially test a three-phase-to-ground balanced overload fault in Zone 4 to verify I^2t protection. Then test a single line-to-ground fault condition in Zone 4 to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Relay Settings = A (Delayed)

Load Bank 4 = 60kW

Load Bank 6 = 10kW

To simulate a high impedance three-phase-to-ground fault in Zone 4, the

Overload Load Bank of 85kW was connected by cable/plug into the exterior receptacle of Cabinet 5a. This would add an additional 85kW to Zone 4 when initiated, causing an overload because the load is currently set at 60kW from Load Bank 4.

After the dead-bus closing of the static switch from the EMS, the Microgrid Test

Bed was connected to the utility grid with approximately 55kW at Meter 2**.** A simulated fault (i.e., Overload Load Bank of 85kW) with a duration set for 99 seconds was initiated to Zone 4 from the DAS Load Control Program. Figure 10a shows when the overload bank was initiated and the load in Zone 4 increased from approximately 55kW to 130kW.

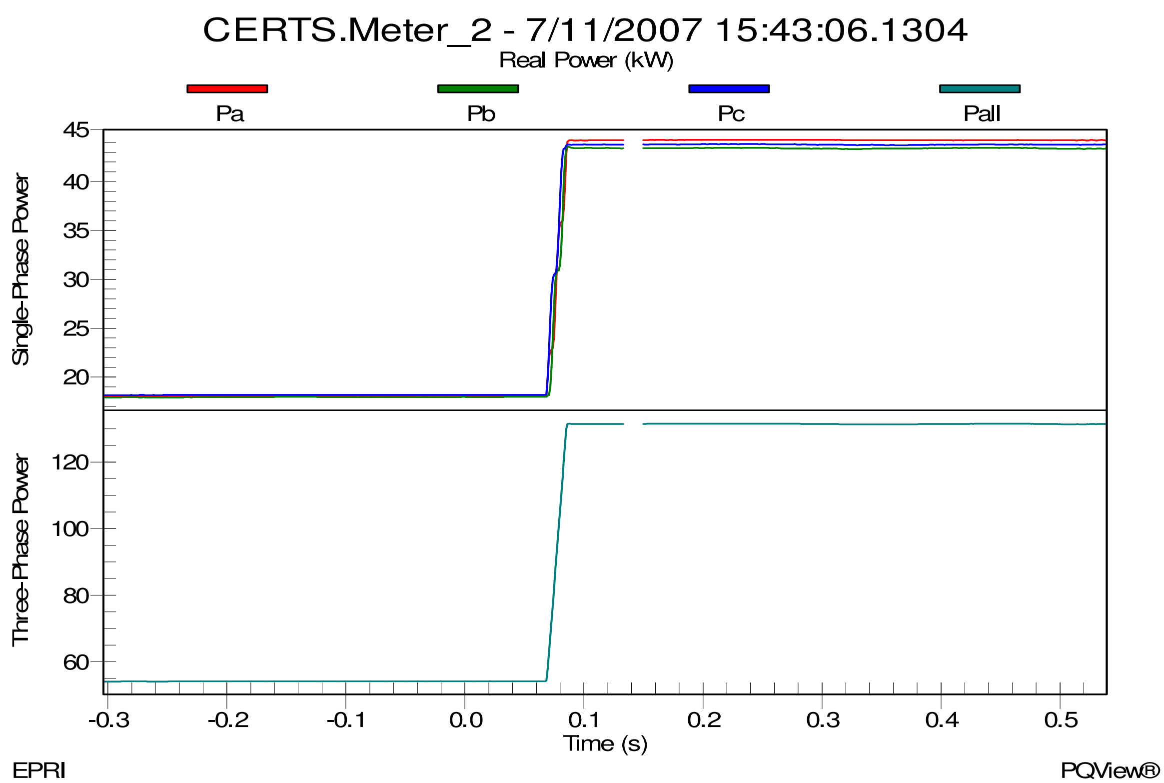

Figure 10a - Load in Zone 4 when the overload fault is initiated

When the load increased in Zone 4, CB41 internally detected an I^2t protection event and opened after 71.3 seconds, clearing the fault from Zone 4, shown in Figure 10b.

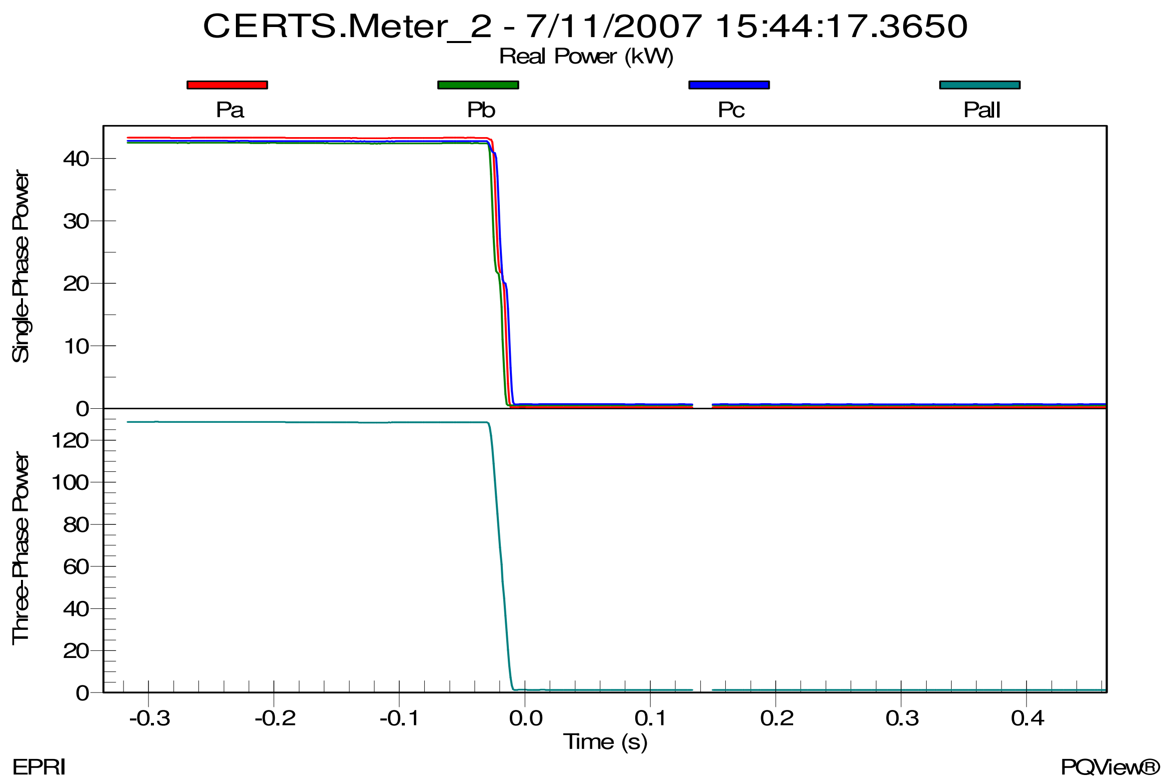

Figure 10b - Load in Zone 4 after circuit breaker CB41 "Opens" to isolate and clear the fault

The static switch, nor any of the other breakers, opened up at the time the fault was initiated. The main purpose of this test was designed for CB41 to isolate the fault and then clear it.

Once the fault was cleared and all the alarms and circuit breakers were reset and brought back to the initial setup, the Overload Load Bank in Cabinet 5A was reconfigured from a three-phase-to-ground fault into a single phase-to-ground fault. This was accomplished by removing phases B and C from the Overload Load Bank cabling which leaves approximately 28.3kW on A-phase when the fault is initiated.

After the dead-bus closing of the static switch from the EMS, the Microgrid Test

Bed was connected to the utility grid with approximately 51kW at Meter 2**.** A simulated overload fault (i.e., Overload Load Bank of 28.3kW on A-phase) with a duration set for 10 seconds was initiated to Zone 4 from the DAS Load Control Program. Figure 10d shows when the overload bank was initiated and load in Zone 4 increased from approximately 52kW to 75kW three-phase power and approximately 17.5kW to 41kW on A-phase. Also in Figure 10d, you can see where the fault is cleared and the load is reduced to 0kW.

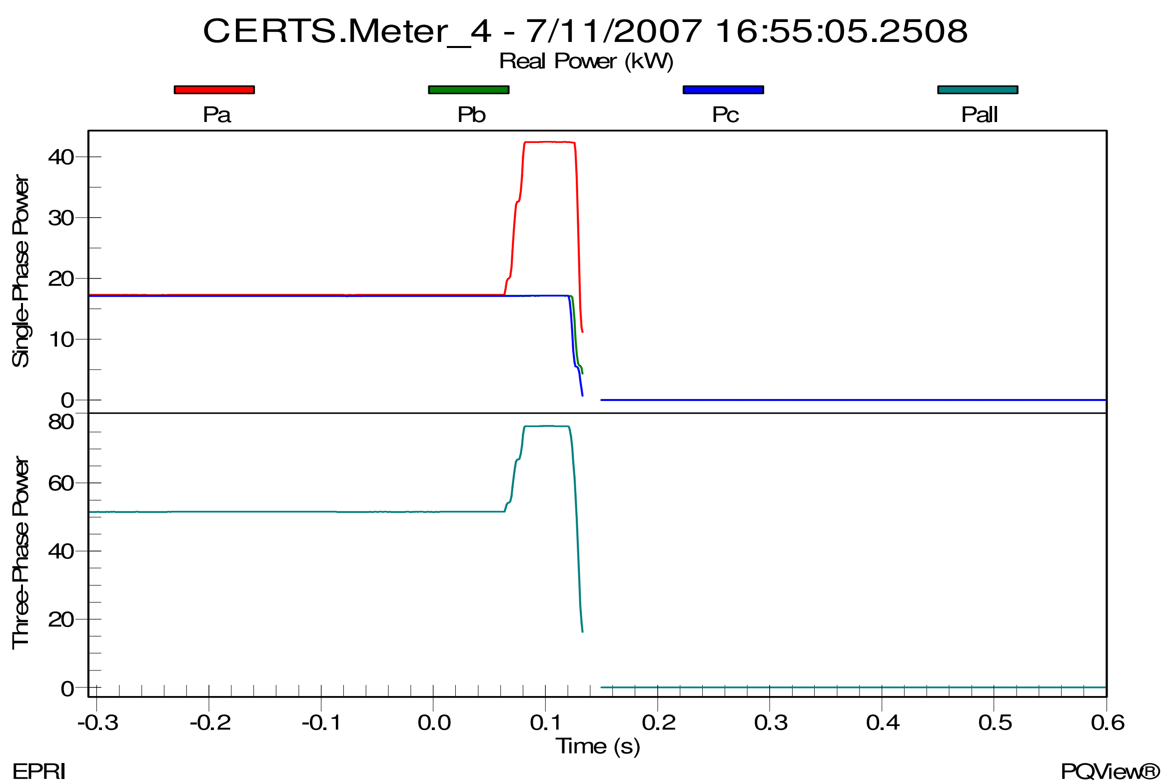

Figure 10d - Load in Zone 4 before/after the single phase-to-ground fault is applied

It's important to note that all four protection relays (i.e., relays 2 through 5) have residual CT's wired to the neutral input of the relay. Thus, any neutral current measurements are actually measurements of ground current.

When the load increased in Zone 4, the static switch (i.e., Relay 2) detected a ground over-current (67N1T), shown in Figure 10e. The static switch opened after 0.023 seconds (1.5 cycles) clearing the fault from Zone 4, shown in Figures 10d and 10e.

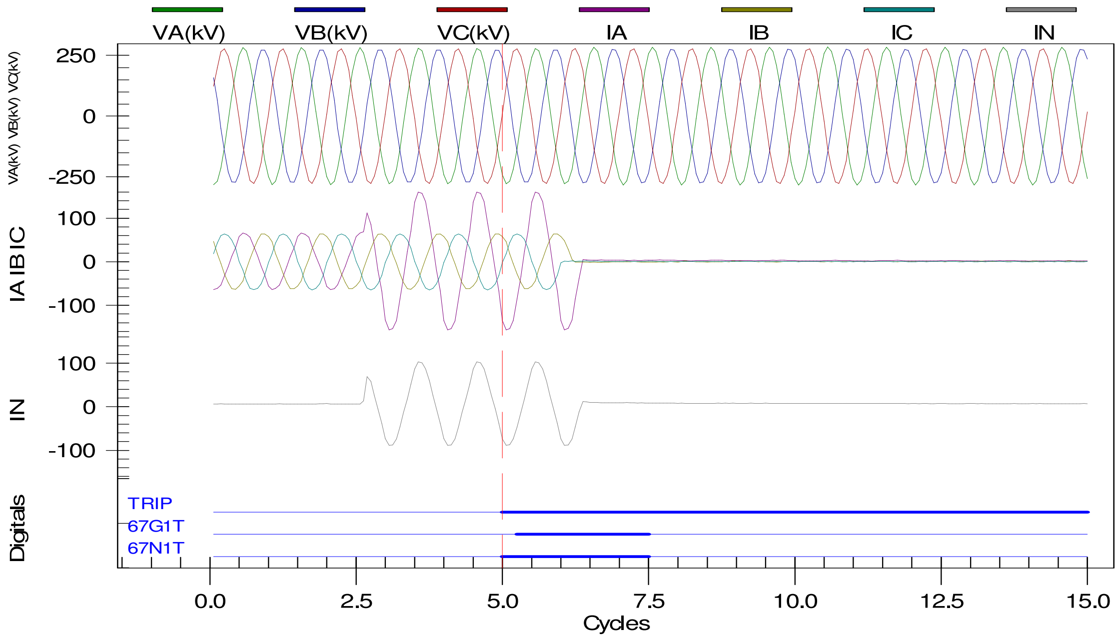

Figure 10e - Voltages, Currents, and Ground Current (IN) at Relay 2 when the fault is detected and cleared by the static switch.

After the static switch opened, the breakers in protection zones (i.e., CB31 in Zone 3, CB41 in Zone 4 and CB51 in Zone 5) remained closed. This was expected since the fault was isolated and cleared by the static switch.

The electrical system was stable in both the microgrid and utility grid, after CB41 opened for the three-phase-to-ground fault. In addition the static switch opened for a single phase-to-ground fault condition in Zone 4, separating the microgrid from the utility system. All loads and alarms were reset and equipment was prepared for the next test.

6.1.2 <u>Zone 3 Circuit Breaker Settings and Utility Connected</u>

Performance Goal:

Initially test a three-phase-to-ground balanced overload fault condition in Zone 3 to verify I^2t protection. Then test a single line-to-ground fault condition in Zone 3 to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Relay Settings = A (Delayed)

Load Bank 3 = 75kW

Load Bank 4 = 75kW

Load Bank 6 = 10kW

To simulate a high impedance three-phase-to-ground fault in Zone 3, the

Overload load Bank of 85kW was connected by cable/plug into the exterior receptacle of Cabinet 3a. This additional 85kW of load in Zone 3 when initiated would cause an overload in Zone 3, because load is currently set at 75kW in Load Bank 3 and in Load Bank 4.

After the dead-bus closing of the static switch from the EMS, the Microgrid Test

Bed was connected to the utility grid with approximately 140kW at Meter 2. A simulated fault (i.e., Overload Load Bank of 85kW) with a duration set for 99 seconds was initiated to Zone 3 from the DAS Load Control Program. Figure 11a shows when the overload bank was initiated and load in Zone 3 increased from approximately 140kW to 220kW.

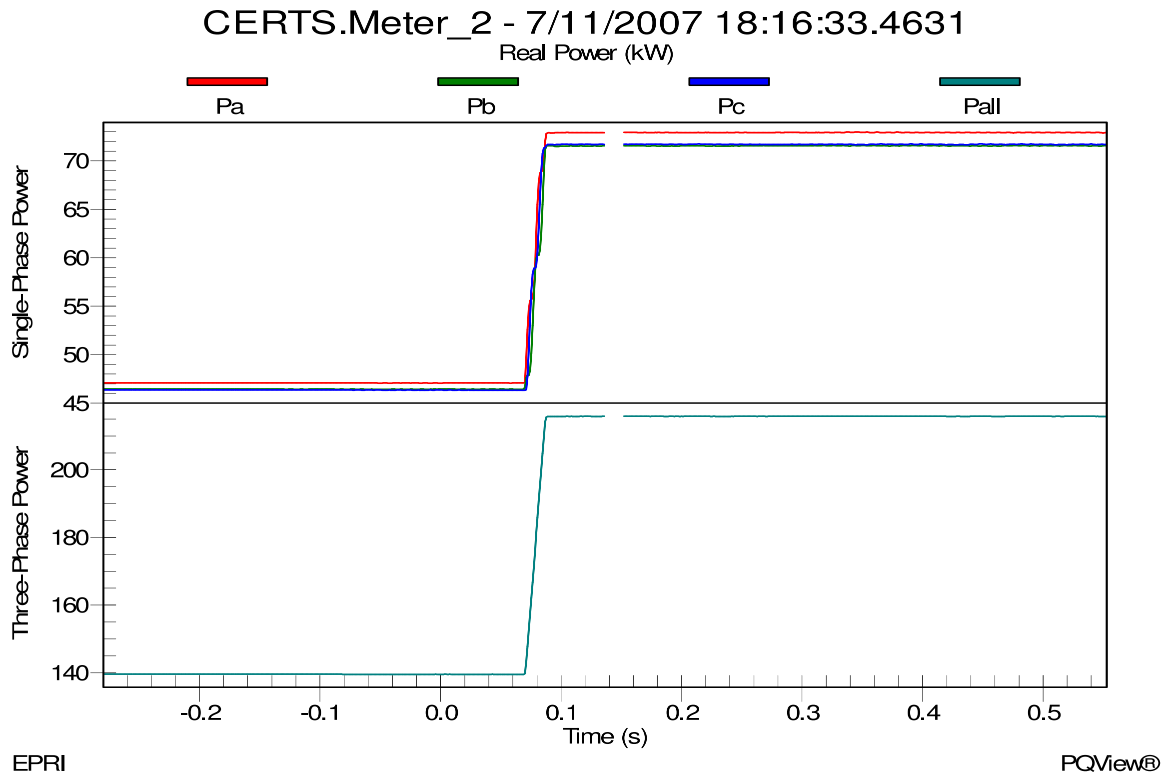

Figure 11a – Load change due to Zone 3 when the overload fault was initiated

When the load increased in Zone 3, CB31 internally detected an I^2t protection event and opened after 84 seconds, clearing the fault from Zone 3, as shown in Figure 11b.

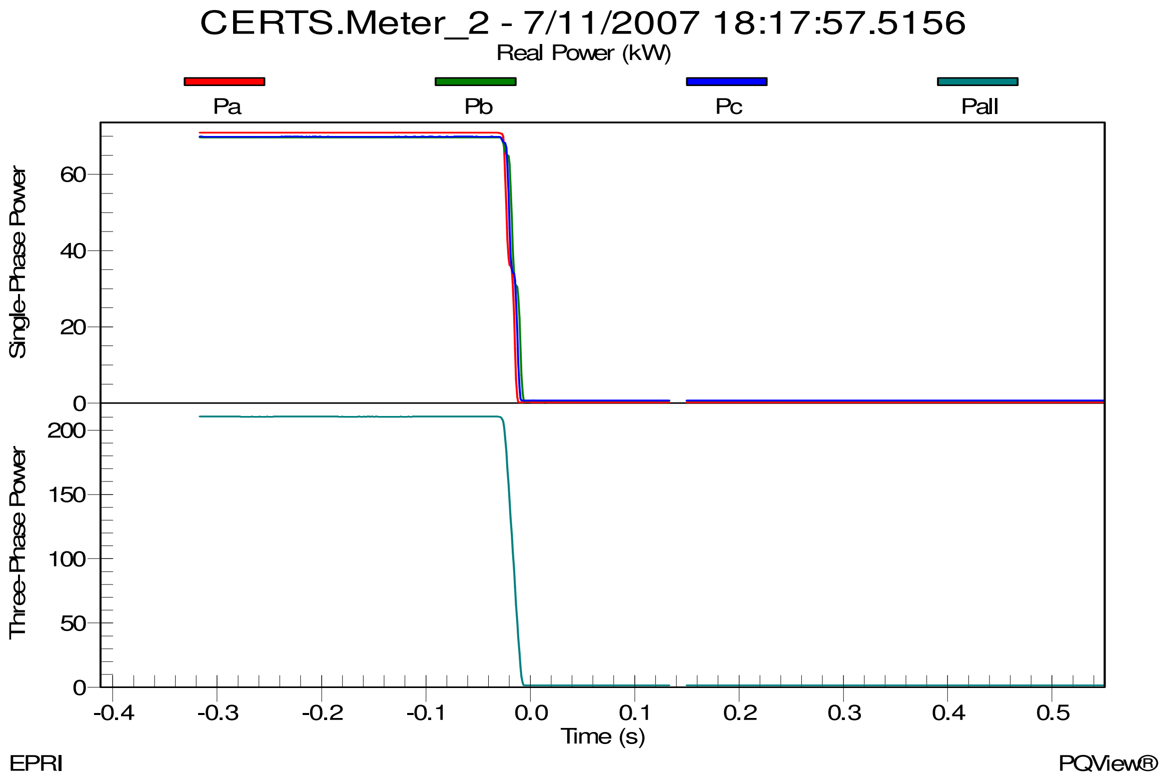

Figure 11b - Load change in Zone 3 after CB31 opened" to isolate and clear the fault

The static switch, nor any of the other breakers, opened at the time when the fault was initiated. The main purpose of this test was designed for CB31 to isolate the fault in Zone 3 and then clear it.

Once the fault was cleared, all alarms and circuit breakers were reset and brought back to the initial setup. In addition, the load in Load Bank 3 and in Load Bank 4 was reset to 60kW. The Overload Load Bank in Cabinet 3 was reconfigured from a three-phase-to-ground fault into a single phase-to-ground fault. This was accomplished by removing phases A and C from the Overload Load Bank cabling which leaves approximately 28.3kW on B-phase when the fault is initiated.

After the dead-bus closing of the static switch from the EMS, the Microgrid Test

Bed was connected to the utility grid with approximately 111kW at Meter 2. A simulated fault (i.e., Overload Load Bank of 28.3kW on B-phase) with a duration set for

10 seconds was initiated to Zone 3 from the DAS Load Control Program. Figure 11c shows when the overload bank was initiated and load in Zone 3 increased from approximately 111kW to 133kW three-phase power and approximately 35kW to 60kW on B-phase. Also, Figure 11c, shows where the fault is cleared and load is reduced to 0kW.

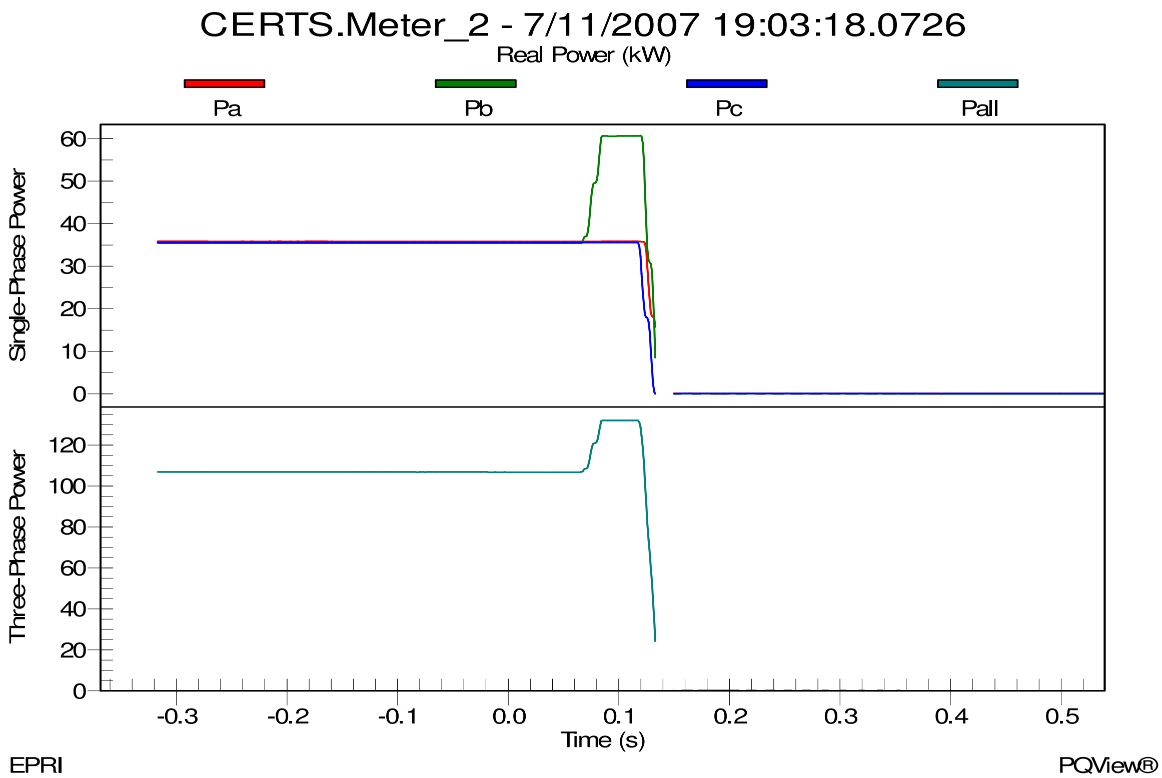

Figure 11c - Load change before/after the single phase-to-ground fault was applied in Zone 3.

When load increased in Zone 3, the static switch (Relay 2) detected a ground over-current (67N1T) shown in Figure 11d. The static switch then "Opens" after 0.016 seconds (1 cycle) clearing the fault from Zone 3 shown in Figures 11c and 11d.

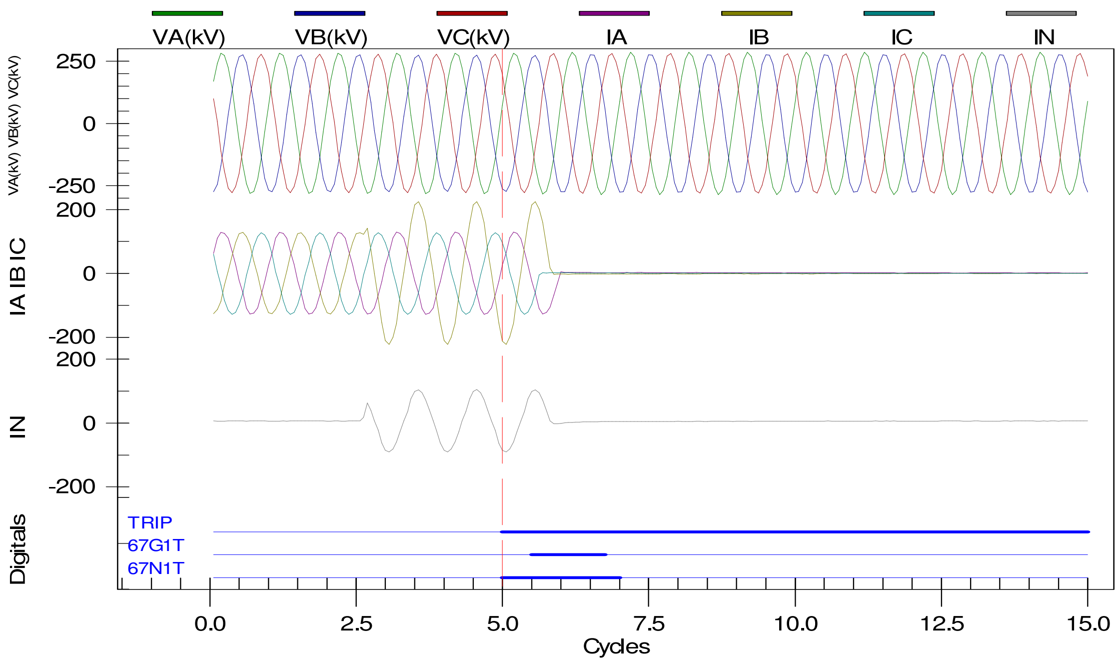

Figure 11d - Voltages, Currents, and Ground current (IN) at Relay 2 when the fault is detected and cleared by the static switch

After the static switch opened, the breakers in the protection zones (i.e., CB31 in Zone 3, CB41 in Zone 4 and CB51 in Zone 5) remained closed. This was expected, since the fault was isolated and cleared by the static switch.

The electrical system was stable in both the microgrid and utility grid, after circuit breaker CB31 opened for the three-phase-to-ground overload fault. In addition, the static switch opened for a single phase-to-ground fault condition in Zone 3, separating the microgrid from the utility system. All loads and alarms were reset and equipment was prepared for the next test.

6.1.3 <u>Zone 5 Circuit Breaker Settings and Utility Connected</u>

Performance Goal:

Initially test a three-phase-to-ground balanced overload fault condition in Zone 5 to verify I^2t protection. Then test a single line-to-ground fault condition in Zone 5 to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Relay Settings = A (Delayed)

Load Bank 5 = 60kW

To simulate a high impedance three-phase-to-ground fault in Zone 5, the

Overload Load Bank of 85kW was connected by cable/plug into the exterior receptacle of Cabinet 7a. This additional 85kW of load in Zone 5 when combined with the 60kW in Load Bank 5 causes an overload condition.

After the dead-bus closing of the static switch from the EMS, the Microgrid Test

Bed was connected to the utility grid with approximately 55kW at Meter 2**.** A simulated fault (i.e., Overload Load Bank of 85kW) with the duration set for 99 seconds was initiated in Zone 5 from the DAS Load Control Program. Figure 12a shows when the overload bank was initiated and load in Zone 5 increased from approximately 55kW to 130kW.

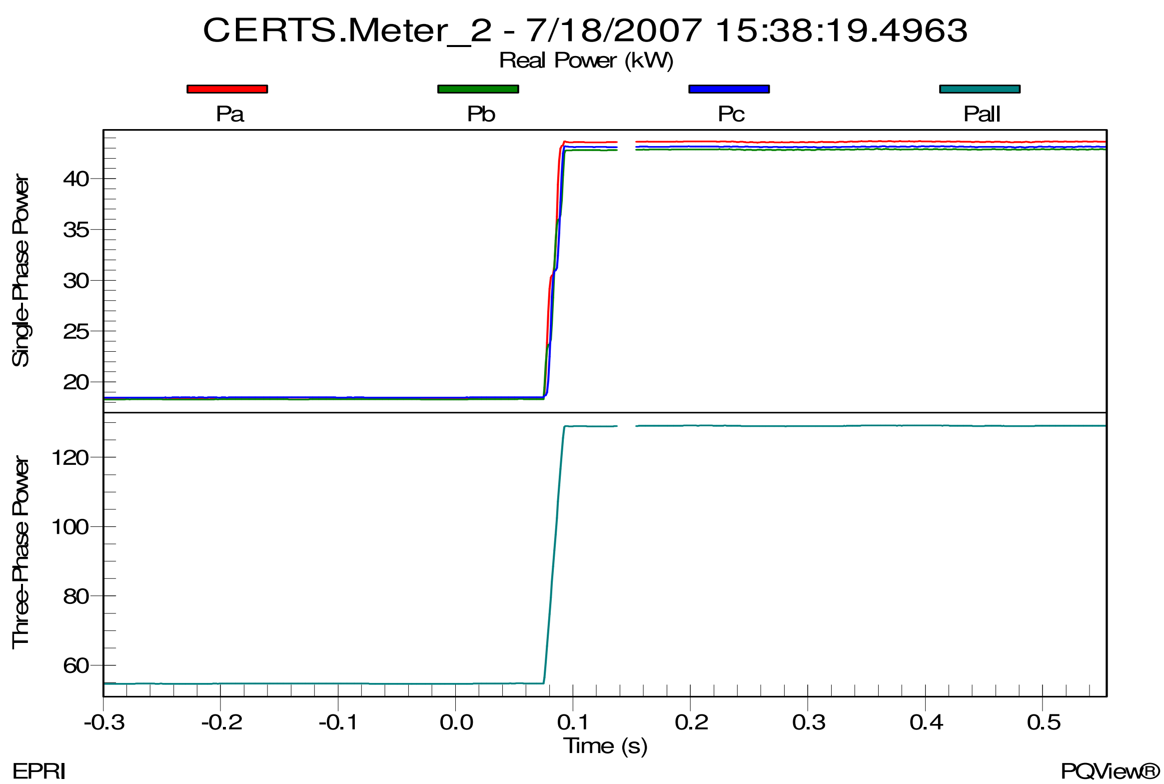

Figure 12a - Load change when the overload fault was initiated in Zone 5.

When the load increased in Zone 5, CB51 internally detected an I^2t protection event and opened after 72.8 seconds, clearing the fault from Zone 5, as shown in Figure 12b.

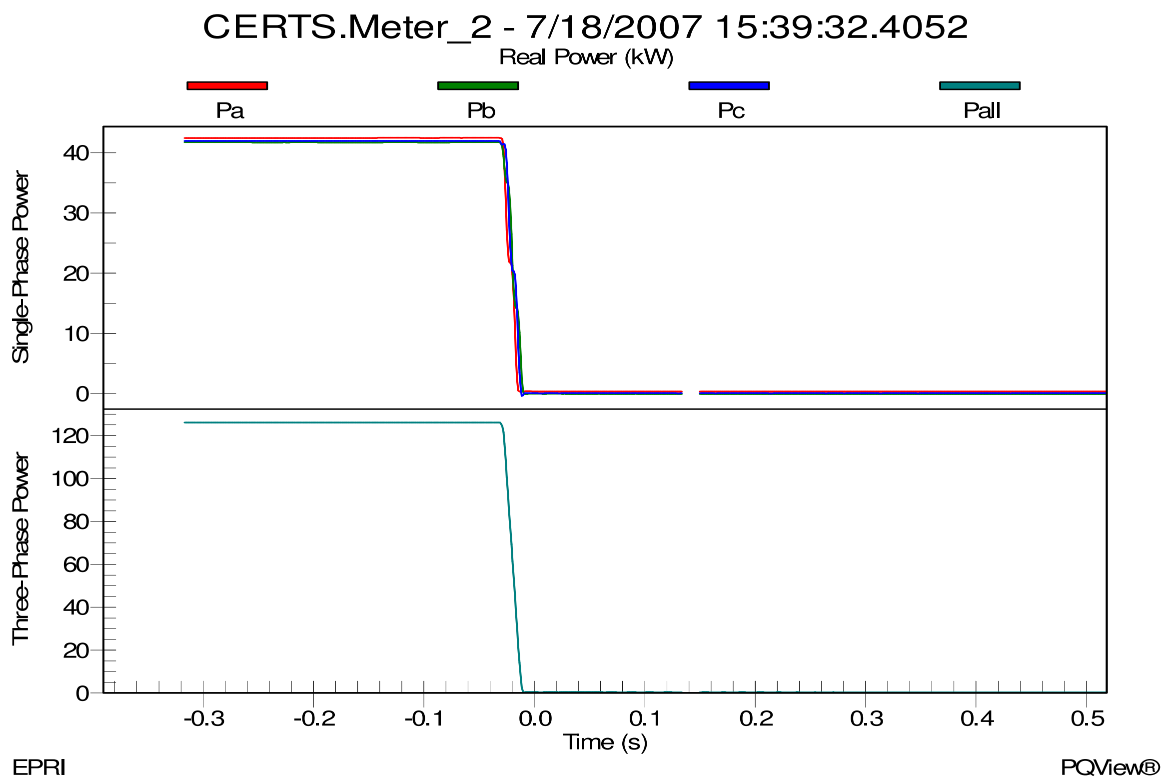

Figure 12b - Load change before/after CB51 opened to isolate and clear the fault in Zone 5.

The static switch, nor any of the other breakers, opened at the time the fault was initiated. The main purpose of this test was designed for CB51 to isolate the fault in Zone 5 and then clear it.

Once the fault was cleared and all the alarms and circuit breakers were reset and brought back to the initial setup, the Overload Load Bank in Cabinet 7a was reconfigured from a three-phase-to-ground fault into a single phase-to-ground fault. This was accomplished by removing phases A and B from the Overload Load Bank cabling which leaves approximately 28.3kW on the C-phase when the fault is initiated.

After the dead-bus closing of the static switch from the EMS, the Microgrid Test

Bed was connected to the utility grid with approximately 54kW at Meter 2**.** A simulated fault (i.e., Overload Load Bank of 28.3kW on C-phase) with a duration set for 10 seconds was initiated to Zone 5 from the DAS Load Control Program. Figure 12c shows when the overload bank was initiated and the load in Zone 5 increased from approximately 51kW to 74kW three-phase power and approximately 16.5kW to 40kW on C-phase. Also, Figure 12ce, shows where the fault is cleared and the load is reduced to 0kW.

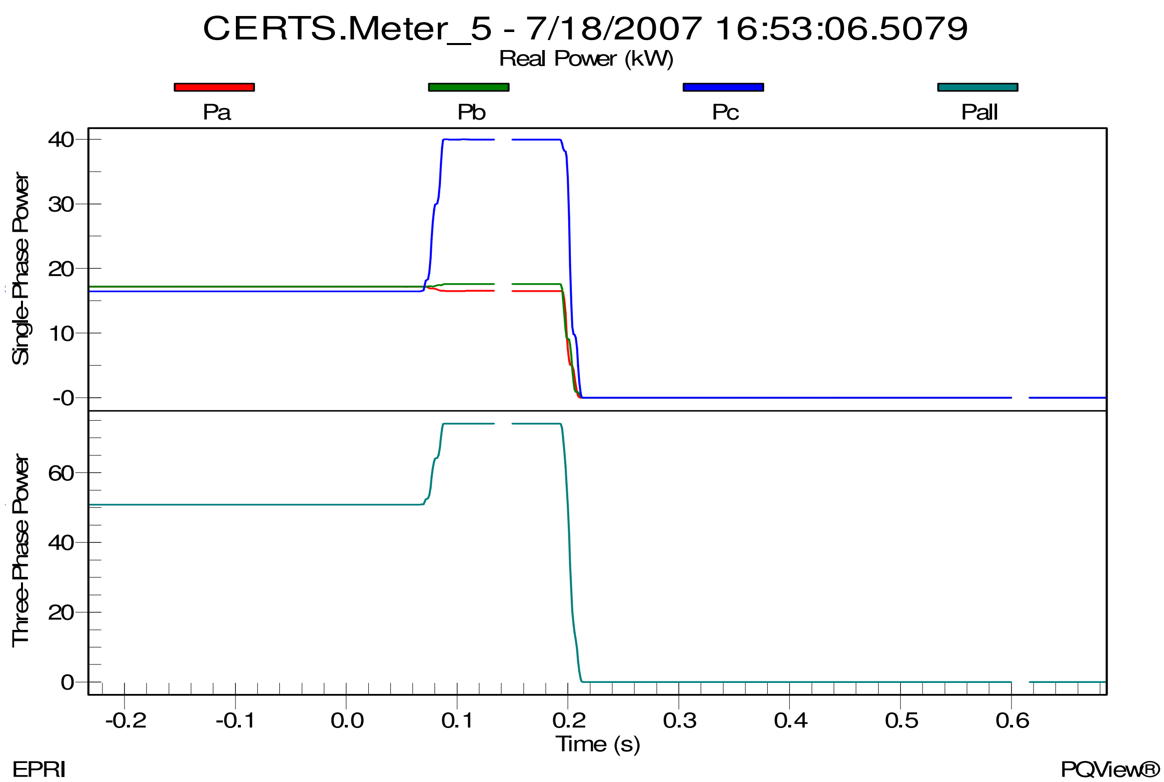

Figure 12c - Load in Zone 5 before/after the single phase-to-ground fault was applied.

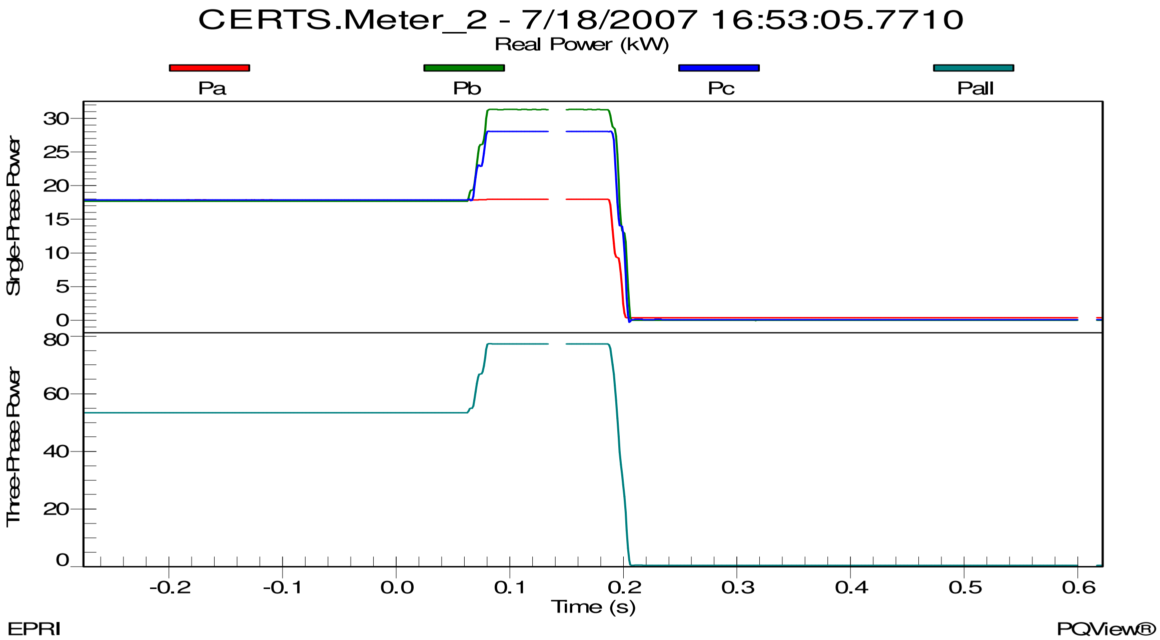

Figure 12d - Load change before/after the single phase-to-ground fault was applied in Zone 5.

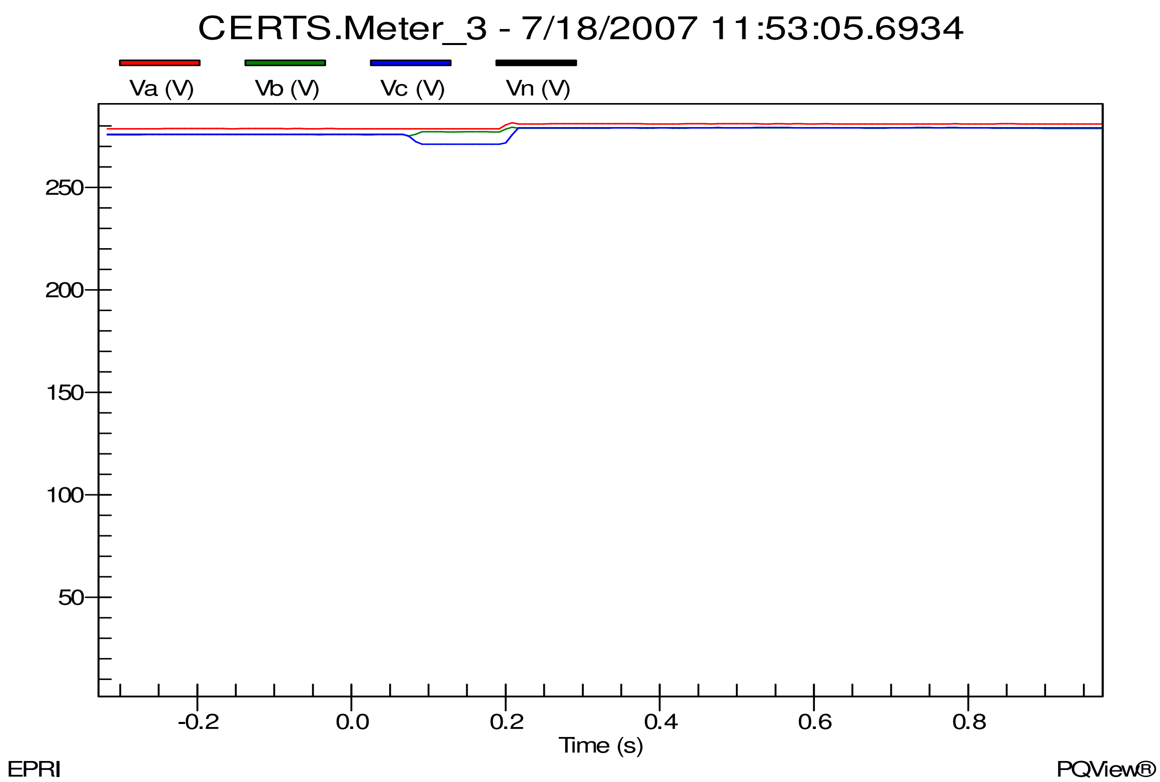

Figure 12e – RMS Voltage in Zone 3 before/after the single phase-to-ground fault was applied

From Figure 12d it can be seen at the static switch that the phase C real power appears reduced in magnitude and distributed over both phases B and C. This reduces the sensitivity of the static switch to this type of fault in Zone 5. From Figure 12e it is apparent that the static switch did not operate, since the RMS voltage never collapsed.

When the load increased in Zone 5, Relay 5 detected a negative-sequence over-current (67Q1T) event, shown in Figure 12f. CB51 opened and cleared the fault from Zone 5 shown in Figure 12f. The opening of CB51 was past the end of the recorded relay waveform, but it can be seen that the real power at Meter 5 reduces to zero, shown in Figure 12c.

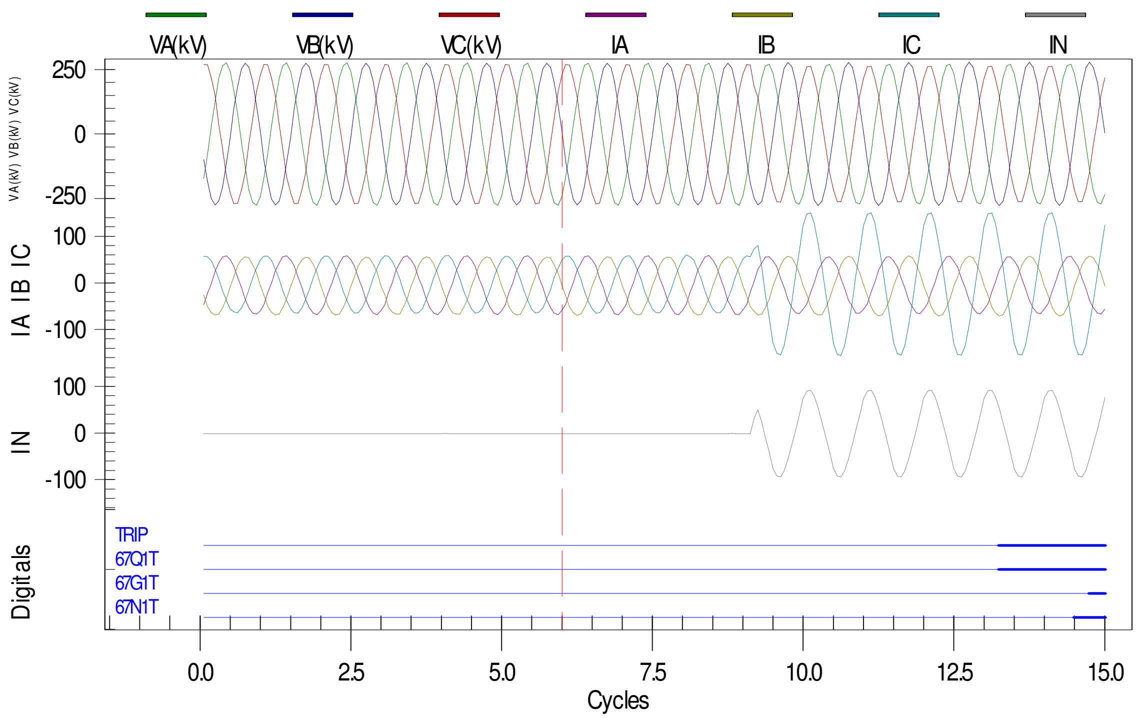

Figure 12f - Voltages, Currents, and Sequence Currents at Relay 2 when the fault was detected and cleared by the static switch.

After circuit breaker CB51 opened, the breakers in other protection zones, (i.e., CB31 in Zone 3 and CB41 in Zone 4) and the static switch remained closed. This was expected since the fault was isolated and cleared by CB51 in Zone 5.

The electrical system was stable in both the microgrid and utility grid after CB51 opened for both single phase-to-ground and three-phase-to-ground fault conditions in Zone 5. All loads and alarms were reset and equipment was prepared for the next test.

6.1.4 <u>Zone 4 Three-Phase Grounded Fault, Gen-sets (A1+A2) and Utility Connected</u>

Performance Goal:

Test a three-phase-to-ground balanced overload fault condition in Zone 4 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify I^2t protection, plus confirm a reverse power event after the Zone breaker "Opens".

Initial Setup:

Gen-set A1 = Unit Power Control

Gen-set A1 Output Power Command = 50kW

Gen-set A2 Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833Hz/kW

MG Voltage Command = 277V

Reverse Power Set-point = 0kW

Load Bank 3 = 10kW

Load Bank 6 = 40kW

Load Bank 4 = 65kW

To simulate a high impedance three-phase-to-ground fault in Zone 4, the

Overload Load Bank of 85kW was connected by cable/plug into the exterior receptacle of Cabinet 5a. This additional 85kW of load in Zone 4 when initiated and combined with the 65kW in Load Bank 4 would cause an overload condition.

After both Gen-sets A1 and A2 were running for a few minutes and supplied power to Load Bank 3 and Load Bank 4, the test was started with a "Start" command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid was connected to the utility grid with total power flow at Meter 1 equaling approximately 45kW and approximately 5kW at Meter 2. Figure 13a shows when the overload fault was applied in Zone 4, the load increased from 45kW to approximately 125kW at Meter 1.

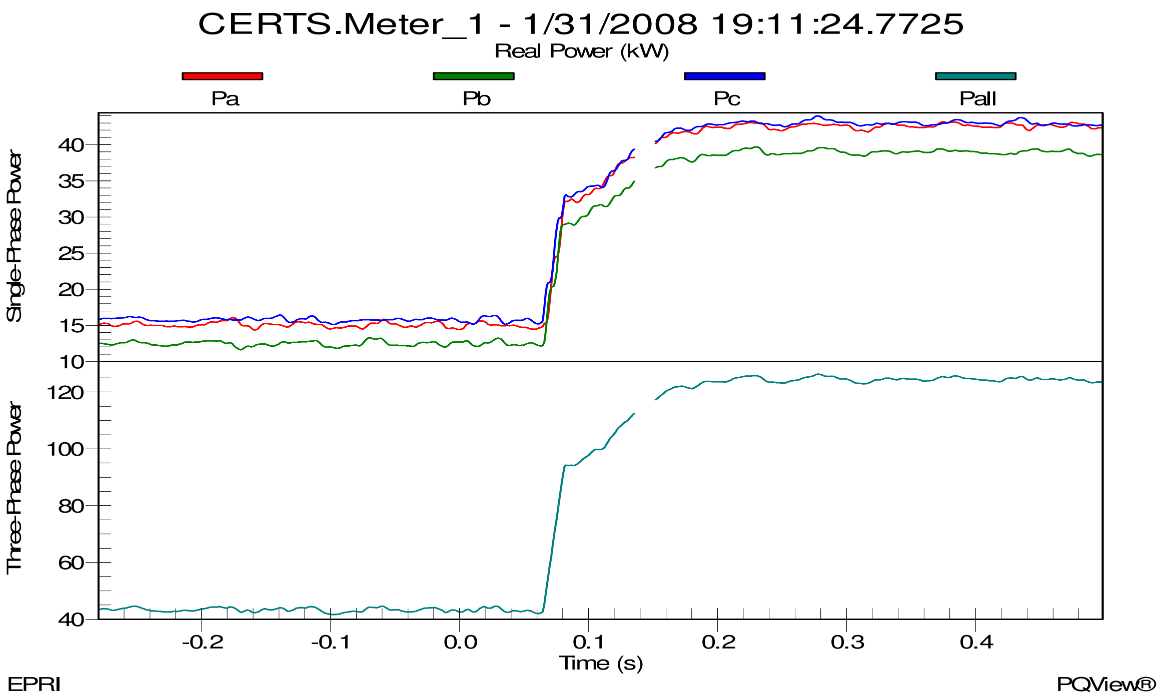

Figure 13a - Power flow at Meter 1 before/after the overload fault was applied.

Using the DAS Load Control program, the three-phase ground fault was set for a duration of 99 seconds and then initiated. CB41 tripped on an I^2t protection event in 86 seconds, shown in Figures 13b, which isolated and cleared the fault as expected in Zone 4. Zone 3 and Gen-set A1 remained connected, displacing the load in Zone 6, as shown in Figure 13b with minus 37kW through the static switch. This results in approximately zero load at the PCC, which in-turn caused the static switch to open after 30 seconds due to a reverse power event.

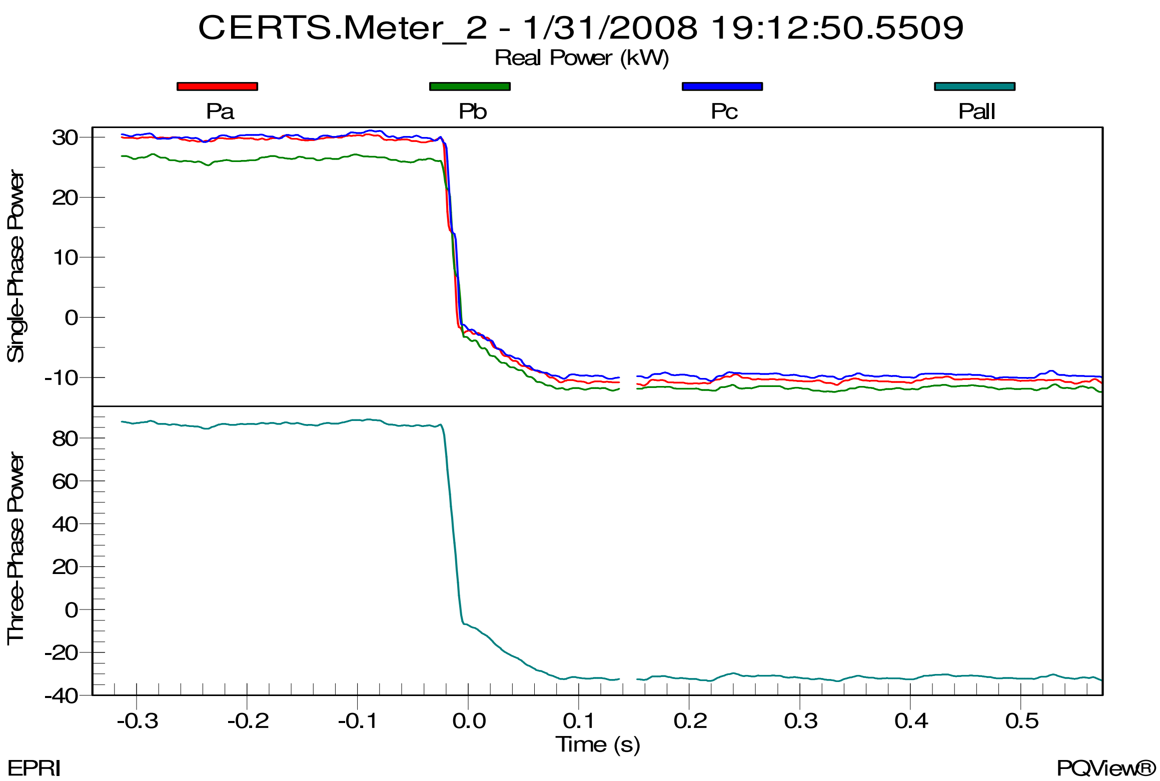

Figure 13b - Power flow at Meter 2 before/after CB41 opened.

Gen-set A2 shut down 0.2619 seconds (~16 cycles) after CB41 opened to clear the fault, shown in Figure 13c. Gen-set A1 remained online after Gen-set A2 shutdown producing approximately 47kW. Note, in Figure 13d there is an instance where Gen-set A1 drops from approximately 47kW to 22kW, which is due to Load Bank 4 being disconnected from the microgrid. Since Gen-set A1 was set for a Unit Power Control of 50kW and there was only 10kW worth of load from Load Bank 3 within the microgrid a reverse power flow occurred opening the static switch islanding it from the utility grid. The static switched opened approximately 56.2 seconds after CB41 opened and Gen-set A1 remained online, serving the microgrid load. Figure 13e shows Gen-set A1 picking up the load from Load Bank 3, approximately 12kW after the static switch opened.

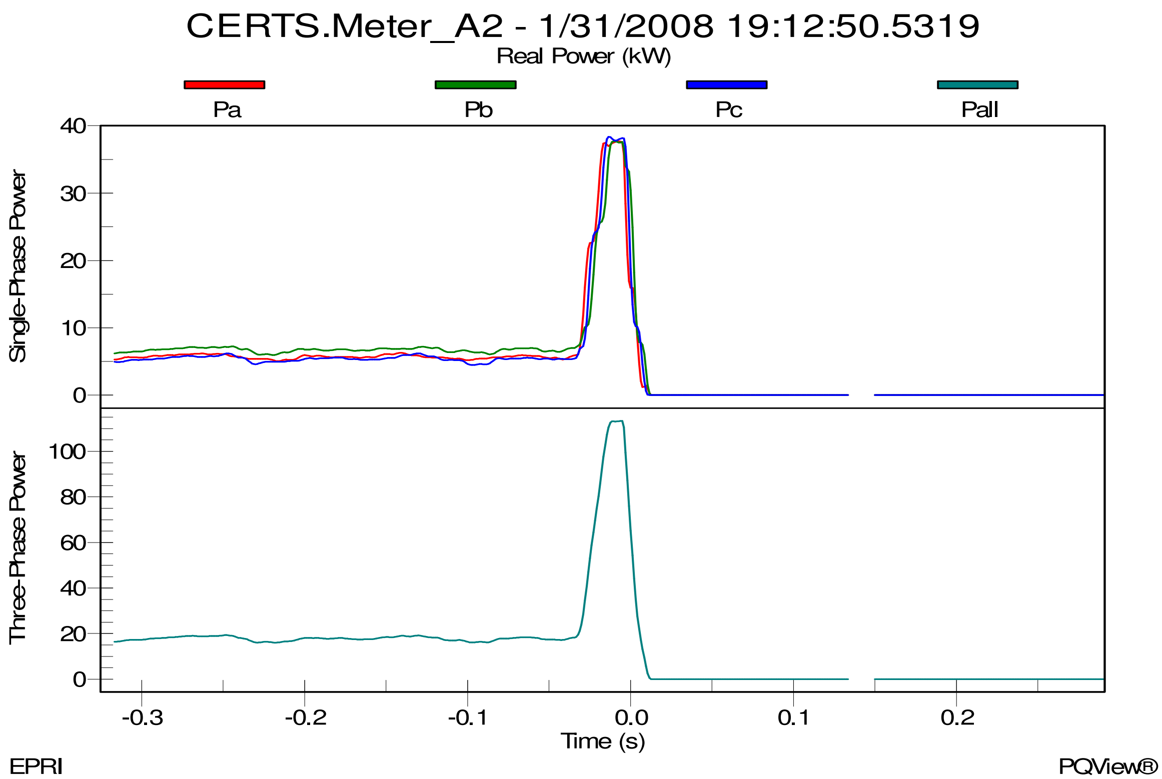

Figure 13c - Gen-set A2 shutting down after CB41 opens

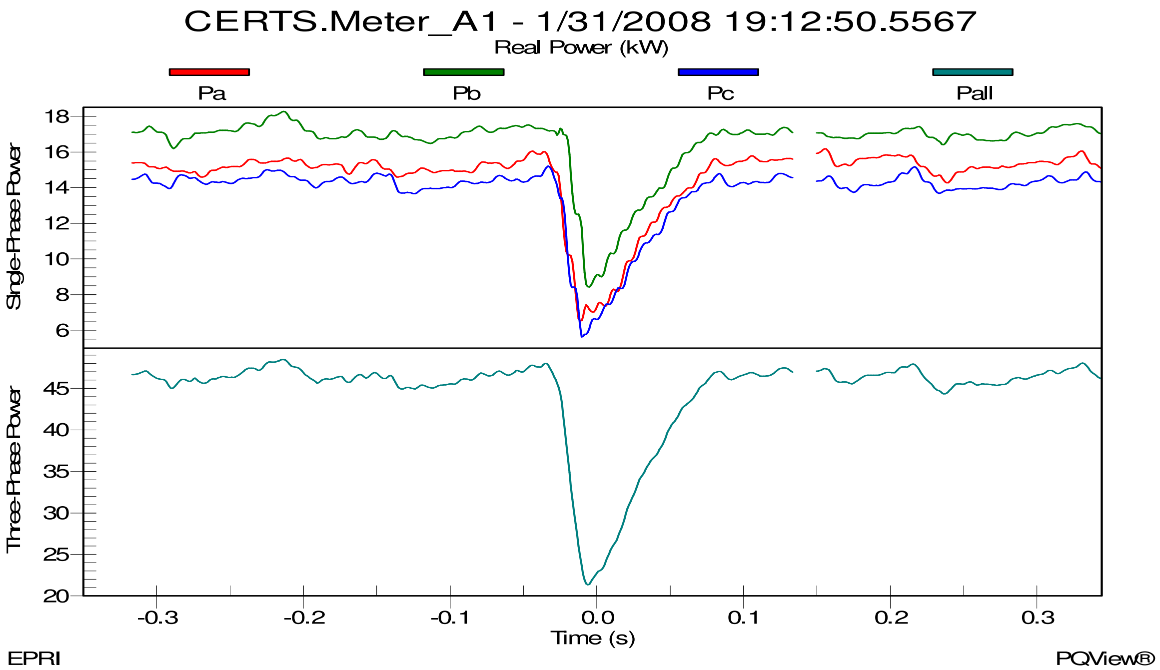

Figure 13d - Gen-set A1 power flow before/after CB41 opened.

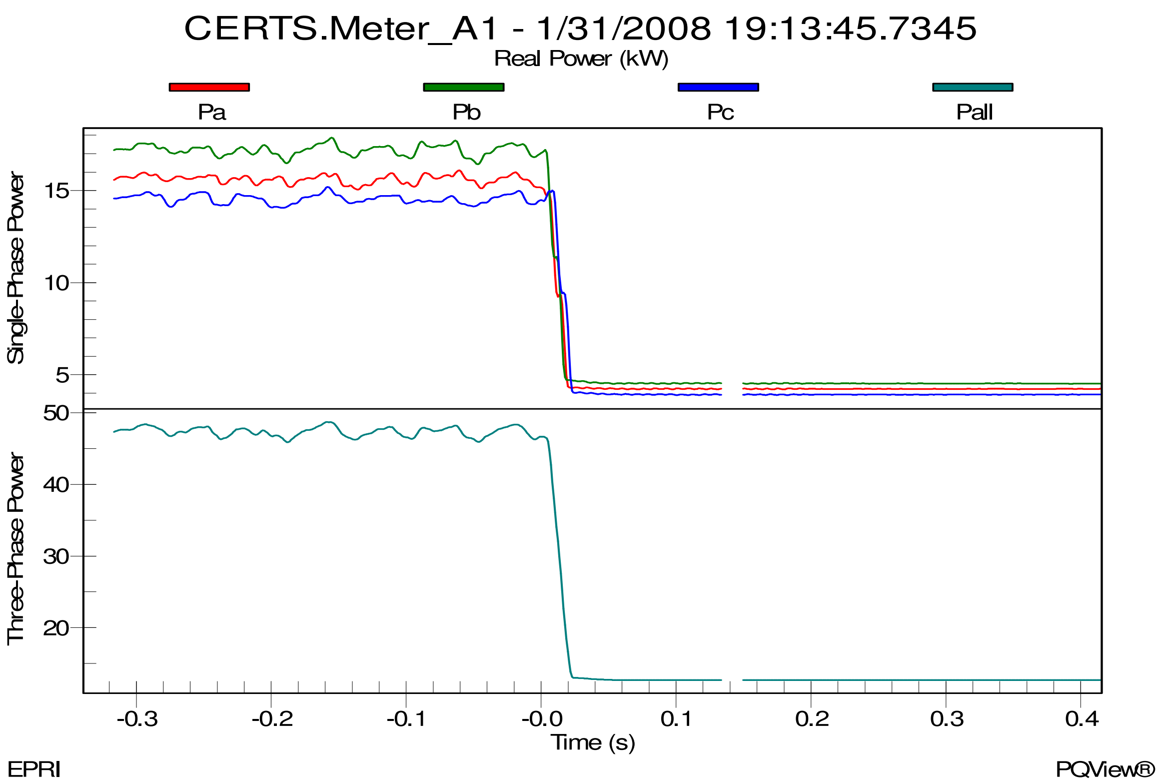

Figure 13e - Gen-set A1 power flow reducing its output power to approximately 12kW after the static switch opens from a reverse power condition.

Gen-set A1 dropped its output power from 50kW to 12kW to satisfy the load requirement. The electrical system was stable in both the microgrid and utility grid after CB31 opened and Gen-set A2 shutdown. Gen-set A1 was manually shutdown, all loads and alarms were reset, and equipment was prepared for the next test.

6.1.5 <u>Zone 3 A-Phase Line-to-Ground Fault, Gen-set A1 and Utility Connected</u>

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 3 with Gen-sets A1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Gen-set A1 = Unit Power Control Mode

Output Power Command = 20kW

MG Power /Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = B(Inst)

Reverse Power Set-point = 0kW

Load Bank 3 = 40kW

Load Bank 6 = 40kW

To simulate a high impedance single phase-to-ground fault in Zone 3 on the A-phase the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 3a with phases B and C disconnected. This, when combined with the load in Load Bank 3 of 40kW (approximately 13.3kW per phase), added 28.3kW to A-phase of Zone 3 causing an overload condition.

After Gen-set A1 was running for a few minutes and supplying power to Load Bank 3, the test was started with a "Start" command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid with the total power flow at Meter 1 equaling approximately 57.5kW, shown in Figure 14a, and 21kW at Meter 2 shown in Figure 14b before the fault was applied.

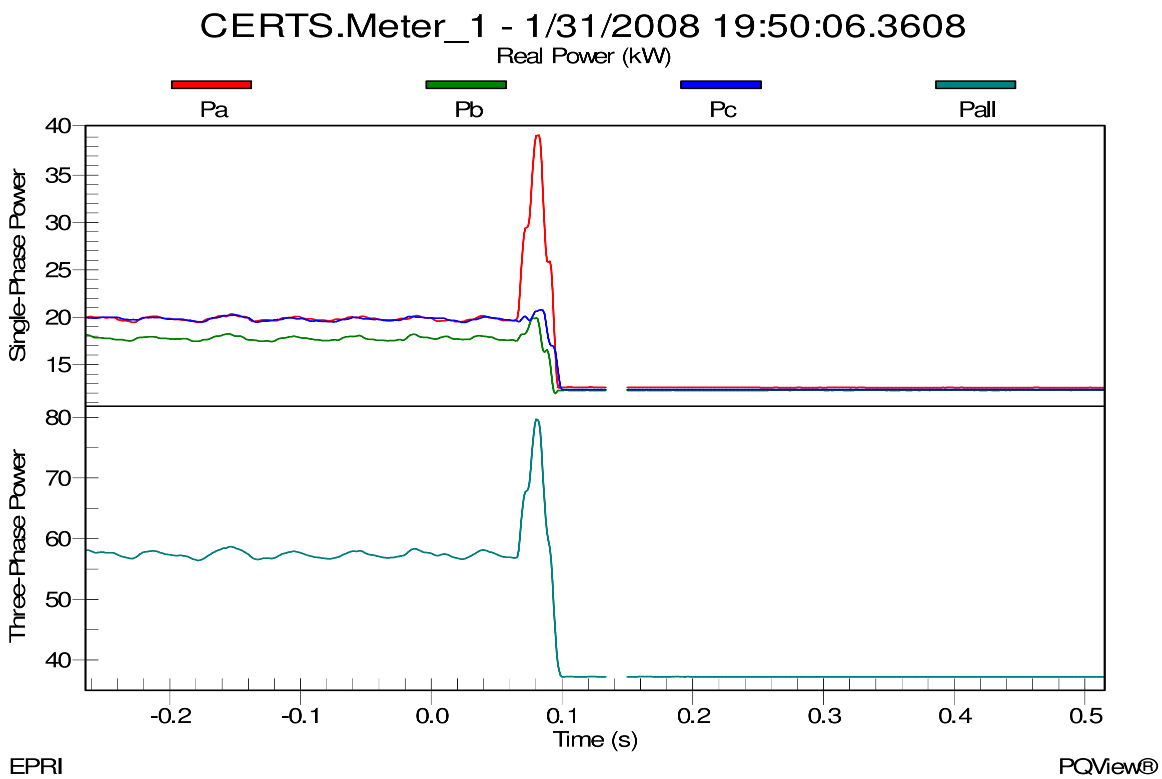

Figure 14a - Power flow in Meter 1 before/after the fault was cleared in Zone 3.

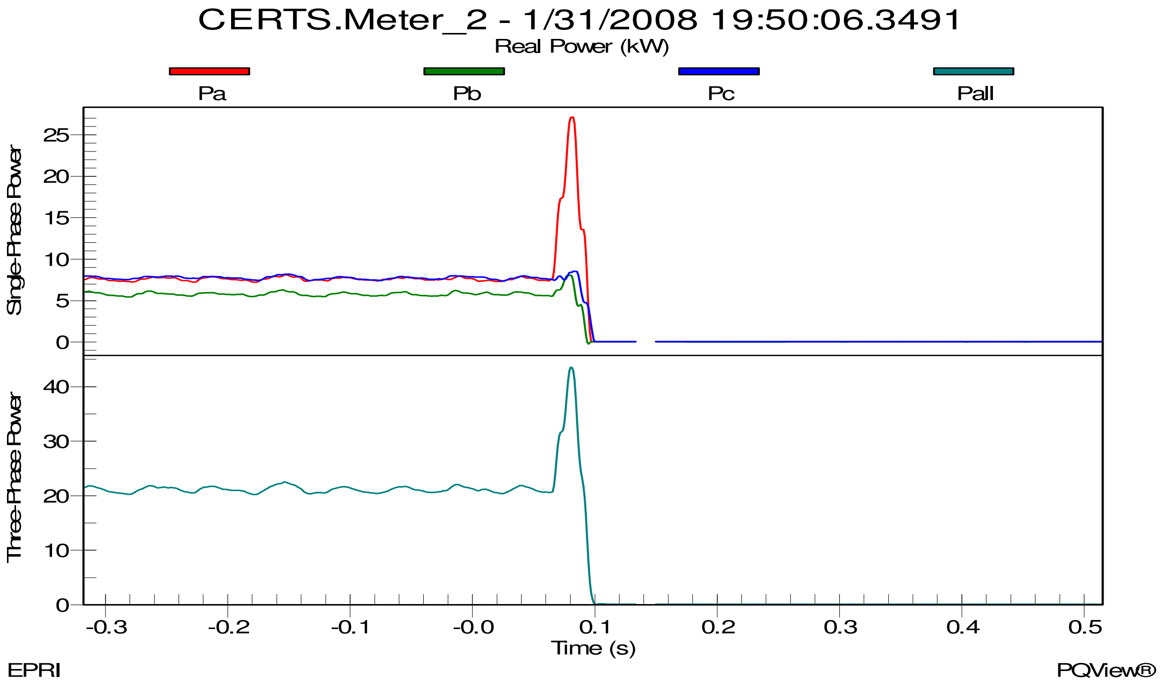

Figure 14b - Power flow in Meter 2 before/after the fault was cleared in Zone 3.

Using the DAS Load Control program, the single phase-to-ground fault on A-phase was set for 10 seconds and then initiated. The static switch tripped first in approximately 0.016 seconds (~1 cycle) from a ground over-current (67N1T), shown in Figure 14c, isolating the microgrid from the utility grid. Relay 3 tripped CB31, opening in 0.15 seconds (~9 cycles) after the static switch opened due to a ground over-current (67N1T), shown in Figure 14d, isolating Zones 3 and 4 from the rest of the microgrid and shutting down Gen-set A1. It is also worth noting that once the static switch opens the phase currents measured by the relay reduce to zero. However, because of the grounding layout, ground current from the fault, fed by Gen-set A1, is still measured and tripped. Once CB31 opens Zones 3 and 4 are isolated, no longer being satisfied by the grid or Gen-set A1 as shown by the collapsed voltage in Figure 14d. The approximate 39kW load in Load Bank 6 is still being satisfied by the grid as shown in Figure 14a.

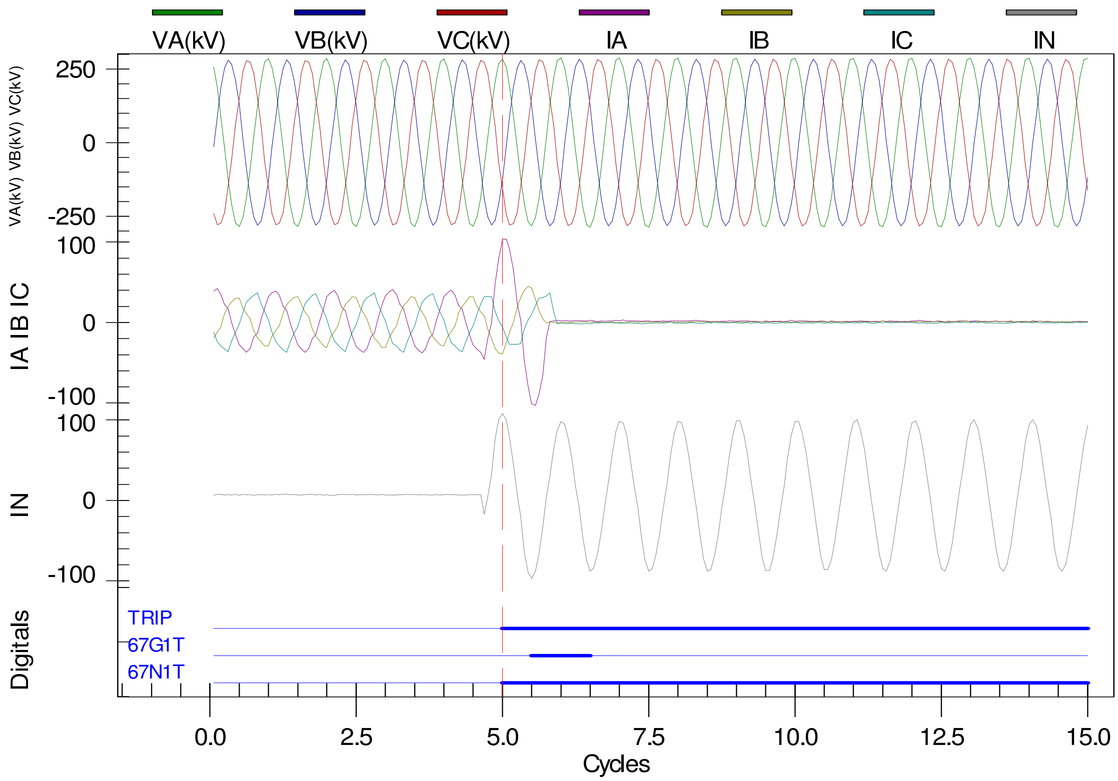

Figure 14c - Relay 2 (static switch) tripped due to ground over-current (67N1T) in 1 cycle after the single phase-to-ground fault was applied in Zone 3.

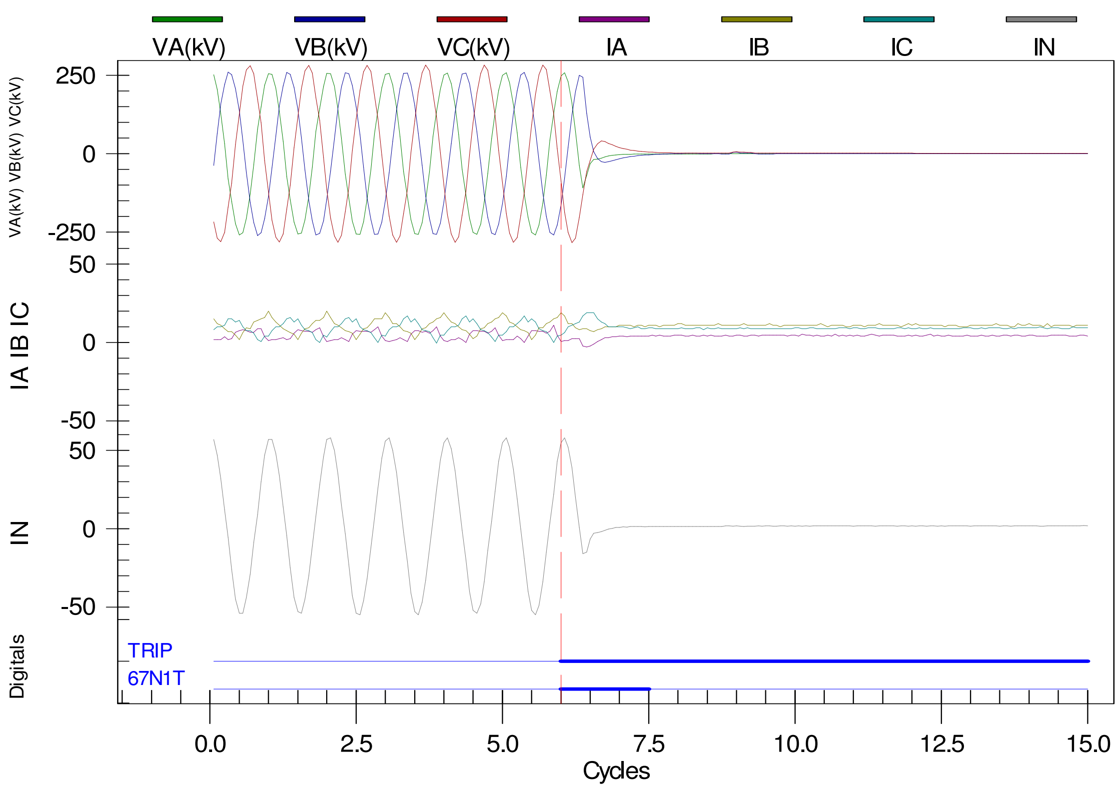

Figure 14d - Relay 3 (CB31) tripped on a ground over-current (67N1T) after the single phase-to-ground fault was applied in Zone 3.

Gen-set A1 shutdown 0.166 seconds (~10 cycles) after Zones 3 and 4 were separated when CB31 opened. Figure 14e shows Gen-set A1 produced approximately 19kW before the single phase-to-ground fault was initiated, increased to approximately 57kW to satisfy Load Bank 3 when the static switch opened and shutdown when CB31 separated Zones 3 and 4.

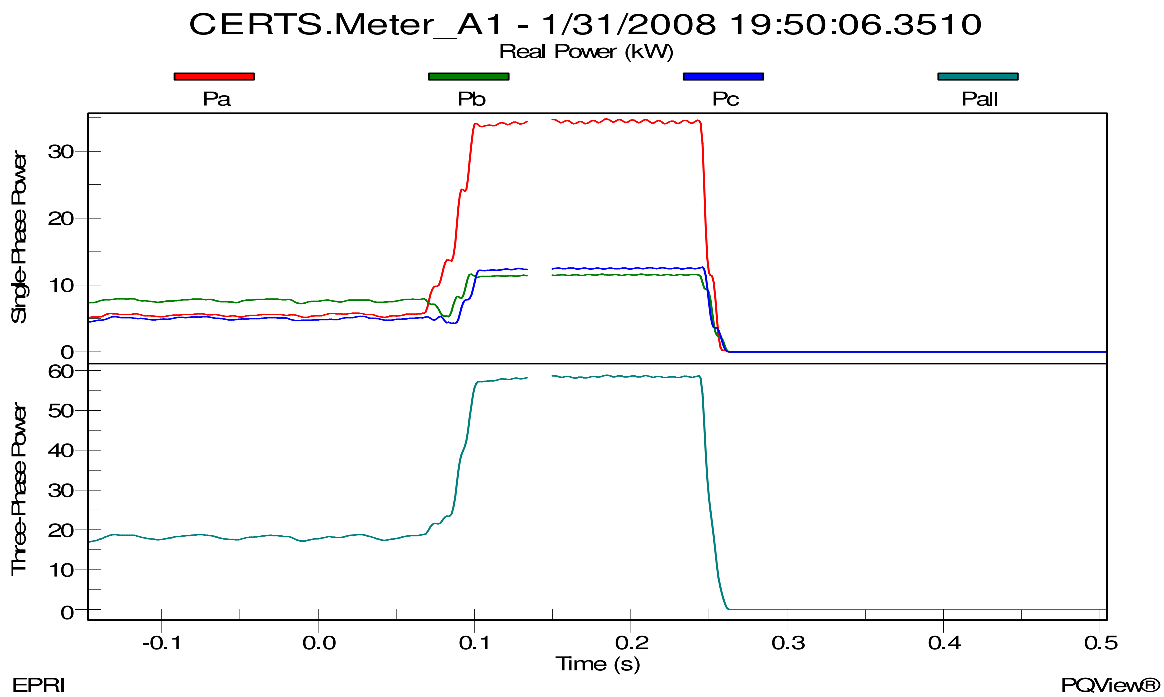

Figure 14e - Gen-set A1 output power before/after the static switch opens and then when Zones 3 and 4 are isolated from the rest of the Microgrid.

The electrical system was stable in the microgrid and utility grid after the static switch opened, CB31 opened and Gen-set A1 shutdown. All loads and alarms were reset and equipment was prepared for the next test.

6.1.6 Zone 3 A-Phase Line-to-Ground Fault, Gen-sets (A1+A2) and Utility Connected

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 3 with Gen-sets A1 and A2, operating in-parallel with the utility grid, to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Gen-set A1 = Unit Power Control

Gen-set A2 = Unit Power Control

Gen-set A1 Output Power Command = 20kW

Gen-set A2 Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = B (Inst)

Reverse Power Set-point = 0kW

Load Bank 3 = 40kW

Load Bank 4 = 40kW

Load Bank 6 = 40kW

To simulate a high impedance single phase-to-ground fault in Zone 3 on A-phase, the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 3a with phases B and C disconnected. This, when combined with the load in Load Bank 3 of 40kW (approximately 13.3kW per phase), added 28.3kW to A-phase when initiated and caused an overload condition in Zone 3.

After both Gen-sets A1 and A2 were running for a few minutes and supplying power to Load Banks 3 and 4, the test was started with a “Start” command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid. Before the fault was applied the total power flow at Meter 1 was approximately 72.5kW shown in Figure 15a and approximately 35kW at Meter 2 shown in Figure 15b.

Using the DAS Load Control program, the single phase-to-ground overload fault on A-phase was set for 10 seconds and then initiated. The static switch tripped first in approximately 0.02 seconds (~1.3 cycles) from a ground over-current (67N1T), shown in Figure 15c, islanding the microgrid from the utility grid.

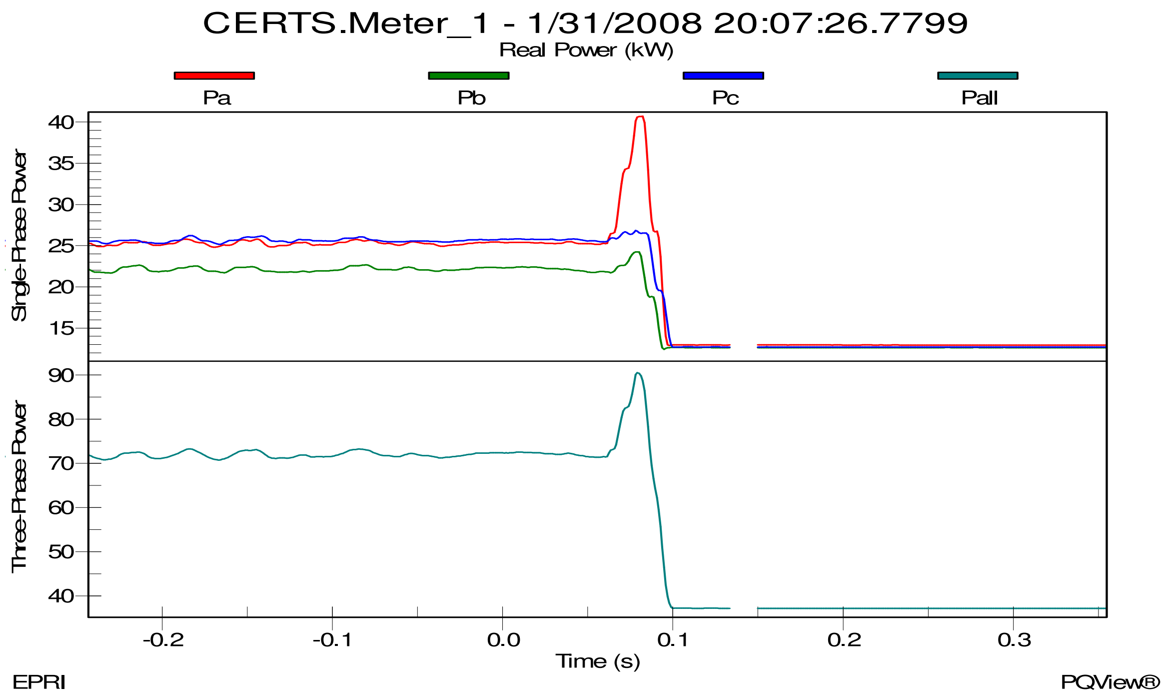

Figure 15a - Meter 1 power flow before/after the static switch opens, islanding the microgrid from the utility grid after a single phase-to-ground fault was applied to Zone 3.

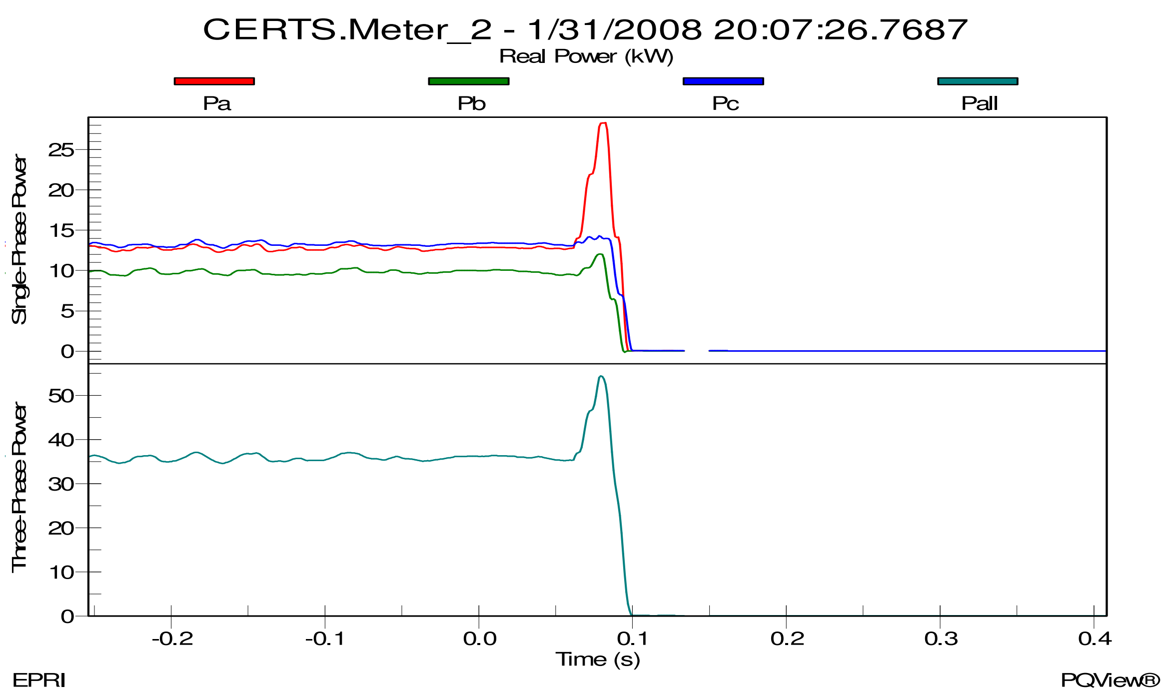

Figure 15b - Meter 2 power flow before/after the static switch opened, isolating the microgrid from the utility grid after a single phase-to-ground fault was applied to Zone 3.

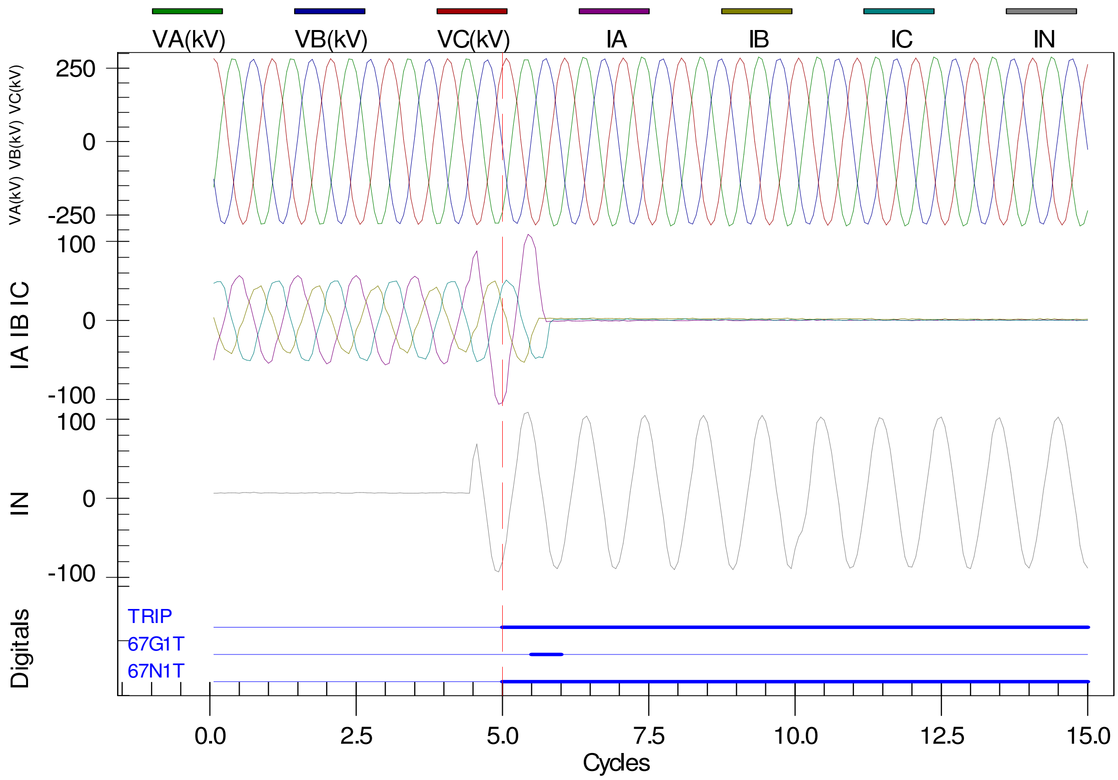

Figure 15c - Relay 2 (static switch) tripped after the single phase-to-ground fault was applied in Zone 3.

Relay 4 trips 0.07 seconds (~4.3 cycles) after the static switch opened due to a neutral over-current (67G1T), shown in Figure 15d, separating Zone 4 from the rest of the microgrid.

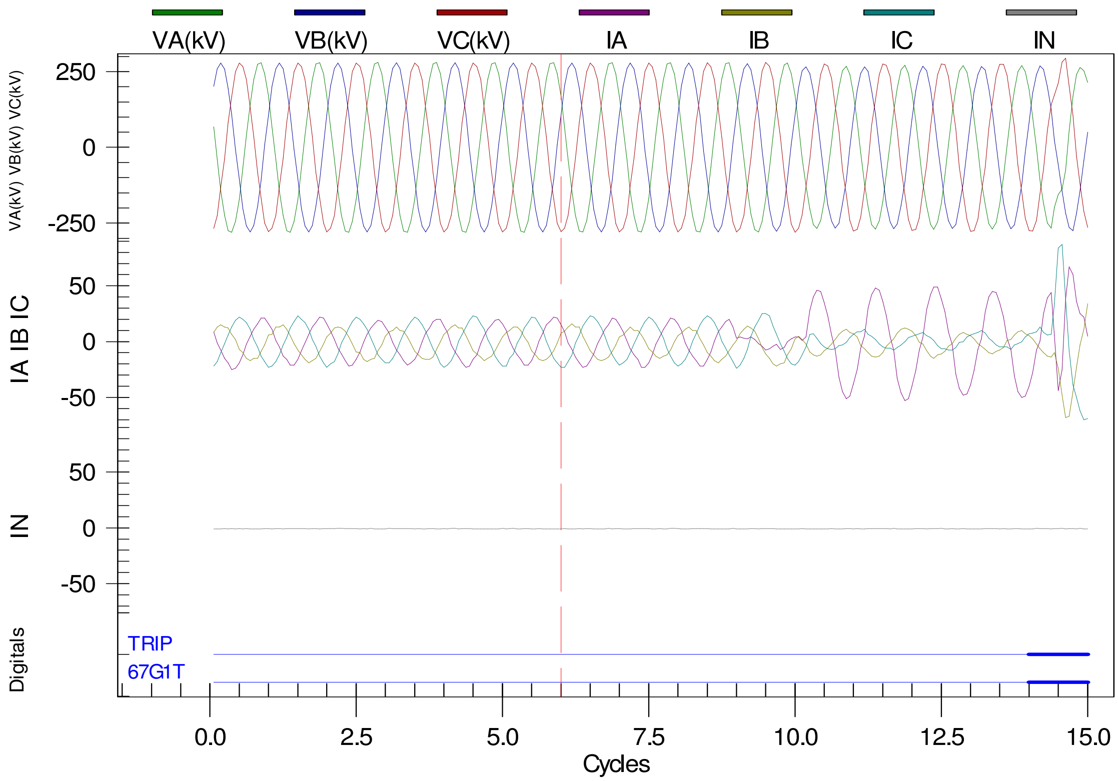

Figure 15d - Relay 4 (CB41) tripped after the single phase-to-ground fault was applied in Zone 3.

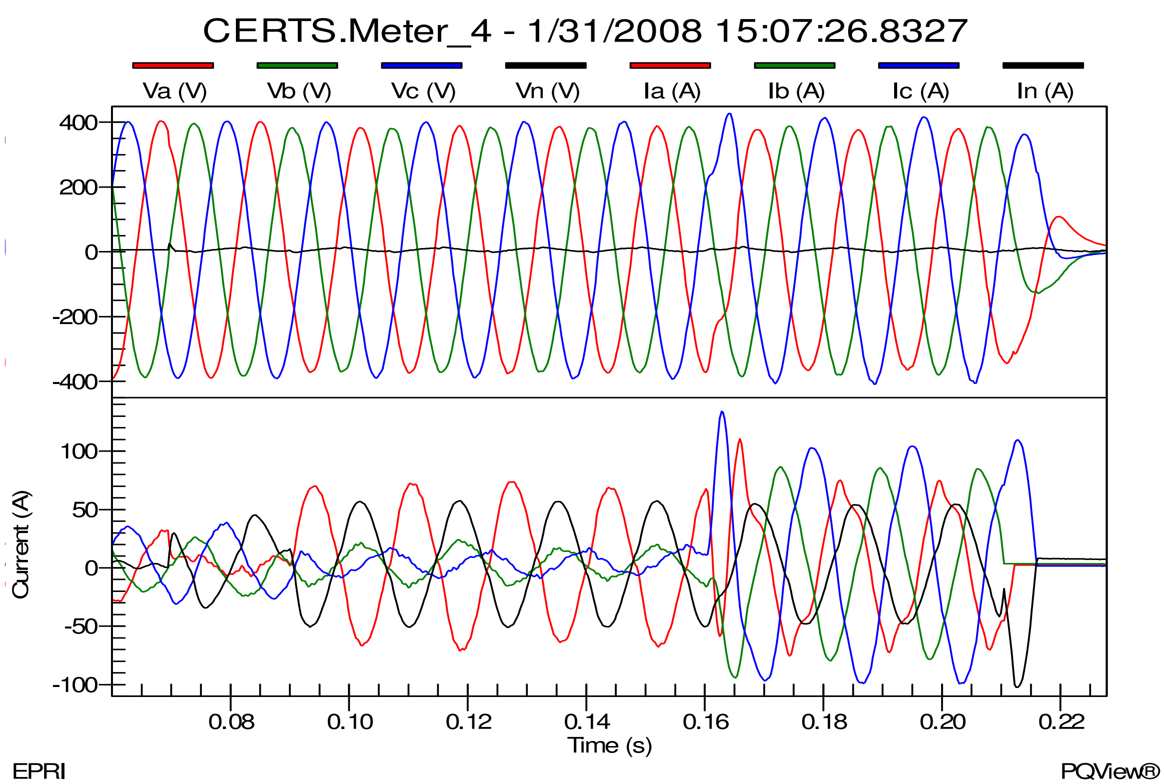

Figure 15e - Meter 4 (CB41) voltage and current for a single phase-to-ground fault applied in Zone 3.

A complex situation took place in Figures 15e, 15f and 15g. The fault was applied at 0.07 seconds which caused the static switch to open at 0.09 seconds. This was followed by a short period where both Gen-sets A1 and A2 were supporting the microgrid load, as well as the fault overload, shown in Figures 15f and 15g between 0.09 and 0.16 seconds. At 0.16 seconds Relay 4 commanded Gen-set A2 to shutdown and CB41 to open. Gen-set A2 first stopped delivering power to the microgrid, as seen by the sudden increase of current at Meter 4, Figure 15e, and Meter A1, Figure 15g. Even though Gen-set A2 stopped switching the inverter output, its interface transformer remained connected to the microgrid. This is evident by the continued current flow though Meter A2 after 0.16 seconds, Figure 15f, due to the Wye/Delta transformation, and also evident in the real power transferred from B and C phases to A phase at Meter A2 in Figure 15h. At 0.215 seconds CB41 opened reducing the current through CB41 to zero and denergizing Zone 4 of the microgrid.

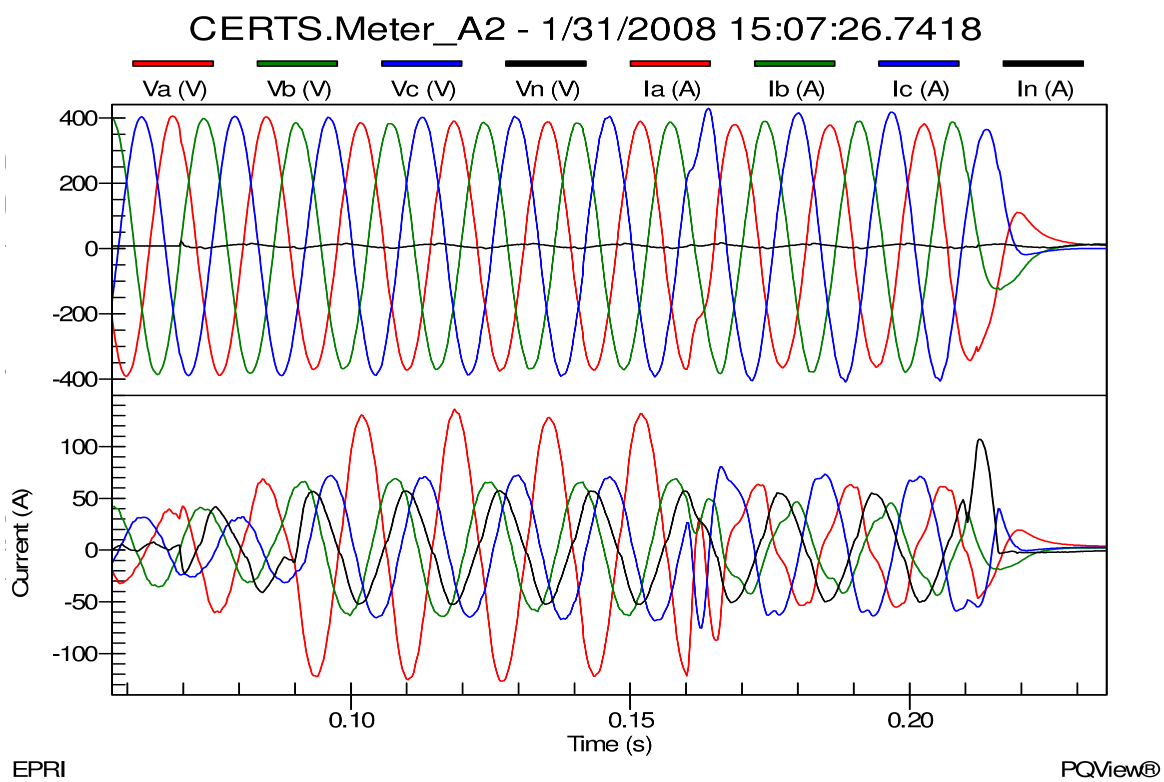

Figure 15f - Meter A2 voltage and current for a single phase-to-ground fault applied in Zone 3.

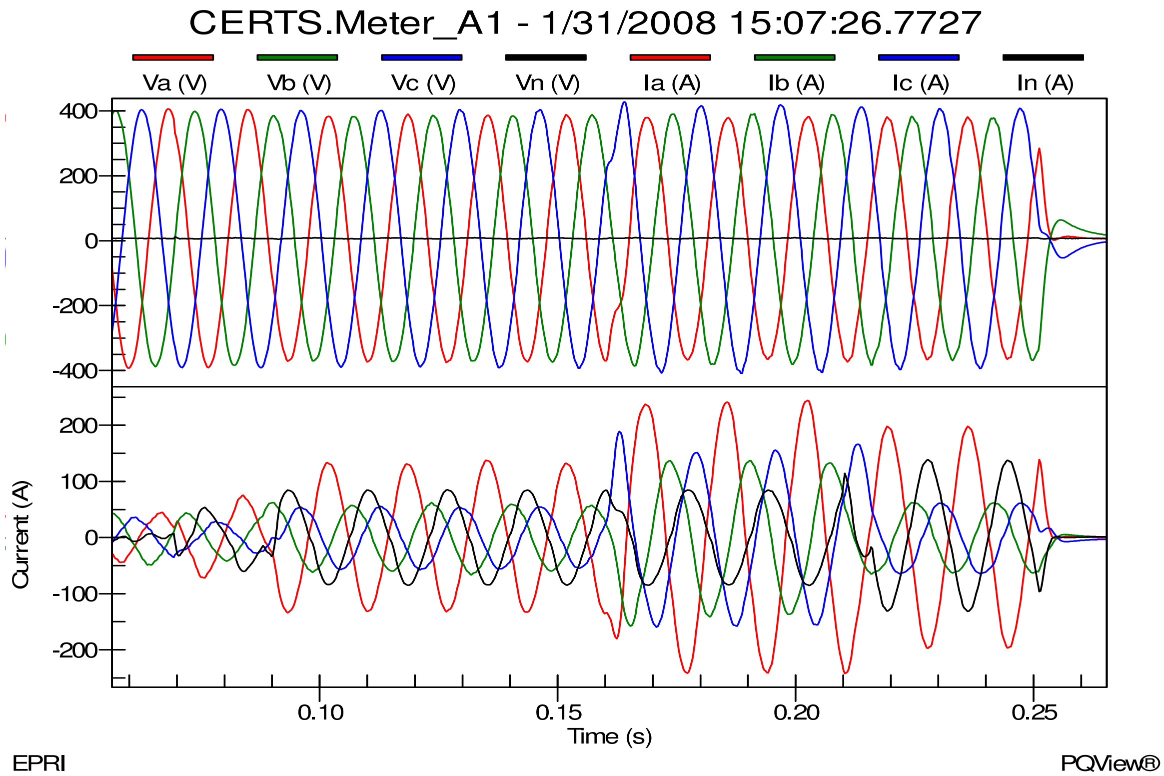

Figure 15g - Meter A1 voltage and current for a single phase-to-ground fault applied in Zone 3.

Relay 3 tripped Gen-setA1 and opened CB31 0.04 seconds (~2.3 cycles) after CB41 opened, due to ground over-current (67N1T), shown in Figure 15i, separating Zone 3 from the rest of the microgrid. In Figure 15j Gen-set A1 produced approximately 20kW before the single phase-to-ground fault was initiated and increased to approximately 48.5kW to satisfy Load Banks 3 and 4 along with generation from Gen-set A2 once the static switch opened. Output power for Gen-set A1 also increased to approximately 100kW for a brief period of time due to Gen-set A2 shutting down while the 40kW of Load Bank 3 and 4 remained connected.

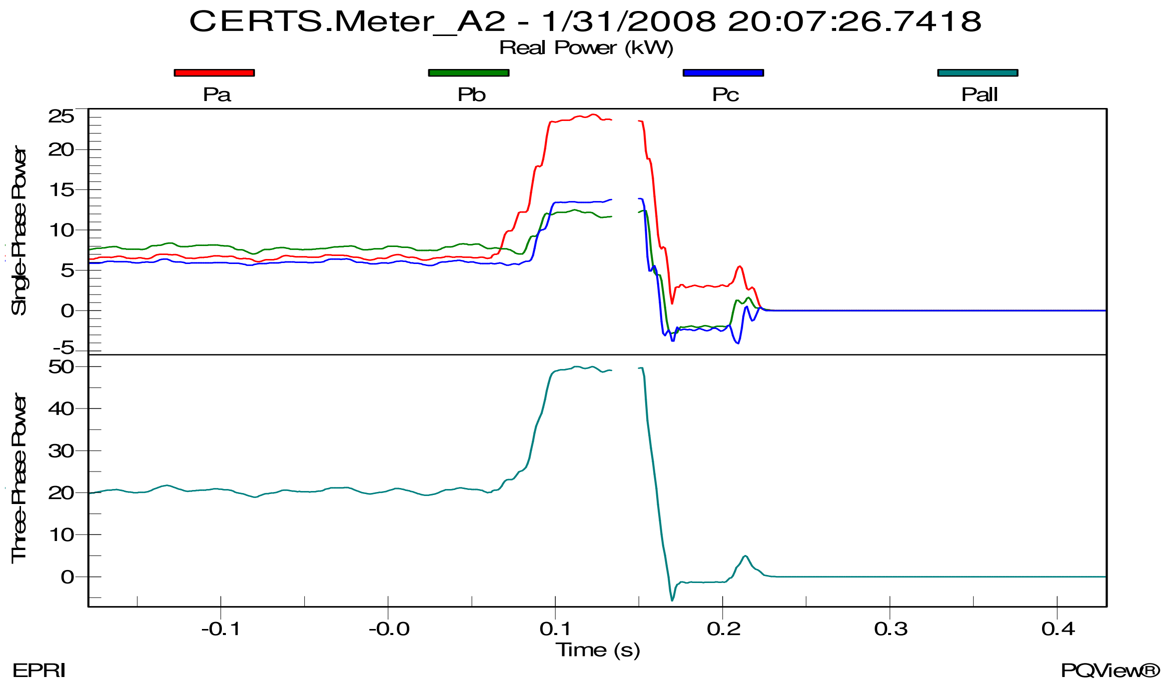

Figure 15h - Gen-set A2 output power before/after the static switch "Opens" and when Zone 4 is separated from the rest of the microgrid.

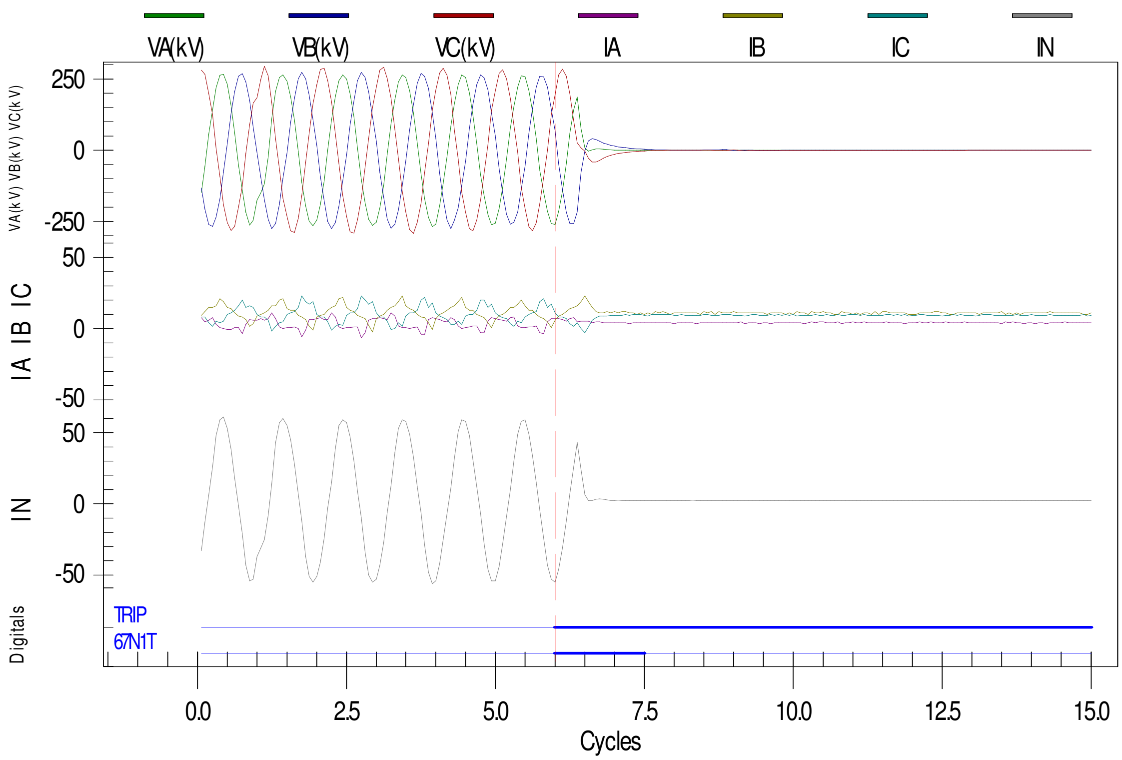

Figure 15i - Relay 3 (CB31) tripped due to a ground over-current (67N1T) when the single phase-to-ground fault was initiated in Zone 3

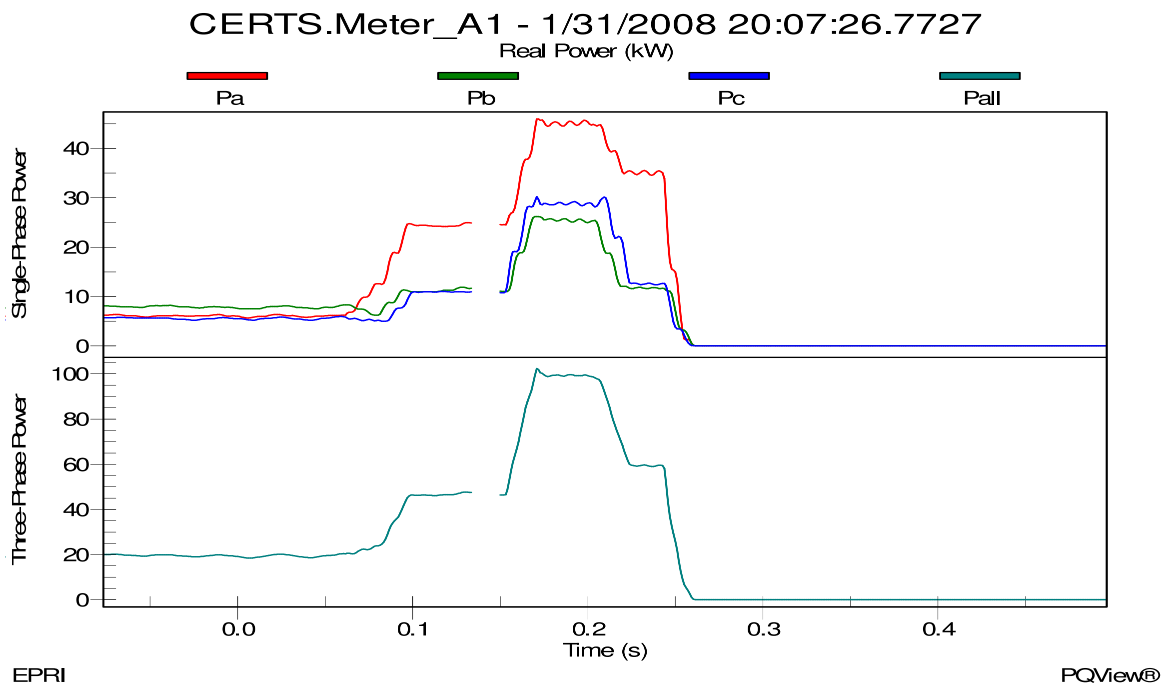

Figure 15j - Gen-set A1 output power before/after the static switch opened, when CB41 opens isolating Zone 4, and when Zone 3 is isolated from the rest of the microgrid.

The electrical system was stable in both the microgrid and utility grid after the static switch had opened, circuit breakers (i.e., CB31, CB41 andCB51) had opened, and Gen-sets A1 and A2 shut down. All loads and alarms were reset and equipment was prepared for the next test.

6.1.7 <u>Zone 5 B-Phase Line-to-Ground Fault, Gen-set B1 and Utility Connected</u>

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 5 with Gen-sets B1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Gen-set B1 = Unit Power Control

Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = B (Inst)

Reverse Power Set-point = 0kW

Load Bank 3 = 40kW

Load Bank 6 = 40kW

To simulate a high impedance single phase-to-ground fault in Zone 5 on the B-phase the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 7a with phases A and C disconnected. When initiated, this 28.3kW on B-phase, with the 40kW in Load Bank 3 of Zone 3, causes an overload.

After Gen-set B1 was running for a few minutes and supplying power to Load Bank 3, the test was started with a "Start" command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid with total power flow at Meter 1 being approximately 54kW, shown in Figure 16a, and approximately 17.5kW at Meter 2 shown in Figure 16b before the fault was applied.

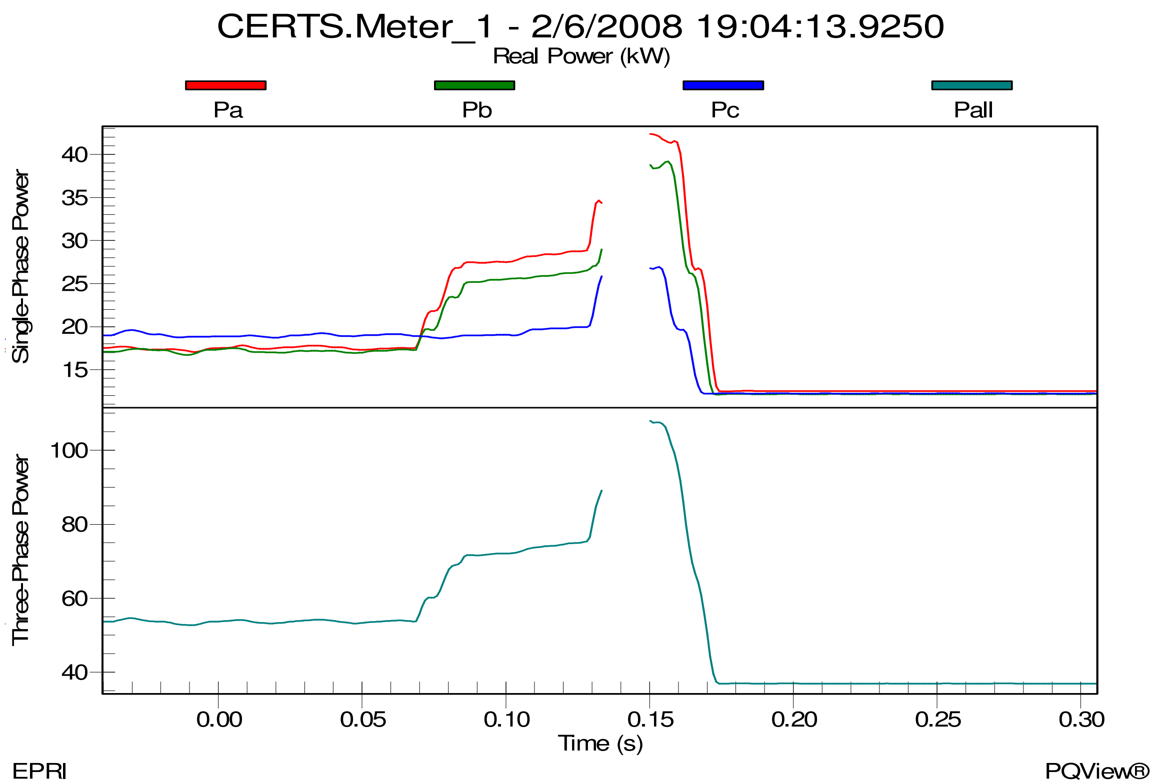

Figure 16a – Meter 1 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 5.

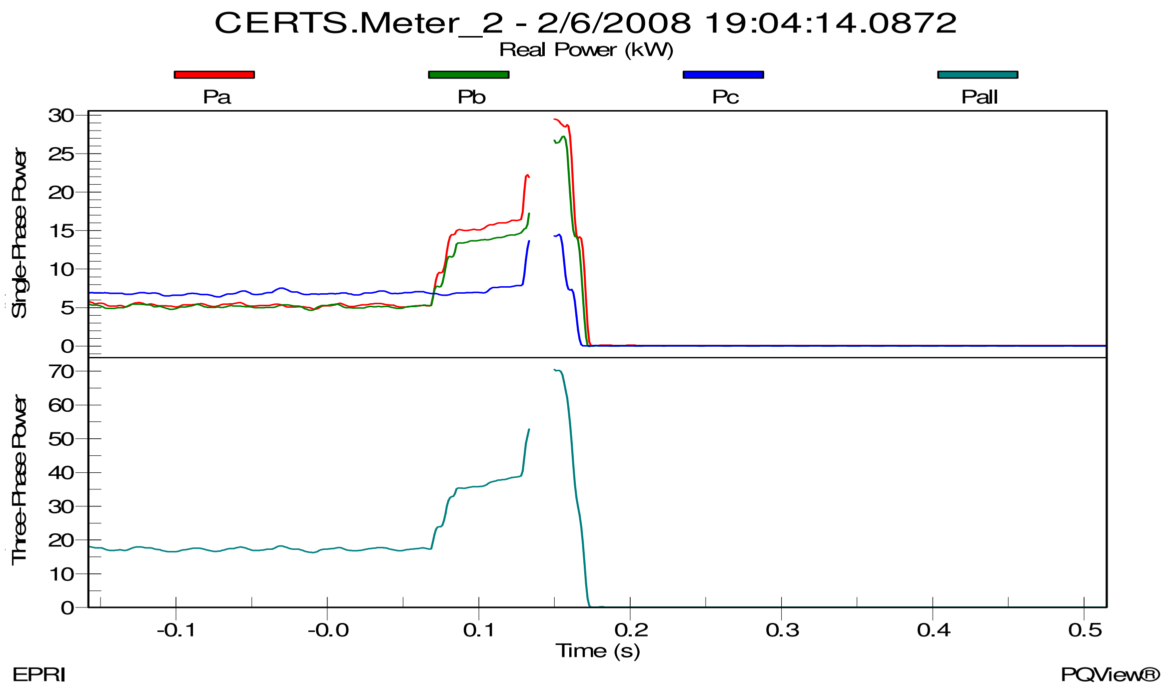

Figure 16b – Meter 2 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 5.

Using the DAS Load Control program, a single phase-to-ground overload fault on B-phase was set for 10 seconds and then initiated. The protection coordination for this event appears to be different than expected. After the fault is initiated Relay 5 first trips shutting down Gen-set B1 and opening CB51, Figure 16c. The Gen-set stops switching the inverter output, however its transformer contactor and CB51 remains closed for a brief period of time, Figure 16d. After the Gen-set stops switching the fault current at the static switch becomes large enough to cause Relay 2 to trip on negative sequence (67Q1T), Figure 16e. Relay 5 tripped first approximately 0.07 seconds (~4.2 cycles) separating Zone 5 from the rest of the microgrid. The static switch opened 0.03 seconds (~1.75 cycles) after Relay 5 tripped, islanding the microgrid from the utility.

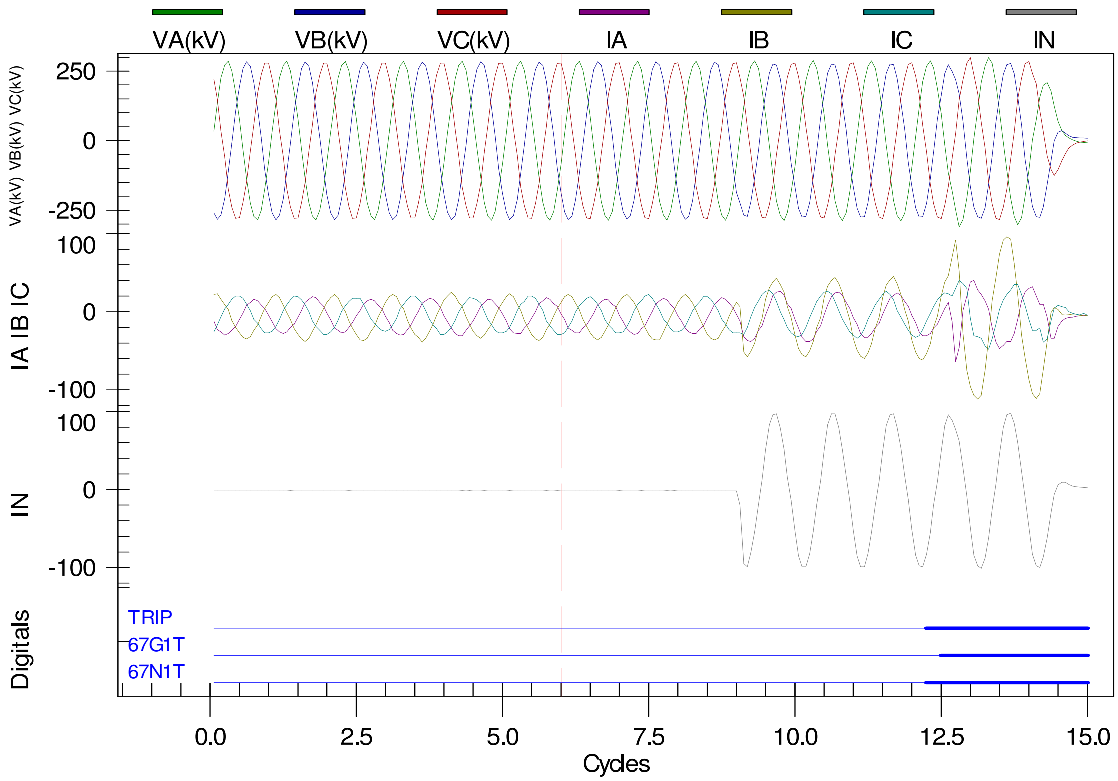

Figure 16c – Relay 5 (CB51) tripped due to ground over-current (67N1T) after the single phase-to-ground fault was initiated in Zone 5.

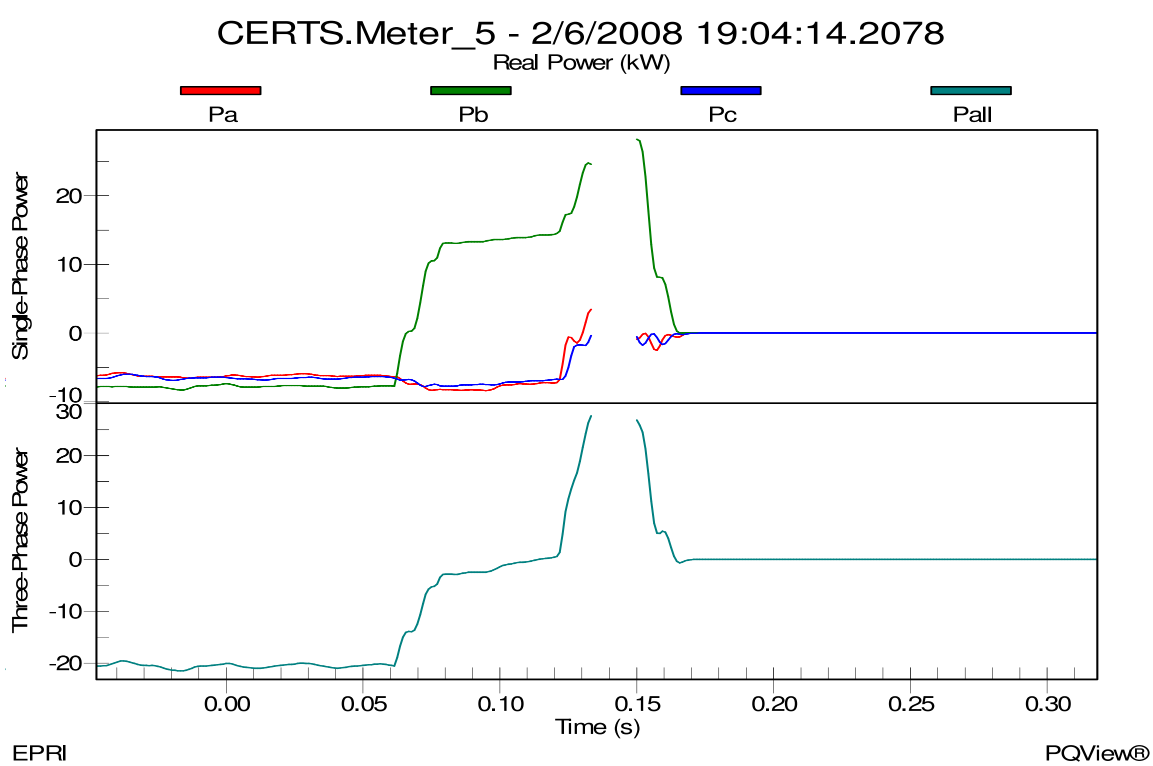

Figure 16d – Meter 5 power flow for a single phase-to-ground fault applied in Zone 5.

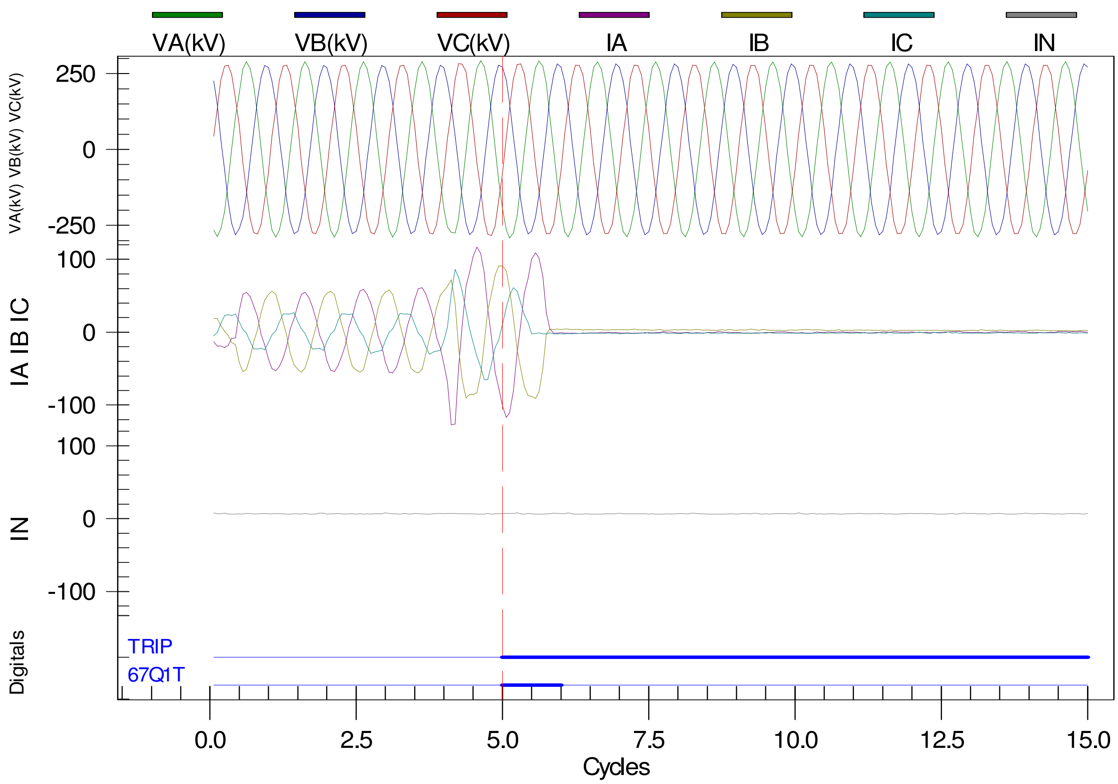

Figure 16e - Relay 2 (static switch) tripped due to negative sequence (67Q1T) after the single phase-to-ground fault was applied in Zone 5.

The electrical system was stable in the microgrid and utility grid after the static switch opened, CB51 opened, and Gen-set B1 shut down. All loads and alarms were reset and equipment was prepared for the next test.

6.1.8 <u>Zone 5 B-Phase Line-to-Ground Fault, Gen-sets (A1+B1) and Utility Connected</u>

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 5 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Gen-set A1 = Unit Power Control

Gen-set B1 = Unit Power Control

Gen-set A1 Output Power Command = 20kW

Gen-set B1 Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = B (Inst)

Reverse Power Set-point = 0kW

Load Bank 3 = 40kW

Load Bank 4 = 40kW

Load Bank 6 = 40kW

To simulate a high impedance single phase-to-ground fault in Zone 5 on B-phase the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 7a with phases A and C disconnected. When initiated, this 28.3kW on B-phase, with the 40kW in Load Banks 3 and 4, causes an overload.

After both Gen-sets A1 and B1 were running for a few minutes and supplying power to Load Banks 3 and 4, the test was started with a “Start” command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid with the total power flow at Meter 1 being approximately 75kW, shown in Figure 17a, and approximately 40kW at Meter 2, shown in Figure 17b. Gen-sets A1 and B1 were producing between 17 to 18kW each, shown in Figures 17c and 17d, before the overload fault was applied.

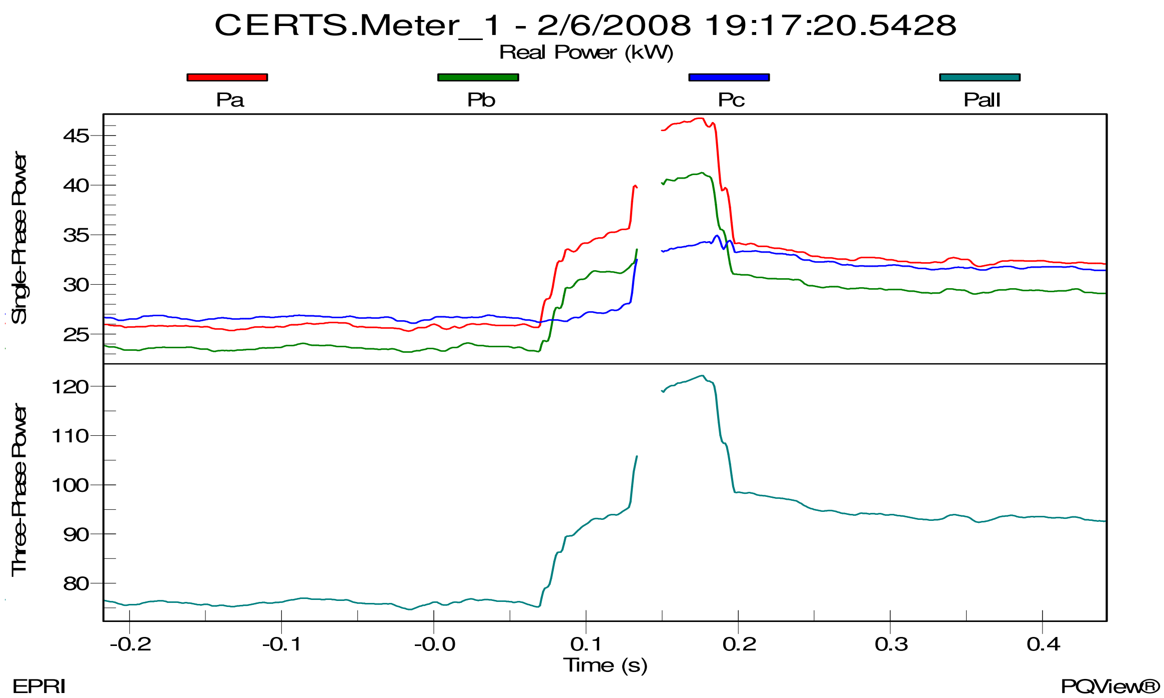

Figure 17a – Meter 1 power flow for a single phase-to-ground fault applied in Zone 5.

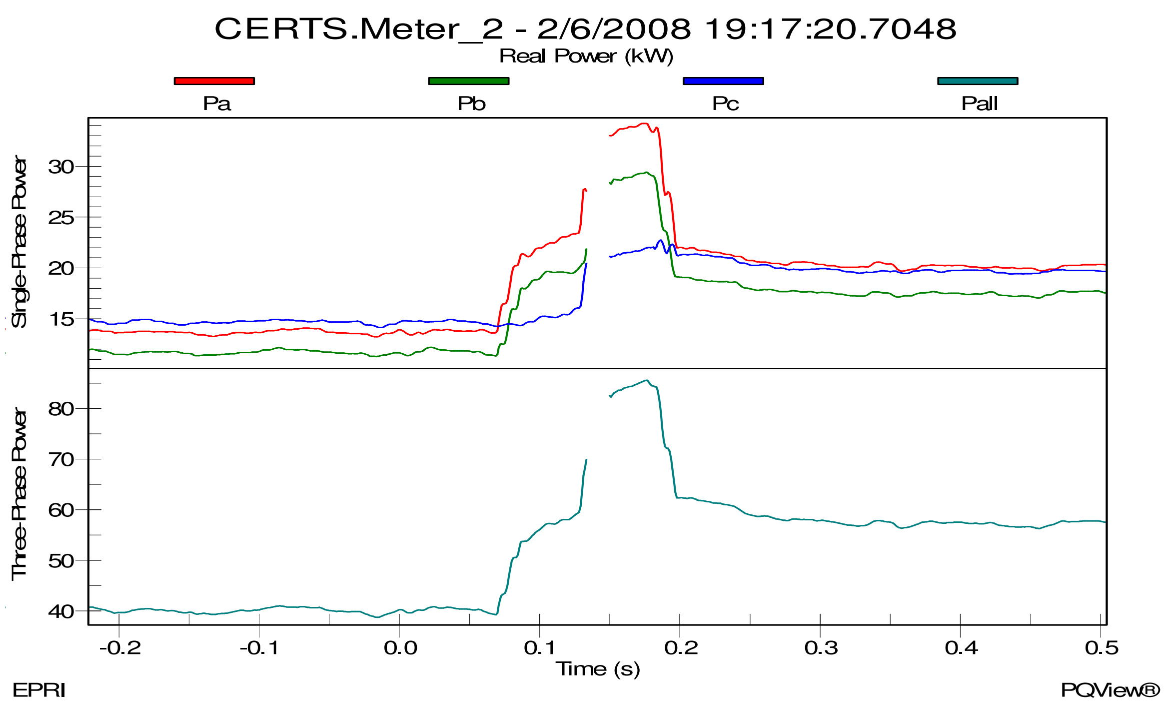

Figure 17b Meter 2 power flow for a single phase-to-ground fault applied in Zone 5.

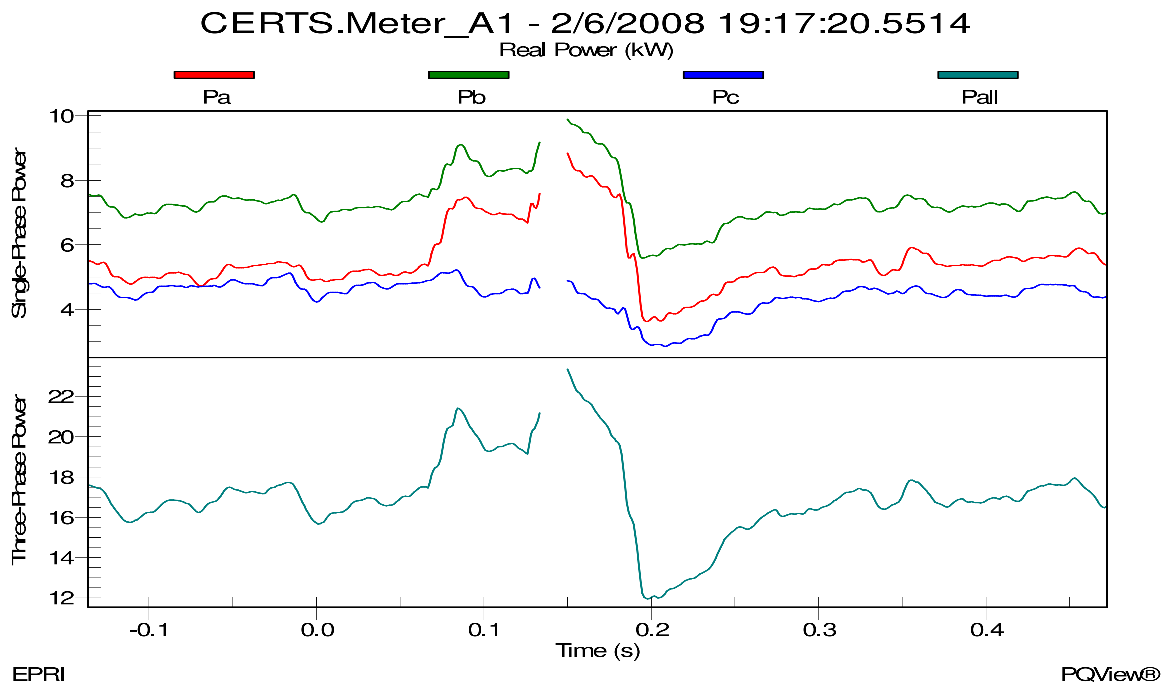

Figure 17c - Power produced by Gen-set A1 before/after a B-phase phase-to-ground fault in Zone 5.

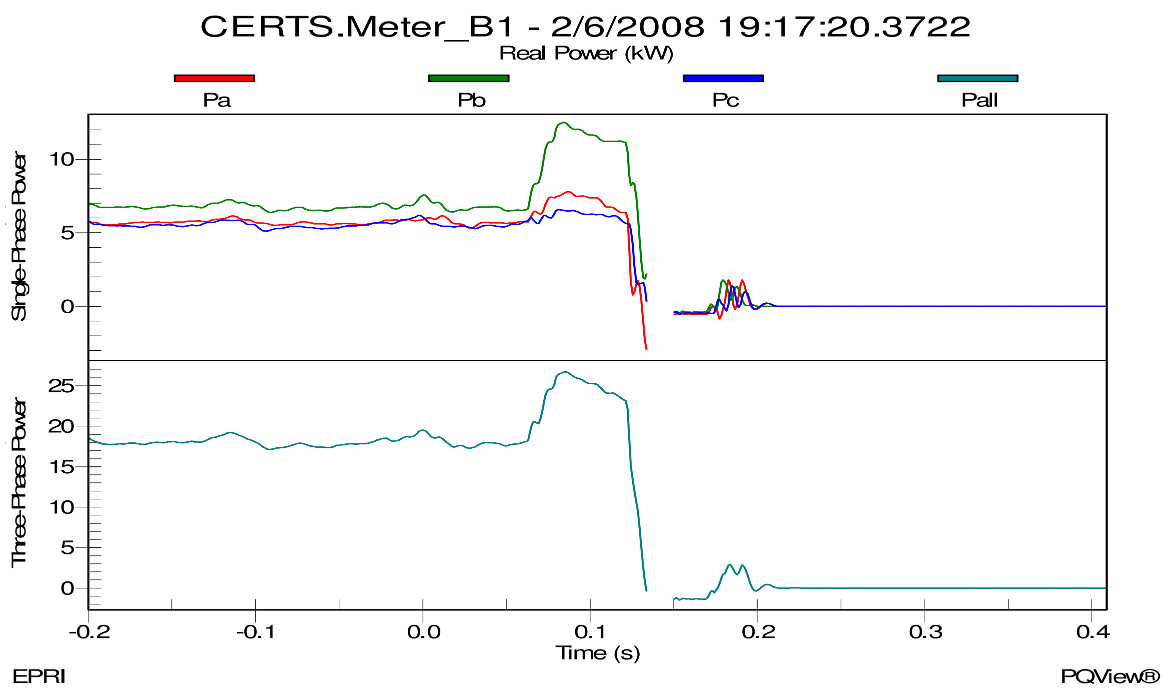

Figure 17d - Power produced by Gen-set A2 before/after a B-phase phase-to-ground fault in Zone 5

Using the DAS Load Control program, the single phase-to-ground fault on B-phase was set for 10 seconds and then initiated.

The protection coordination for this event appears to be different than expected but similar to the previous test. After the fault was initiated, Relay 5 tripped on ground over-current (67N1T), shutting down Gen-set B1 and opening CB51, Figures 17d and 17e. The Gen-set stopped switching the inverter output; however, its transformer contactor and CB51 remained closed for a brief period of time, Figure 17f. Once CB51 cleared 0.06 seconds (3.8 cycles) later the fault was removed and Zone 5 was de-energized, Figure 17g. The static switch and remaining zones of the microgrid remained online and connected.

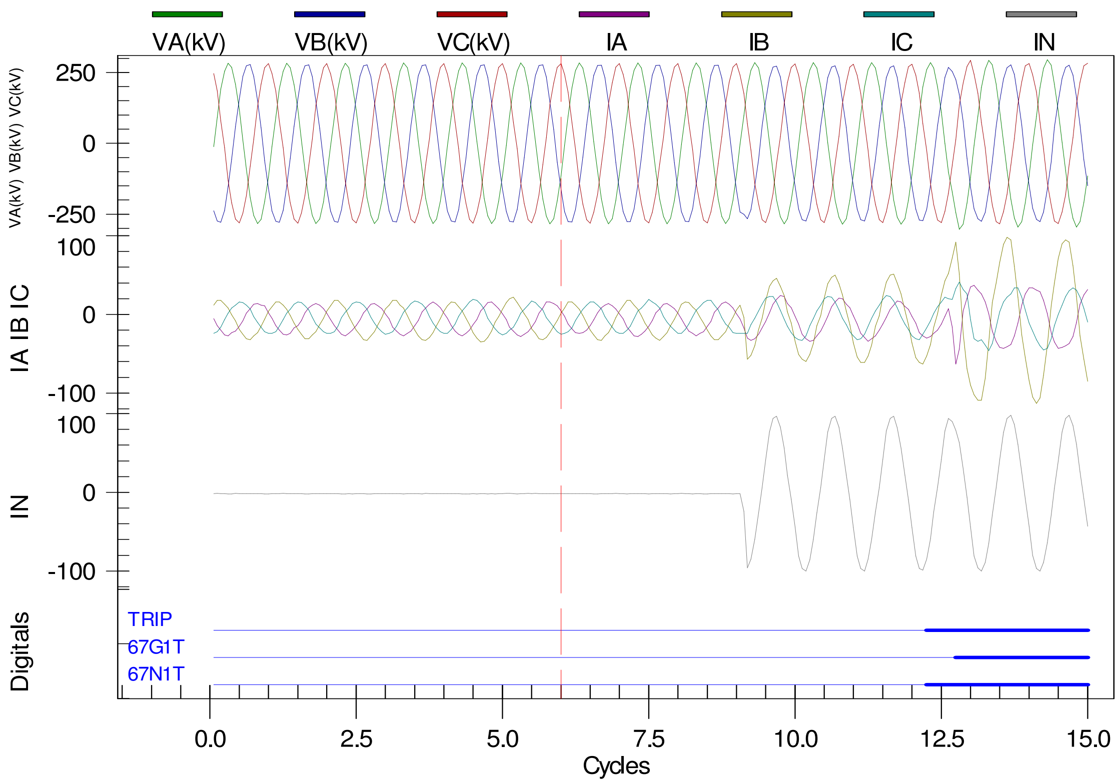

Figure17e - Relay 5 (CB51) tripped due to a ground over-current (67N1) after the single phase-to-ground fault was initiated in Zone 5.

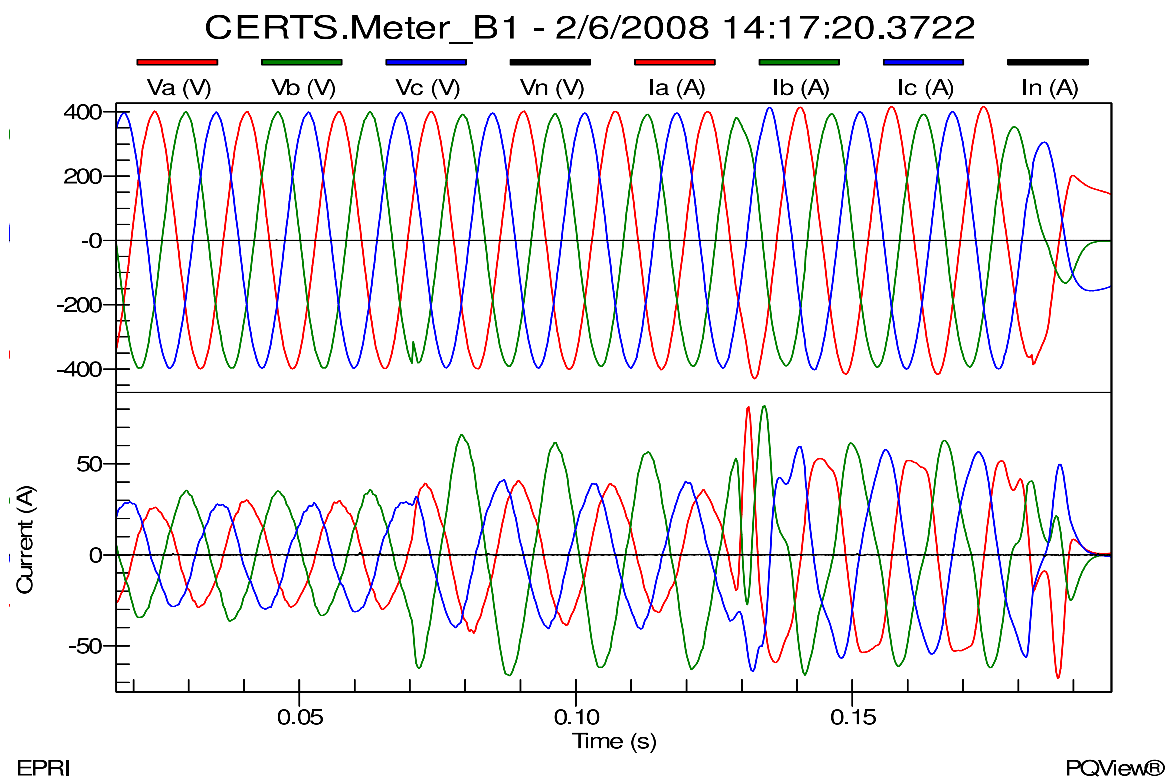

Figure17f – Meter B1 voltage and current for a single phase-to-ground fault applied in Zone 5.

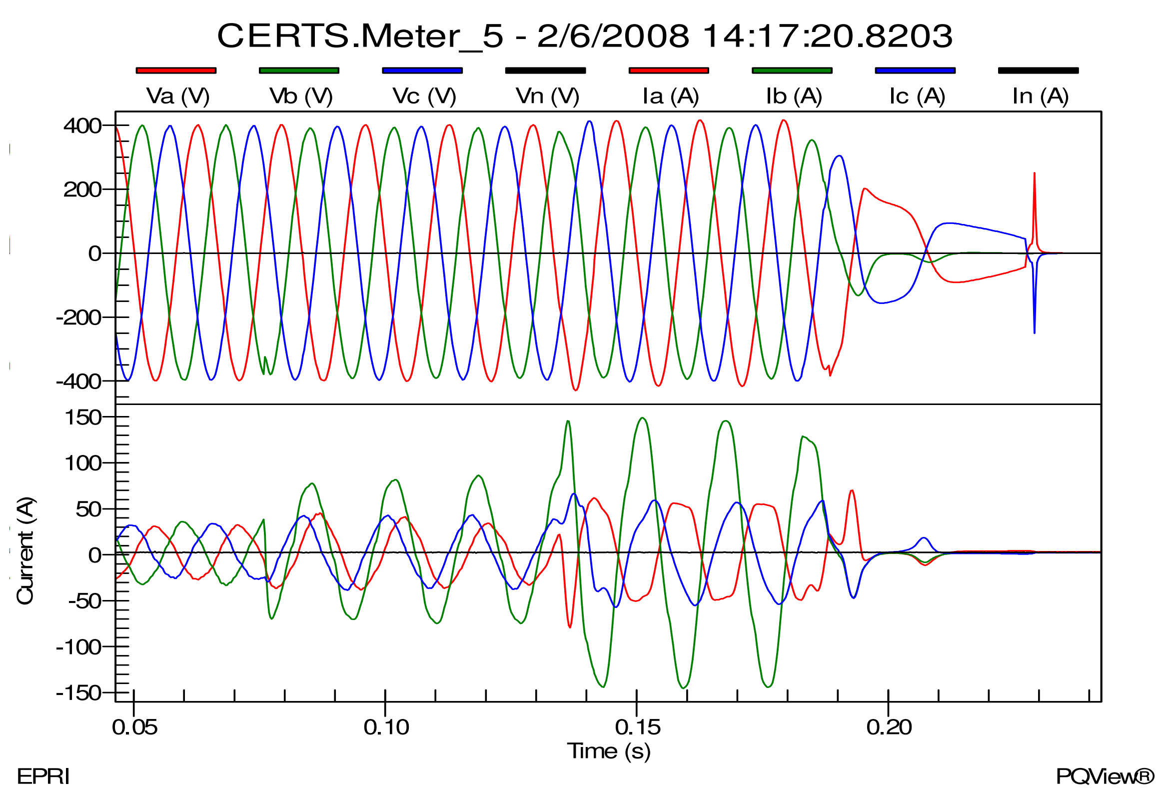

Figure17g- Meter 5 (CB51) voltage and current for a single phase-to-ground fault applied in Zone 5

The electrical system was stable in both the microgrid and utility grid after CB51 opened and Gen-set B1 shut down. Gen-set A1 was shut down manually, all loads and alarms were reset, and equipment was prepared for the next test.

6.1.9 Zone 4 B-Phase Line-to-Ground Fault, Gen-sets (A1+A2) and Utility Connected

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 4 with Gen-sets A1 and A2 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Gen-set A1 = Unit Power Control

Gen-set A2 = Unit Power Control

Gen-set A1 Output Power Command = 20kW

Gen-set A2 Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = B (Inst)

Reverse Power Set-point = 0kW

Load Bank 3 = 40kW

Load Bank 4 = 40kW

Load Bank 6 = 40 kW

To simulate a high impedance single phase-to-ground fault in Zone 4 on B-phase the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 5a with phases A and C disconnected. This, when combined with the load in Load Bank 4 of 40kW (approximately 13.3kW per phase), added 28.3kW to B-phase of Zone 4, causing an overload condition in Zone 4.

After both Gen-sets A1 and A2 were running for a few minutes and supplying power to Load Banks 3 and 4, the test was started with a "Start" command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid with the total power flow at Meter 1 being approximately 74kW, shown in Figure 18a, and approximately 36kW at Meter 2, shown in Figure 18b. Gen-sets A1 and A2 were producing about 20kW each, shown in Figures 18c and 18d before the fault was applied after 0 seconds.

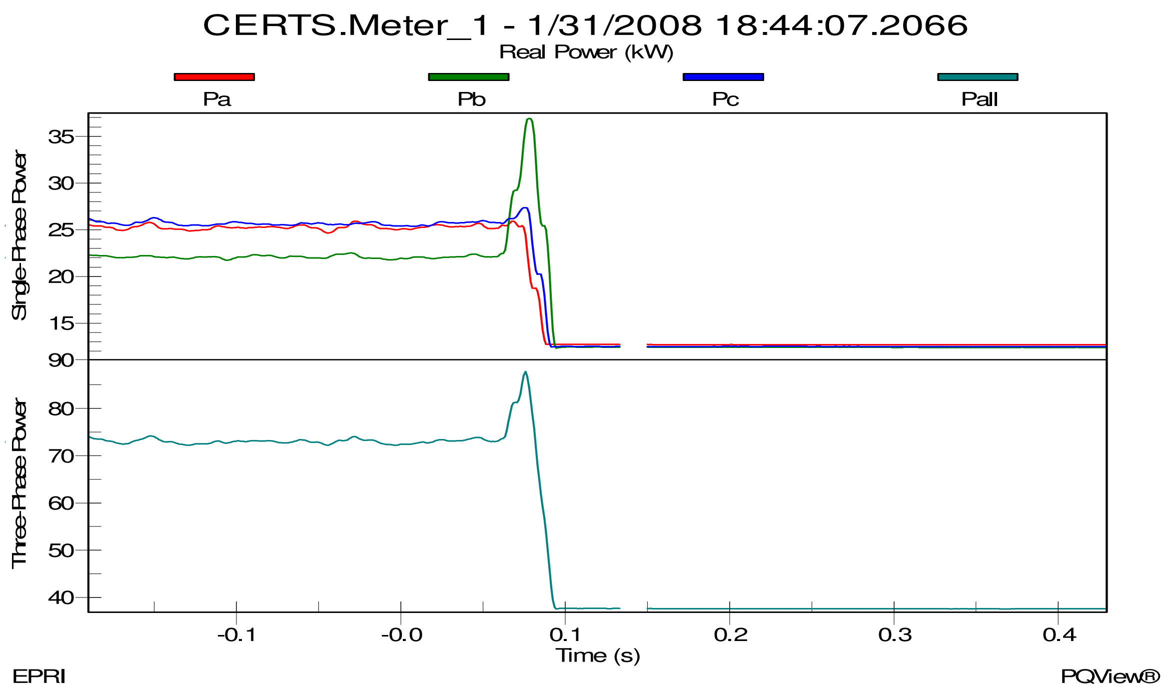

Figure 18a Meter 1 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 4.

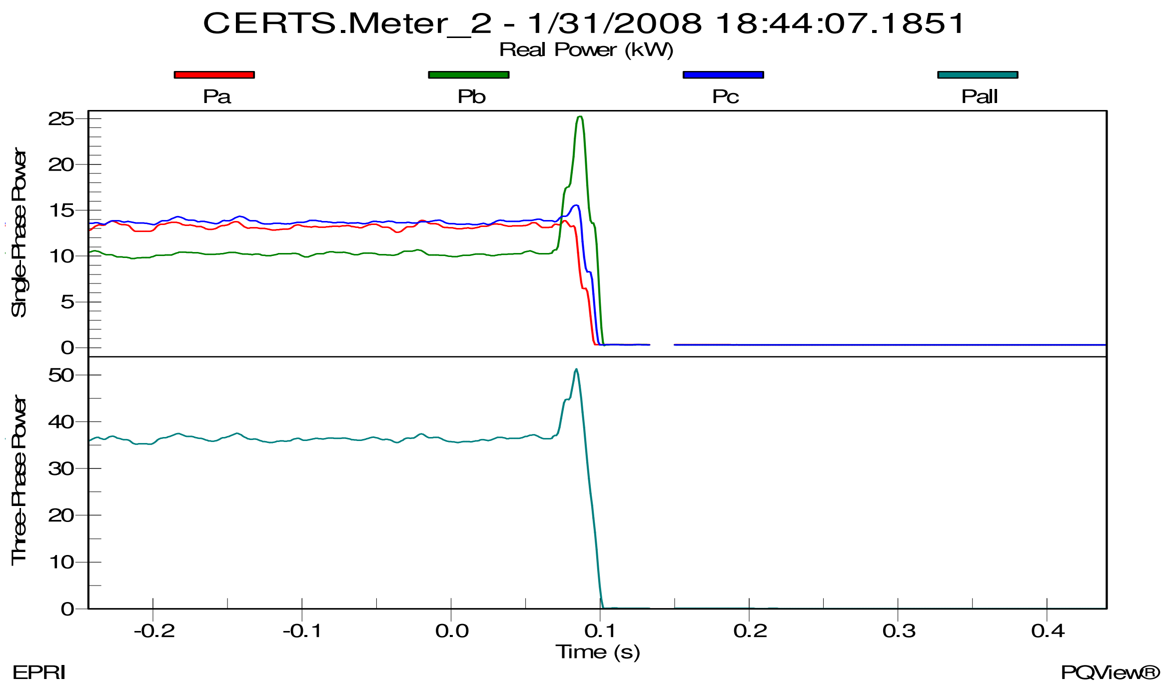

Figure 18b Meter 2 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 4.

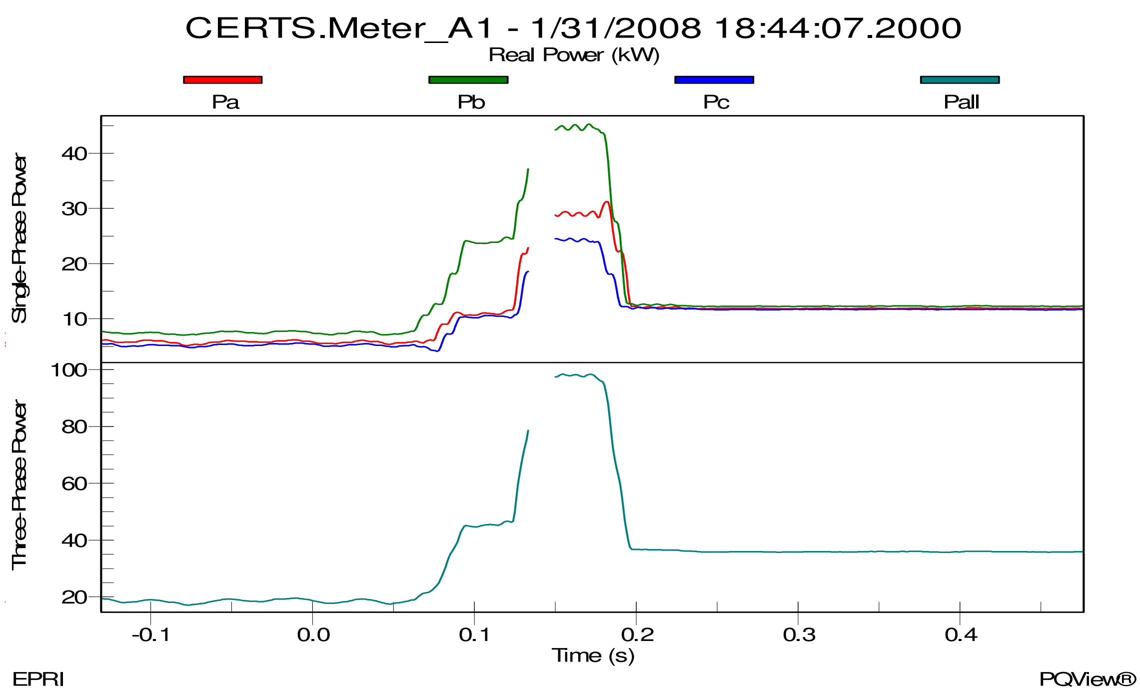

Figure 18c - Power produced by Gen-set A1 before/after the static switch and CB41 opened when a B-phase-to-ground fault was applied in Zone 4.

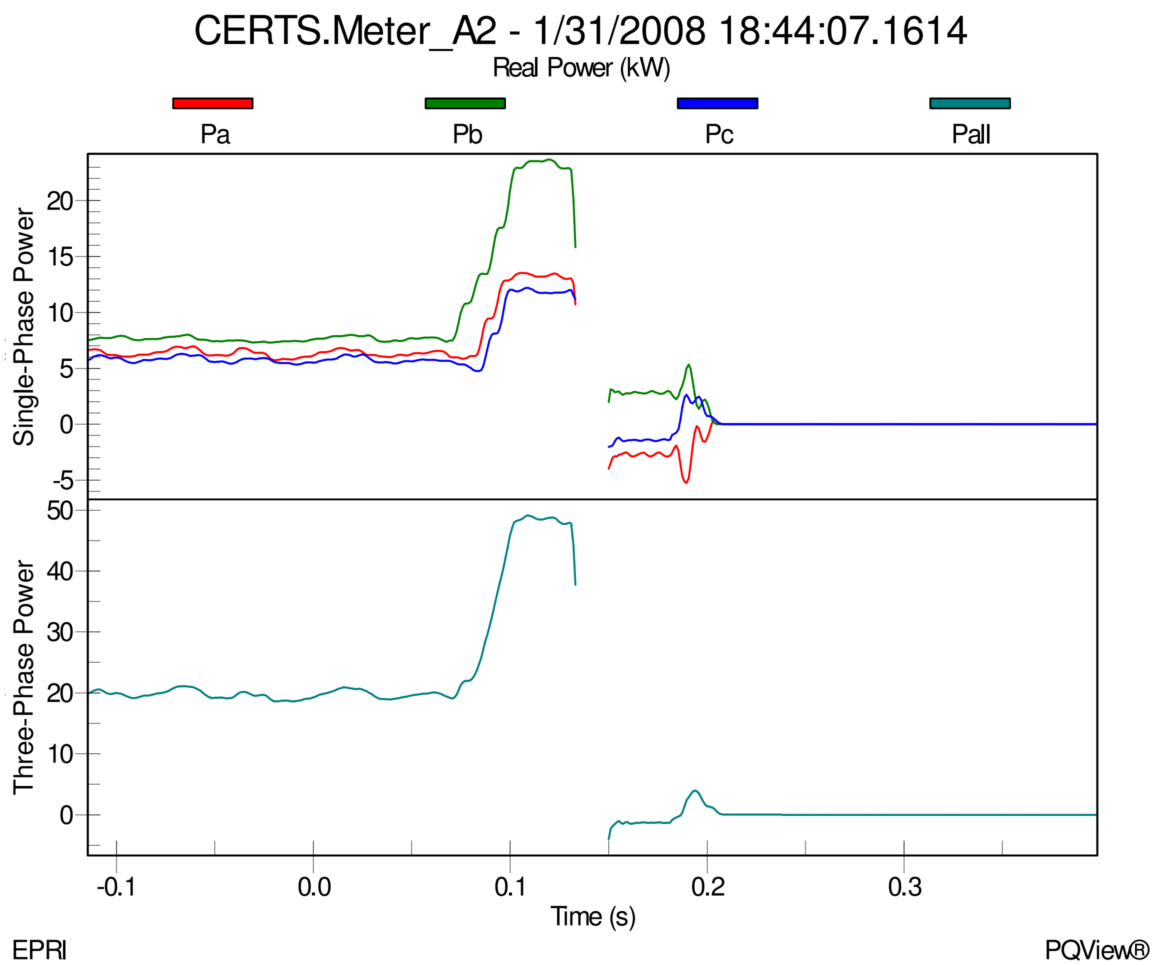

Figure 18d - Power produced by Gen-set A2 before/after the static switch and CB41 opened when a B-phase-to-ground fault was applied in Zone 4.

Using the DAS Load Control program, the single phase-to-ground fault on B-phase was set for 10 seconds and then initiated. The static switch tripped in approximately 0.007 seconds (~0.4 cycles) from a ground over-current (67N1T), shown in Figure 18e, islanding the microgrid from the rest of the utility grid. Relay 4 tripped after approximately 0.058 seconds (~3.5 cycles) on a ground over-current (67N1T) signal, isolating Zone 4 from the rest of the microgrid, shown in Figure 18f.

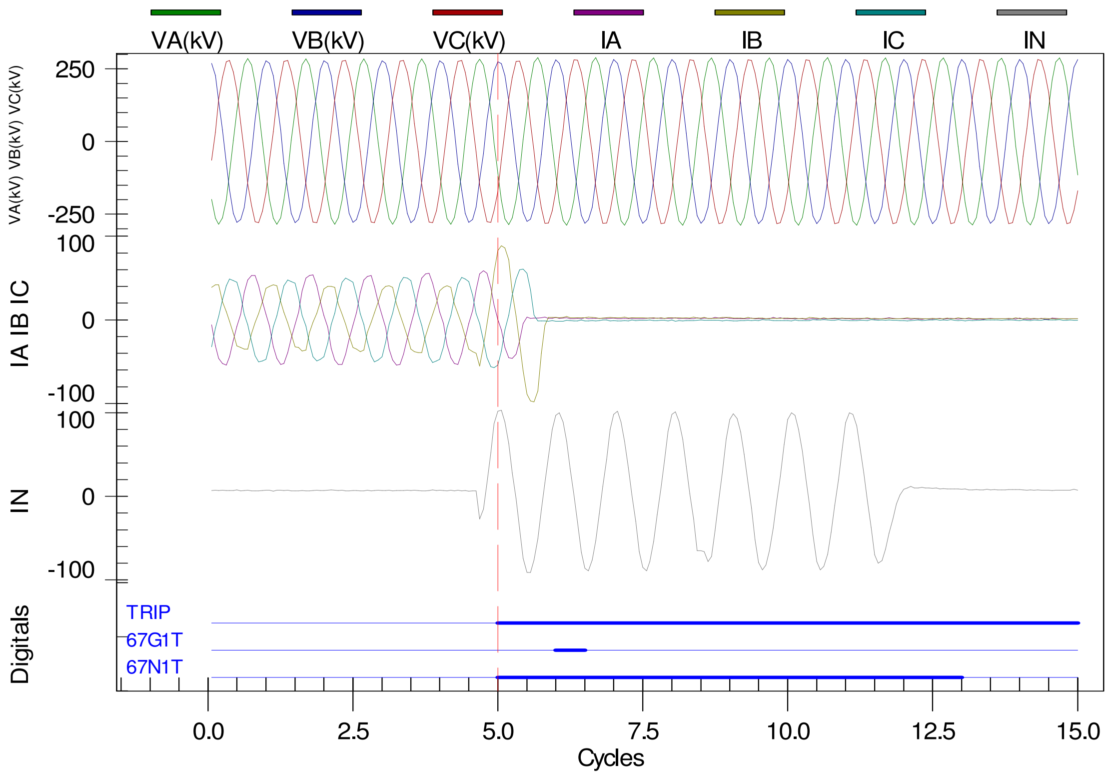

Figure 18e - Relay 2 (static switch) tripped due to a ground over-current (67N1T) when the single phase-to-ground fault is applied in Zone 4.

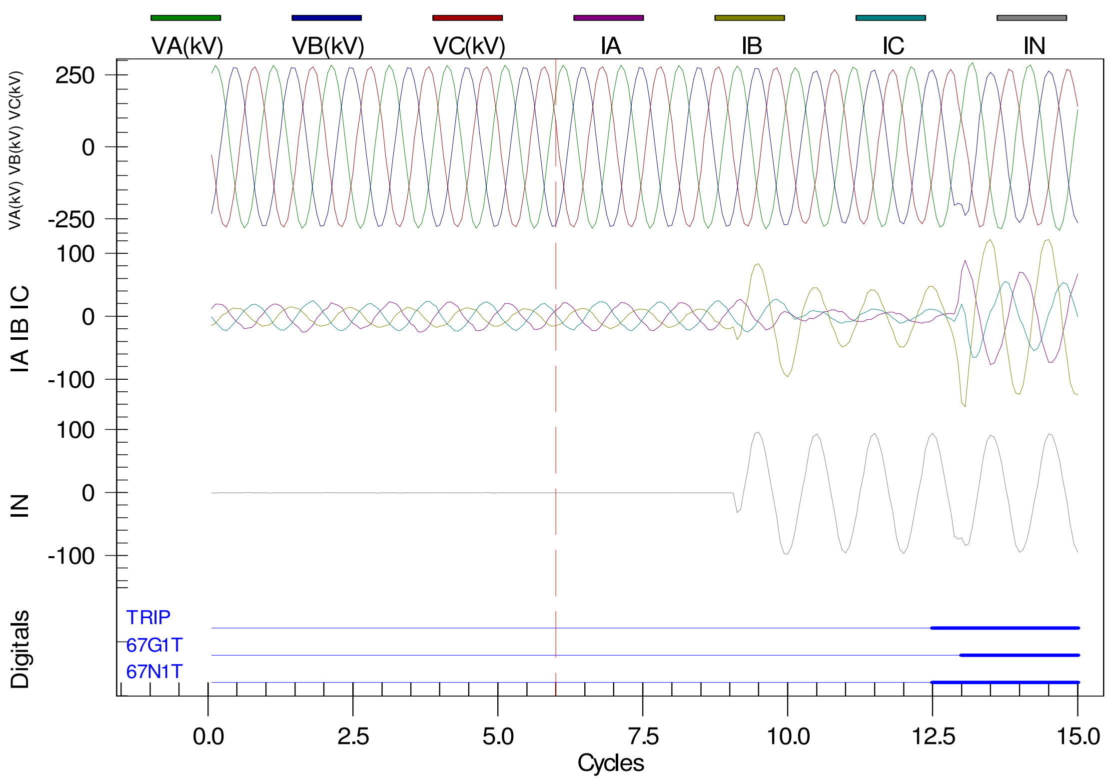

Figure 18f – Relay 4 (CB41) tripped due to a ground over-current (67N1T) when the single phase-to-ground fault was initiated in Zone 4

Gen-set A2 stopped switching approximately 0.008 seconds (~0.5 cycles) after Relay 4 tripped; however, its transformer contactor and CB41 remained closed for a short period. In Figures 18a and 18b power flow through Meter 1 was approximately 37.5kW, supplying only the load in Load Bank 6 from the utility. Load Bank 3 was supplied power from Gen-set A1, within the islanded microgrid, with output power raised from approximately 20kW to about 36kW to meet the load demand, Figure 18c. CB31 and CB51 remained closed throughout the entire test.

The electrical system was stable in both the microgrid and utility grid after the static switch opened, CB41 opened and Gen-set A2 shut down. A short duration later the static switch performed a synchronized close and reconnected the microgrid to the utility grid. Gen-set A1 was shutdown manually, all loads and alarms were reset, and equipment was prepared for the next test.

6.1.10 Zone 2 C-Phase Line-to-Ground Fault, Gen-sets (A1+B1) and Utility Connected

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 2 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify zero-sequence, negative-sequence or residual over-current protection.

Initial Setup:

Gen-set A1 = Unit Power Control

Gen-set B1 = Unit Power Control

Gen-set A1 Output Power Command = 20kW

Gen-set B1 Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = B (Inst)

Reverse Power Set-point = 0kW

Load Bank 3 = 40kW

Load Bank 4 = 40kW

Load Bank 6 = 40 kW

To simulate a high impedance single phase-to-ground fault in Zone 2 on C-phase the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 2d with phases A and B disconnected. This, when combined with the load in Load Banks 3 and 4 of 40kW each (each at approximately 13.3kW per phase), added 28.3kW to C-phase in Zone 2 and caused an overload condition in Zone 2.

After both Gen-sets A1 and B1 were running for a few minutes and supplied power to Load Banks 3 and 4, the test was started with a "Start" command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid with the total power flow at Meter 1 being approximately 68kW, shown in Figure 19a, and approximately 32kW at Meter 2, shown in Figure 19b. Gen-sets A1 and B1 were producing about 20kW each, shown in Figures 19c and 19d before the fault was applied after 0 seconds.

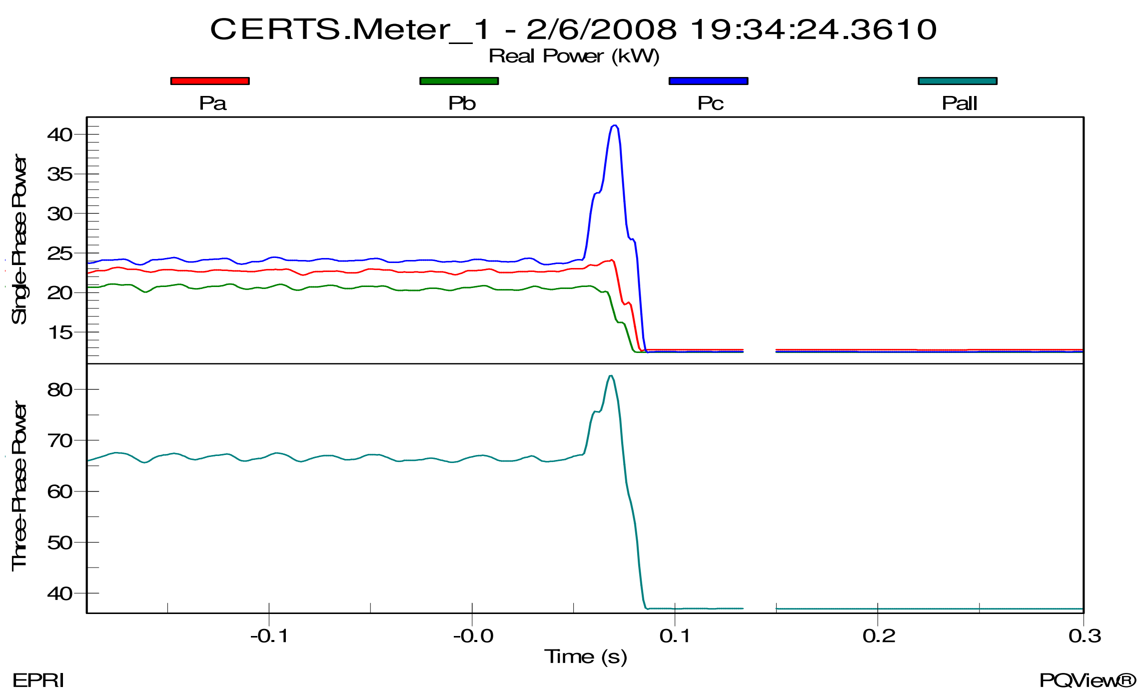

Figure 19a Meter 1 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 2.

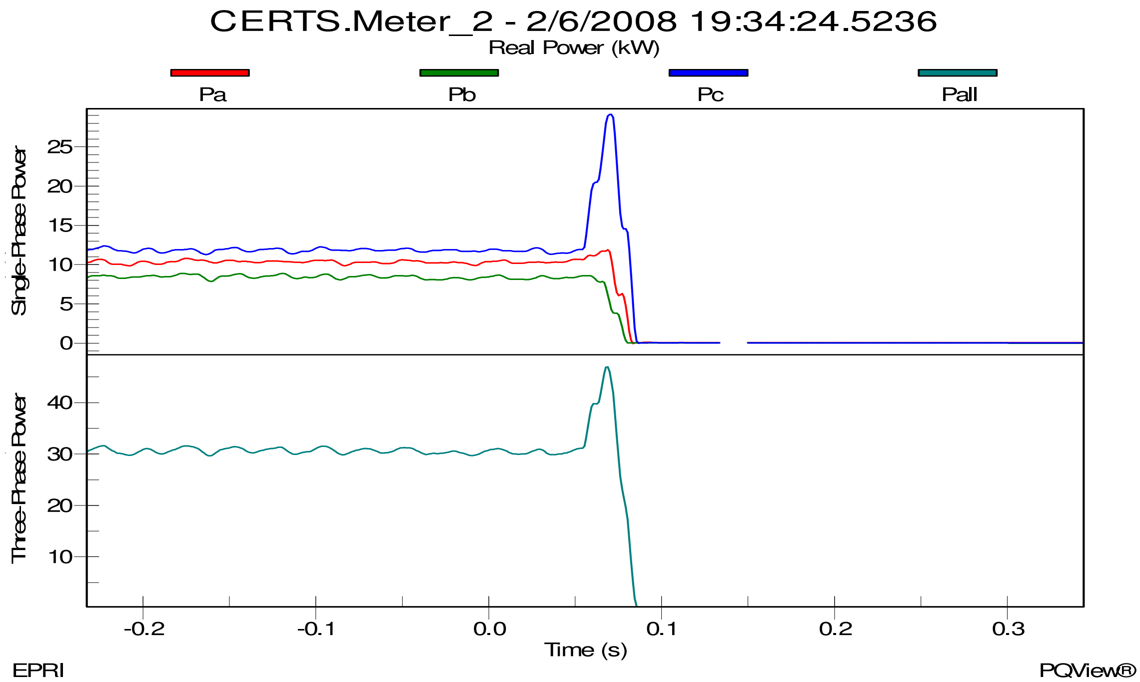

Figure 19b – Meter 2 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 2.

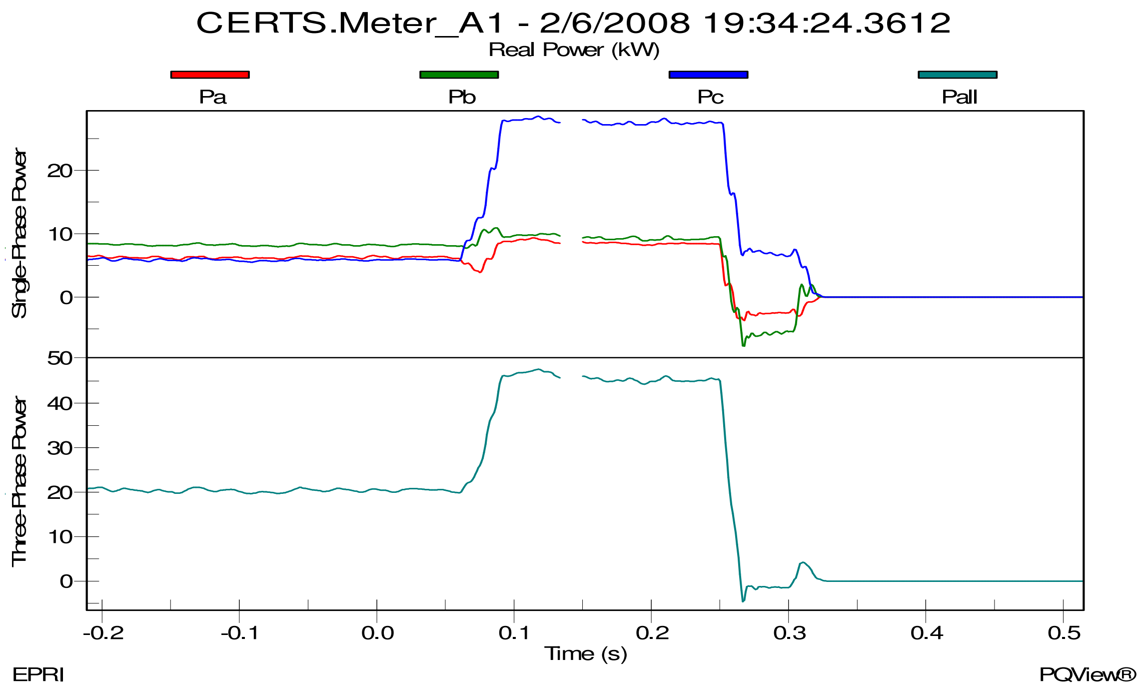

Figure 19c - Power produced by Gen-set A1 before/after the static switch opened from a C-phase-to-ground fault in Zone 2.

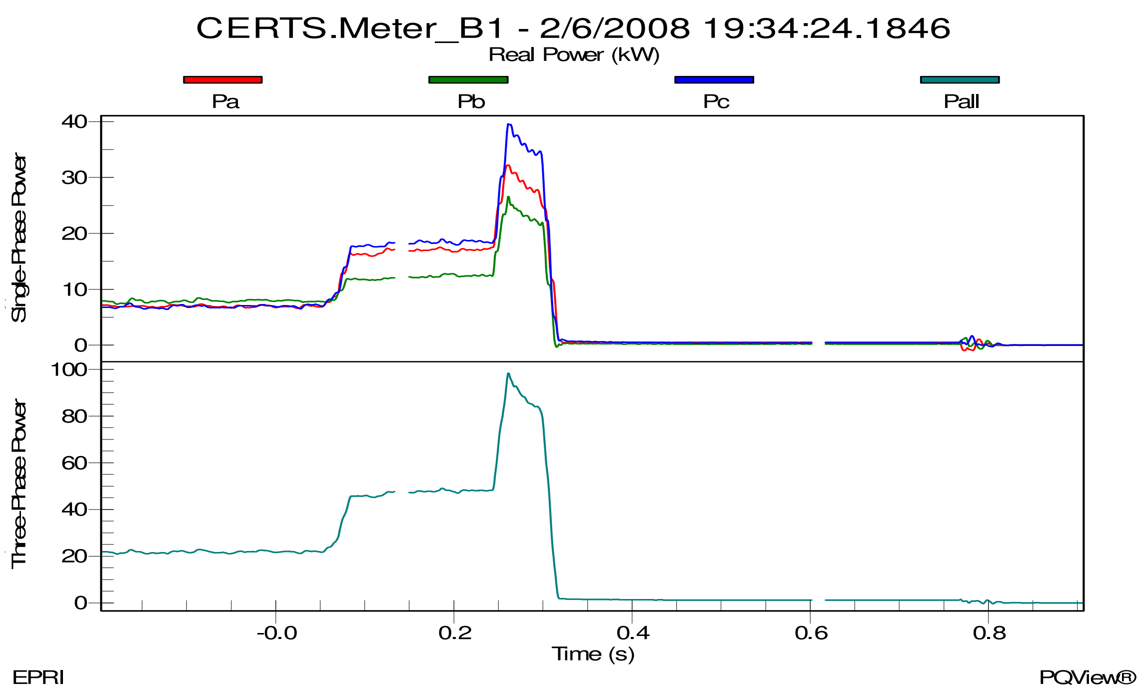

Figure 19d - Power produced by Gen-set B1 before/after the static switch opened from a C-phase-to-ground fault in Zone 2.

Using the DAS Load Control program, the single phase-to-ground fault on C-phase was set for 10 seconds and then initiated. Relay 2 tripped the static switch first on ground over-current (67N1T) in approximately 0.02 seconds (1 cycle) after the fault was applied, Figure 19e. Both Gen-sets A1 and B1 ramped up carrying Load Banks 3 and 4, as well as the C phase overload fault. Relay 3 tripped approximately 0.17 seconds (10.4 cycles) after the static switch opened, causing Gen-set A1 to stop switching its output, although its transformer contactor and CB31 remained closed for a few cycles longer. This can be seen by the reverse power on A and B phases supplying C phase even though the net three phase power remains zero, Figure 19c. CB31 opened 0.046 seconds (2.75 cycles) after receiving the trip signal from Relay 3, separating Zones 3 and 4 from the microgrid.

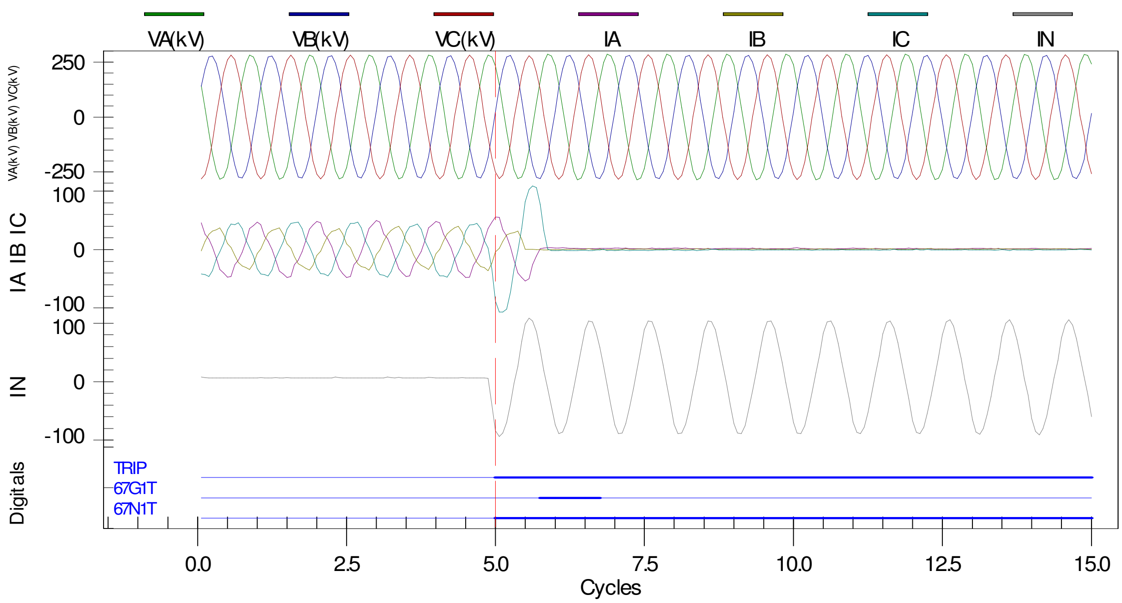

Figure 19e - Relay 2 (static switch) tripped due to a gournd over-current (67N1T) when the single phase-to-ground fault was initiated in Zone 2.

Gen-set B1 remained on-line supporting the fault load bank in Zone 2, Figure 19f. Because the static switch and CB31 were now open, Zone 2 was dominated by the Delta winding of T51 and effectively turned the entire zone into a 3-wire system. However, the measurement transformers which feed the DSP controller and the under-voltage relay 5a were connected wye-wye and likely experienced a full phase to phase voltage (480V) across their primary windings (277V), Figure 19g. Because only high impedance measurement equipment was connected to the secondaries of these transformers, negligible fault current flowed through them. Since the fault was applied from C phase-to-ground there remained no path for current flow and the fault was effectively removed.

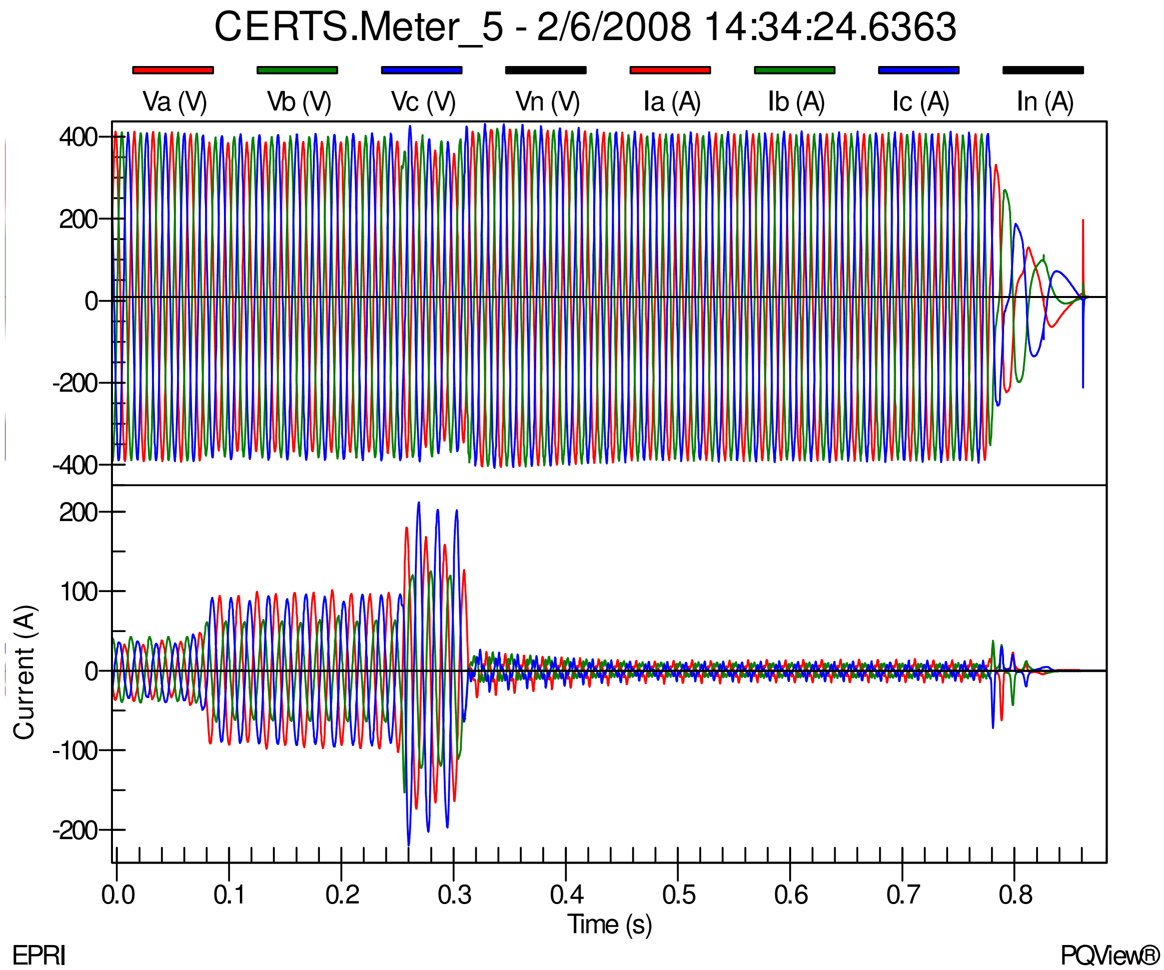

Figure 19f - Meter 5 voltage and current during the applied single-phase-to-ground fault in Zone 2.

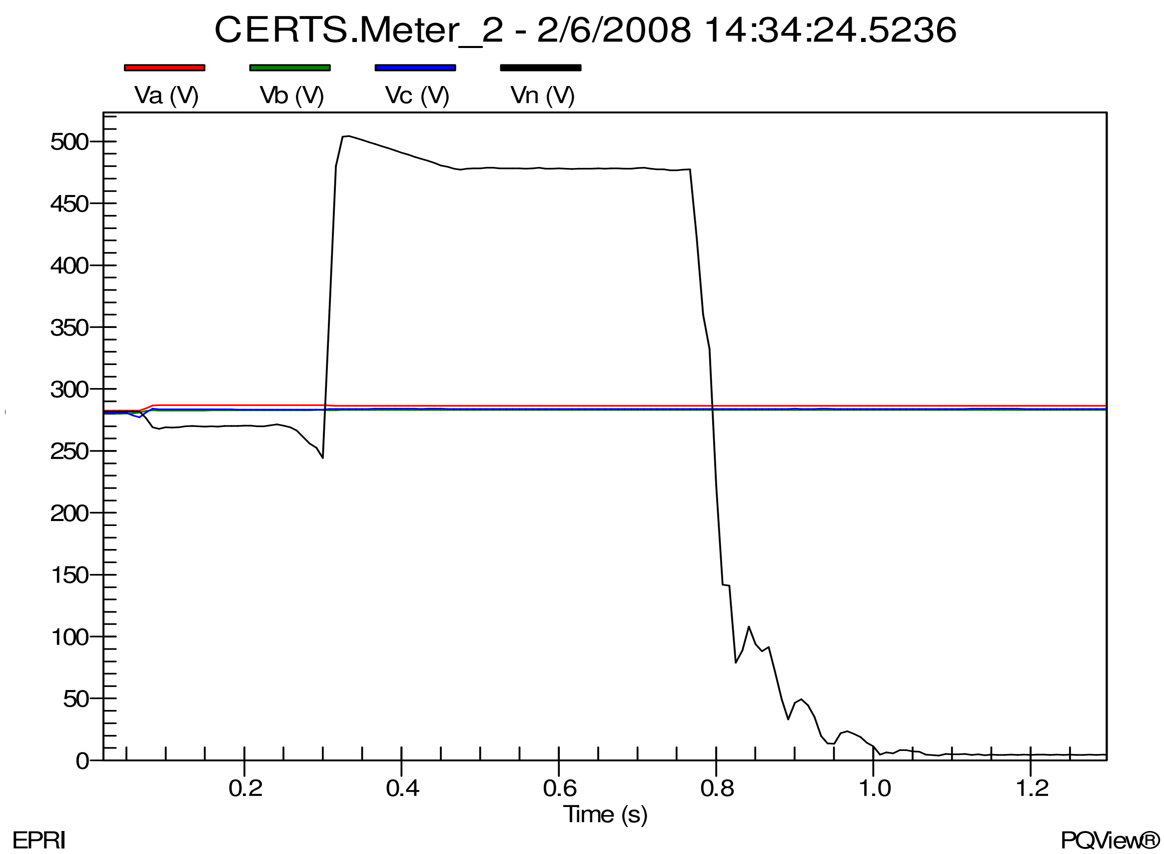

Figure 19g – Meter 2 RMS voltage before/after CB31 opened.

Finally Gen-set B1 was tripped off-line by under-voltage Relay 5a (SV4T) as can be seen in Relay 5, Figure 19h. As mentioned above, voltage remained within Zone 2 after the static switch and CB31 opened, therefore it must be assumed that either the fusing on Relay 5a operated or that it was damaged by excessive voltage that occurred during the fault. This was interpreted as an under-voltage and caused Relay 5 to trip incorrectly, shutting down Gen-set B1 and opening CB51. Relay 5 tripped approximately 0.5 seconds (30 cycles) after CB31 opened.

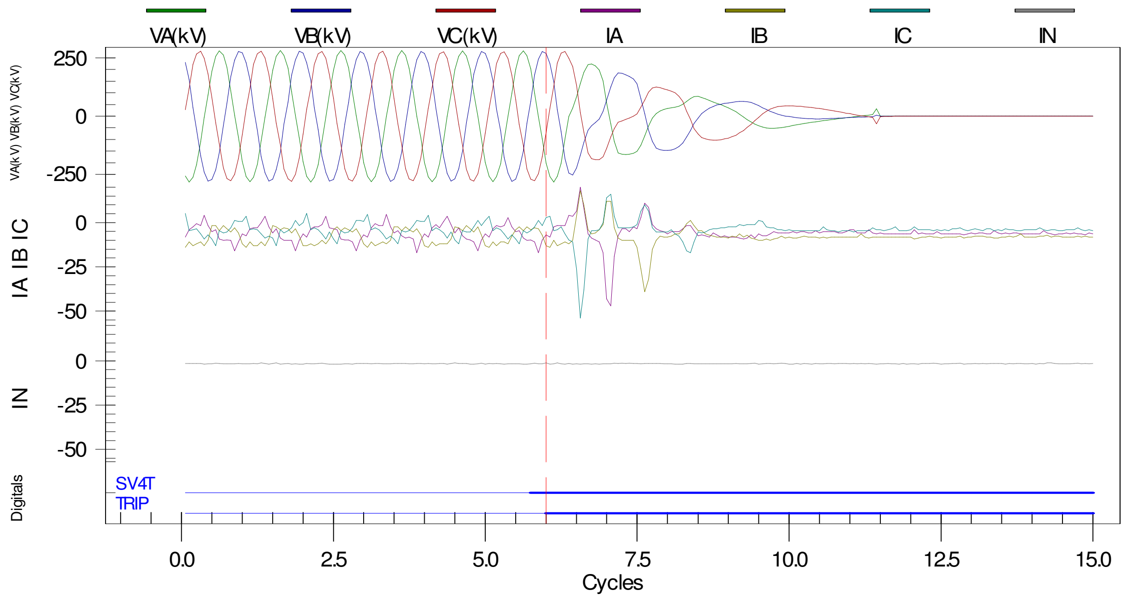

Figure 19h - Relay 5 (CB51) tripped due to an undervoltage at T51 when the single phase-to-ground fault was initiated in Zone 2.

The electrical system was stable in both the microgrid and utility grid after the static switch opened, CB31 and CB51 opened, and Gen-sets A1 and B1 shut down. All loads and alarms were reset and equipment was prepared for the next test.

6.1.11 <u>Zone 6 C-Phase Line-to-Ground Fault, Gen-set A1 and Utility Connected</u>

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 6 with Gen-set A1 operating in-parallel with the utility grid to verify I^2t protection.

Initial Setup:

Gen-set A1 = Unit Power Control

Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = A (Delayed)

Load Bank 3 = 40kW

Load Bank 6 = 60kW

To simulate a high impedance single phase-to-ground fault in Zone 6 on C-phase the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 8a with phases A and B disconnected. This, when combined with the load in Load Bank 6 of 60kW (20kW per phase), added 28.3kW to C-phase in Zone 6 and caused an overload condition.

After Gen-set A1 was running for a few minutes and supplied power to Load Bank 3, the test was started with a "Start" command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid with the total power flow at Meter 1 being approximately 68.5kW, shown in Figure 20a, and approximately 16kW at Meter 2, shown in Figure 20b. Gen-set A1 was producing about 20.5kW, shown in Figures 20c before the fault was applied after 0 seconds.

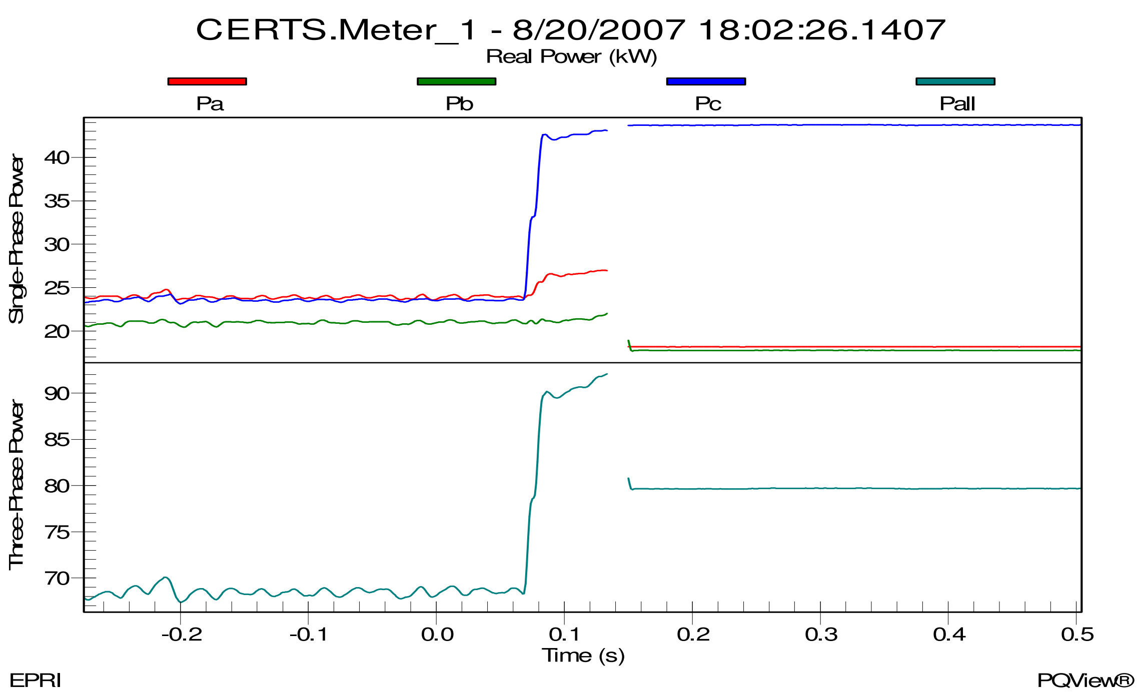

Figure 20a - Meter 1 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 6.

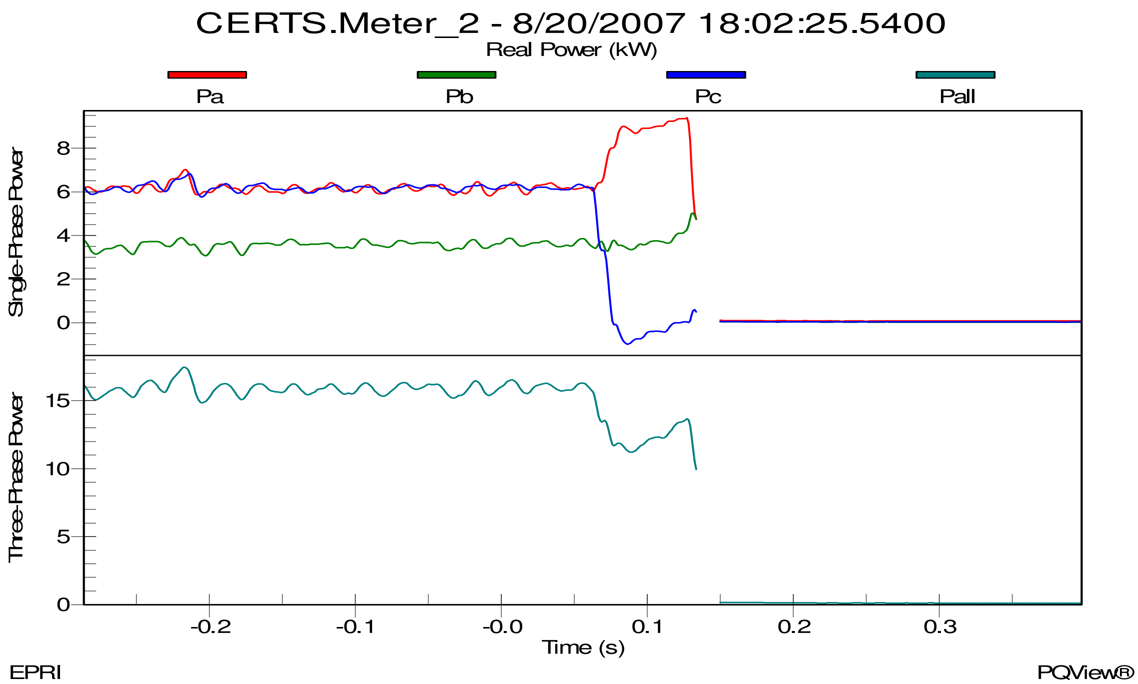

Figure 20b - Meter 2 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 6.

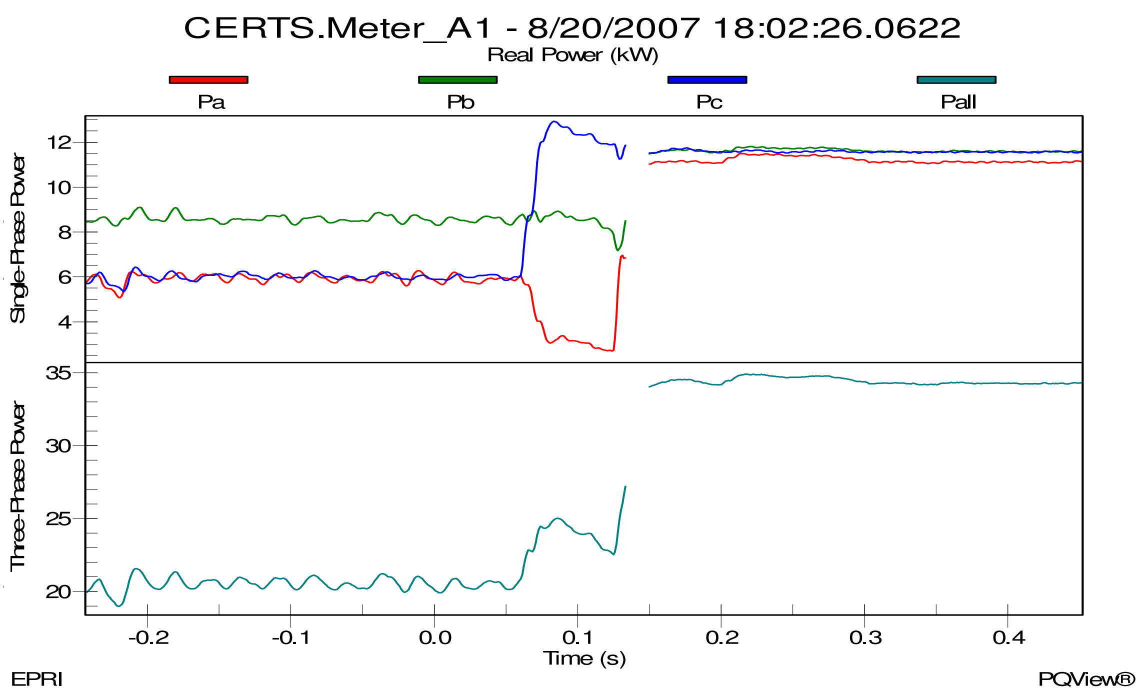

Figure 20c - Power produced by Gen-set A1 before/after the static switch opened from a C-phase phase-to-ground fault in Zone 6.

Using the DAS Load Control program, the single phase-to-ground fault on C-phase was set for 10 seconds and then initiated. The static switch tripped in approximately 0.07 seconds (~4.3 cycles) from a neutral over-current (67G1T), shown in Figure 20d, islanding the microgrid from the utility grid. Following the static switch operation, CB13, which provides protection to Zone 6, tripped on I^2t protection with CB31, CB41 and CB51 remaining closed, since the overload fault was not part of the microgrid, located beyond the static switch.

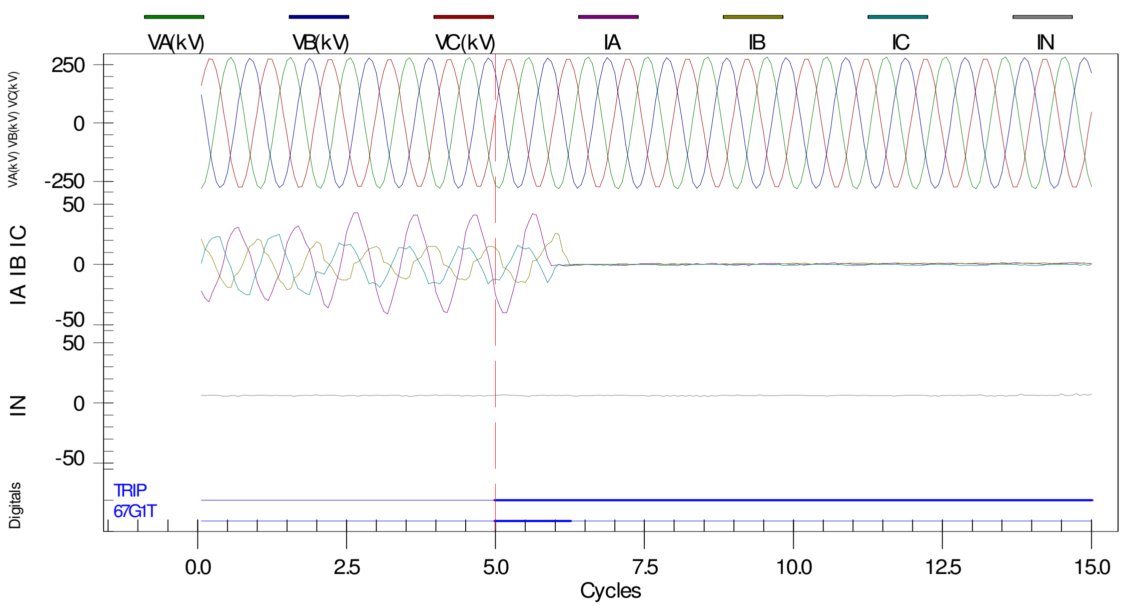

Figure 20d - Relay 2 (static switch) tripping due to a ground over-current (50GR) when the single phase-to-ground fault was initiated in Zone 6.

The electrical system was stable in both the microgrid and utility grid after the static switch opened and CB13 opened. Gen-set A1 was manually shut down with all loads and alarms reset and equipment was prepared for the next test.

A few points of interest for this test include the Gen-set contribution to the fault and the sensitivity of the static switch to an unbalanced load within the unprotected portion (i.e., Zone 6) of the microgrid. In Figure 20c it can be seen that at Meter A1, just after the fault was applied, three phase power increased slightly from 20kW to 25kW, with C-phase output increasing and A-phase output decreasing. Because the three phase power increased by approximately 5kW, it must be concluded that Gen-set A1 did increase its power output. The reduction in A-phase power which contributed to the C-phase increase in power is likely due to the delta winding of the inverter transformer, which cannot be confirmed, since there are no meter provisions on that side.

The second point of interest for this test is that the static switch is sensitive to load unbalance in Zone 6 of the microgrid. In this test, had the unbalance not tripped CB13, removing it from the system, the static switch after a short period of time would have reconnected to the utility briefly before tripping off again. This process would have continued indefinitely or until some other system parameter was altered. In future installations, consideration must be given to this to prevent unattended operation in this manner.

6.1.12 Zone 6 C-Phase Line-to-Ground fault, Gen-sets (A1+B1) and Utility Connected

Performance Goal:

Test a single line-to-ground overload fault condition in Zone 6 with Gen-sets A1 and B1 operating in-parallel with the utility grid to verify I^2t protection.

Initial Setup:

Gen-set A1 = Unit Power Control

Gen-set B1 = Unit Power Control

Gen-set A1 Output Power Command = 20kW

Gen-set B1 Output Power Command = 20kW

MG Power/Frequency Droop = -0.0833 Hz/kW

MG Voltage Command = 277V

Relay Settings = A (Delayed)

Reverse Power Set-point = 0kW

Load Bank 3 = 40kW

Load Bank 5 = 40kW

Load Bank 6 = 60 kW

To simulate a high impedance single phase-to-ground fault in Zone 6 on C-phase the Overload Load Bank of 85kW (approximately 28.3kW per phase) was connected by cable/plug into the exterior receptacle of Cabinet 8a with phases A and B disconnected.

This, when combined with the load in Load Bank 6 of 60kW (approximately 20kW per phase), added 28.3kW to C-phase in Zone 6 and caused an overload condition in Zone 6.

After both Gen-sets A1 and B1 were running for a few minutes and supplied power to Load Banks 3 and 5, the test started with a "Start" command from the EMS. As soon as the static switch closed and steady-state conditions established, the microgrid and Load Bank 6 were connected to the utility grid with the total power flow at Meter 1 being approximately 89kW, shown in Figure 21a, and approximately 35kW at Meter 2, shown in Figure 21b. **B**efore the overload fault was applied, Gen-set A1 was producing approximately 17kW and Gen-set B1 was producing approximately 19kW, shown in Figures 21c and 21d, respectively.

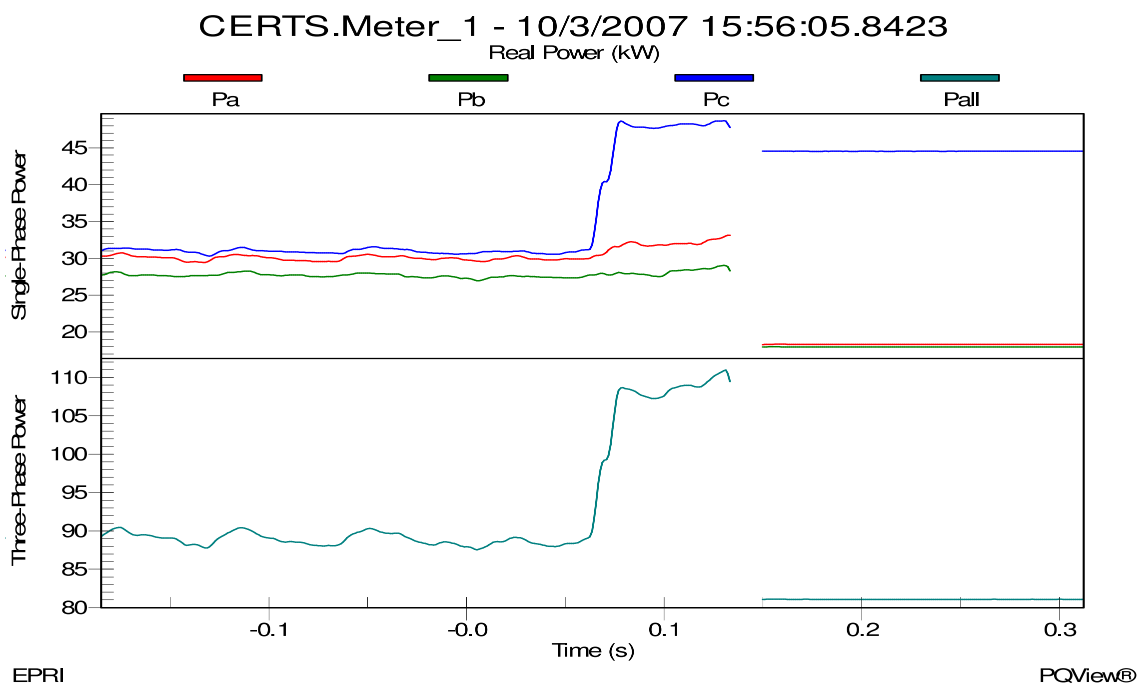

Figure 21a Meter 1 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 6.

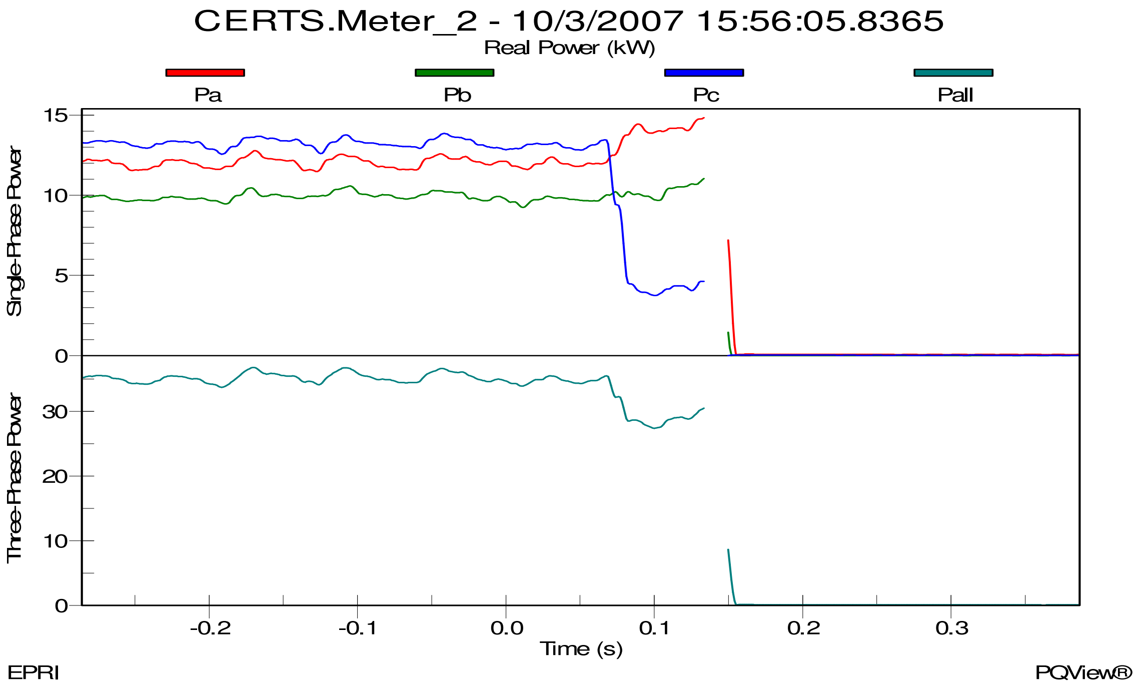

Figure 21b Meter 1 power flow before/after the static switch opened, islanding the microgrid from the utility grid when a single phase-to-ground fault was applied in Zone 6.

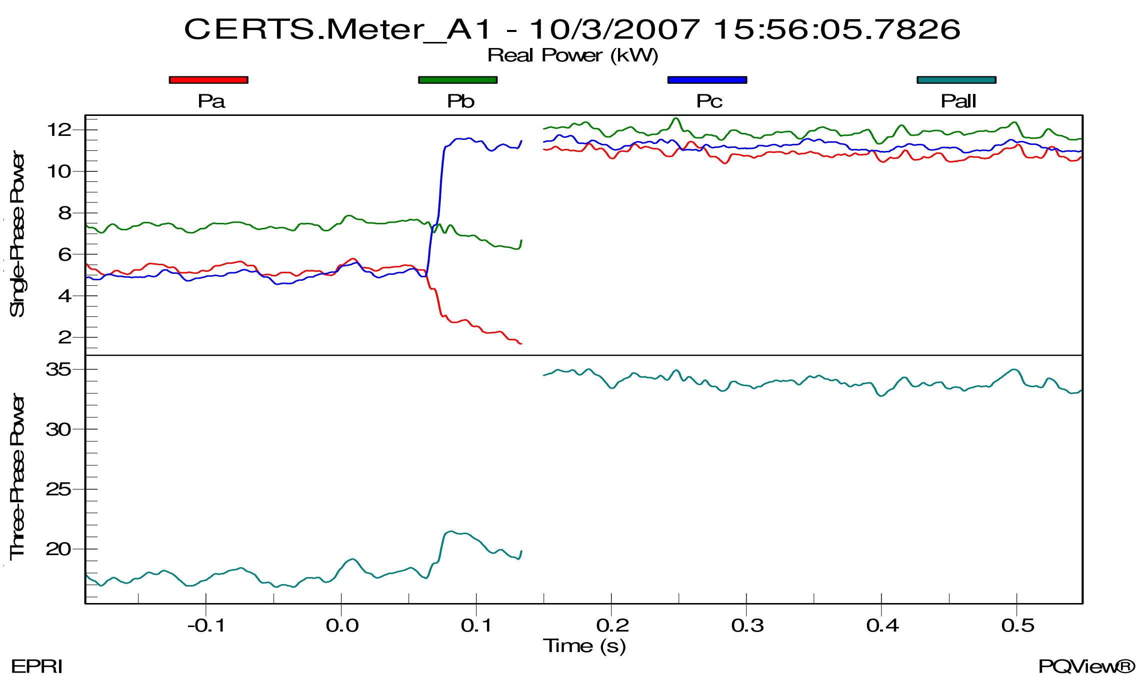

Figure 21c - Power produced by Gen-set A1 before/after the static switch opened from a C-phase-to-ground fault in Zone 6.

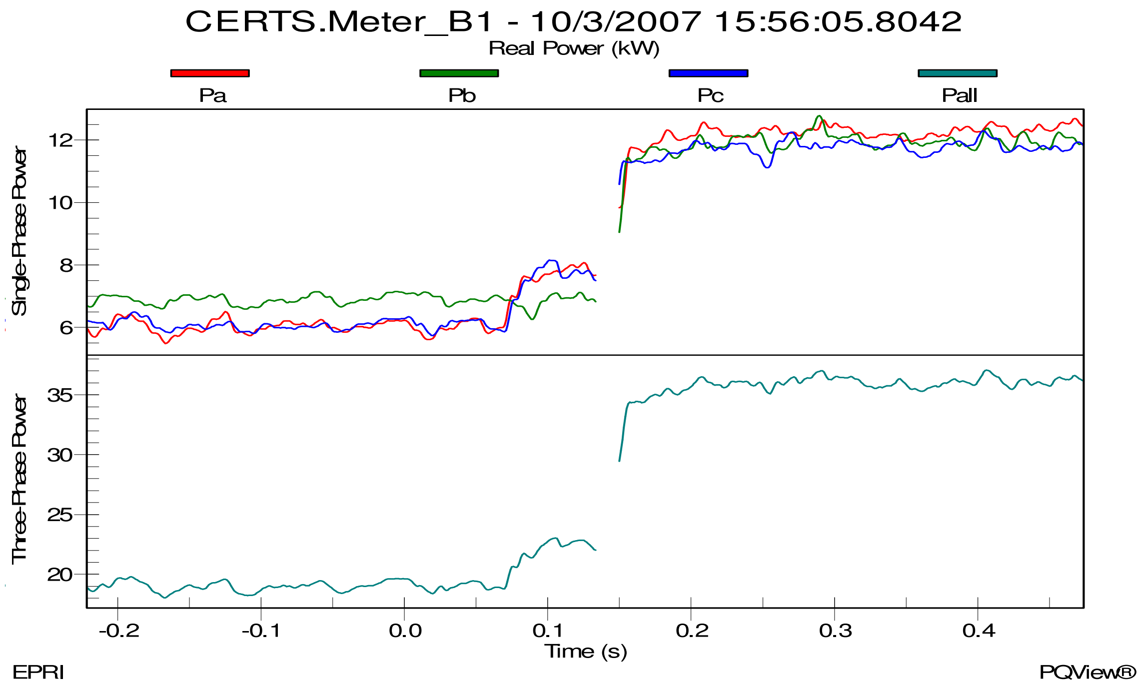

Figure 21d - Power produced by Gen-set B1 before/after the static switch opened from a C-phase-to-ground fault in Zone 6.

Using the DAS Load Control program, the single phase-to-ground fault on C-phase was set for 10 seconds and then initiated. The static switch tripped in approximately 0.07 seconds (~4.3 cycles) from a neutral over-current (67G1T), shown in Figure 21e, islanding the microgrid from the utility grid. Following the static switch operation, CB13, which provides protection to Zone 6, tripped on I^2t protection with CB31, CB41 and CB51 remaining closed, since the overload fault was not part of the microgrid, located beyond the static switch.

Within the islanded microgrid, Gen-sets A1 and B1 increased their output power to Load Banks 3 and 5. Gen-set A1 increased its output power from approximately 17kW to 34kW, and Gen-set B1 increased its output power from approximately 19kW to 36kW, shown in Figures 21c and 21d, respectively. Meter 2 (i.e., Figure 21b) power flow decreased to 0kW after the fault was initiated and the static switch opened. After the overload fault was cleared from the electrical system, Meter 1 (i.e., Figure 21a) power flow decreased to 80kW from the utility grid. The utility grid and microgrid remained in this stable state until the fault was removed.

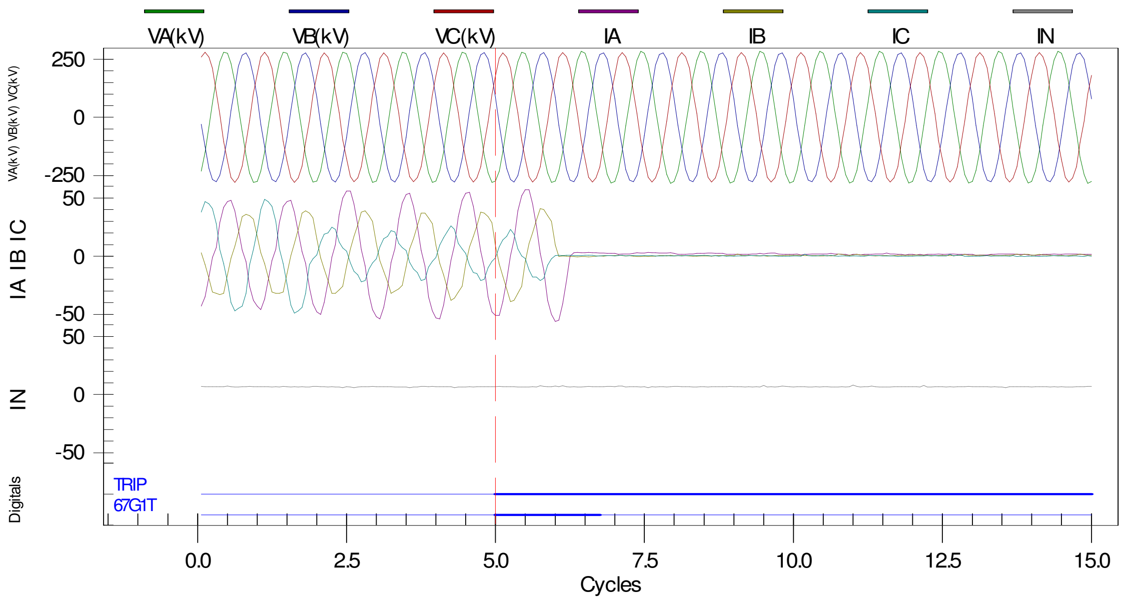

Figure 21e - Relay 2 (static switch) tripped due to a neutral over-current (67G1T) when the single phase-to-ground fault was initiated in Zone 6.

This test also produced the two points of interest mentioned in the previous test. These tests were similar with the exception that Gen-set B1 was less affected by the phase-to-ground fault due to transformer T51. Gen-set B1 did increase its power output by approximately 2kW; however, it was spread more evenly across A- and C-phases. Also, both A- and C-phases increased in power output instead of A-phase reducing as in the last test. The static switch still remains sensitive to unbalanced load within Zone 6 of the microgrid.

A third point of interest developed in this test, while waiting for the data to finish being collected from the metering equipment. Both Gen-set A1 and B1 shut down prematurely after the test was completed. This shutdown was captured by the metering equipment and can be used as insight into what caused the shutdown. Gen-set A1 reported a "No Field Fault" and B1 reported a "Boost Fault". Figure 21f indicated Gen-set A1 produced a 150kW increase of power for a short period of time. This matched up with Figure 21g indicating Gen-set B1 draws-in a large amount (i.e., 95kW) of power for a short period of time. These Gen-sets were not designed to absorb power, thus, it can be assume that the cause for this premature shutdown was attributed to Gen-set B1.

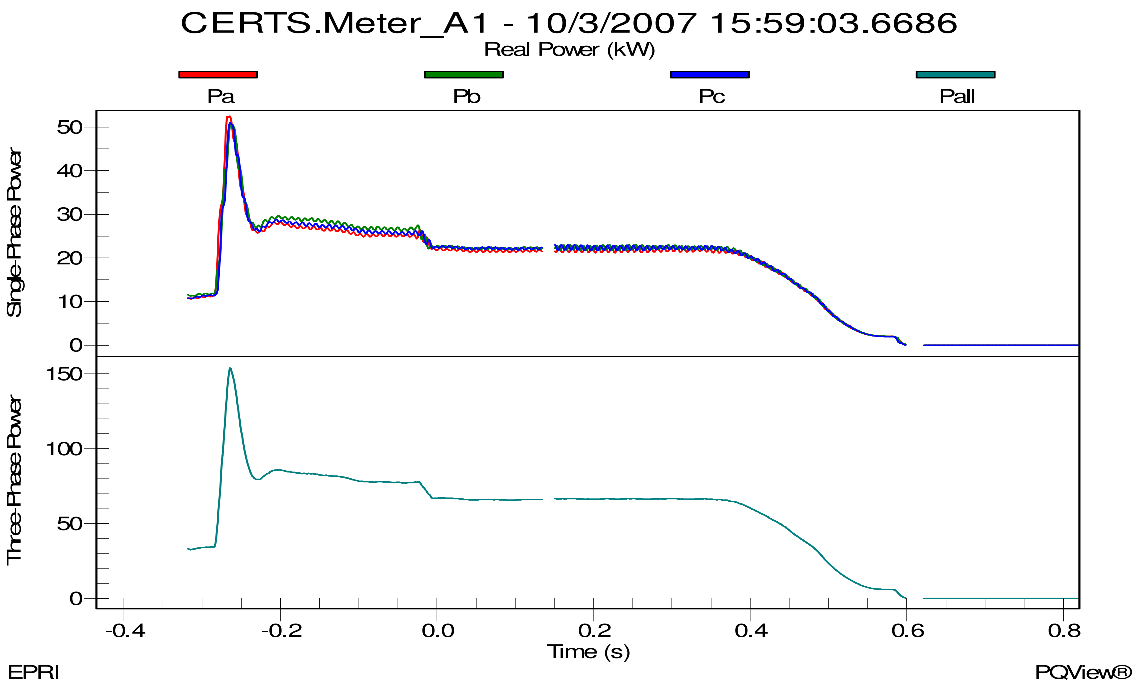

Figure 21f – Gen-set A1 shutting down due to a "No Field" fault.

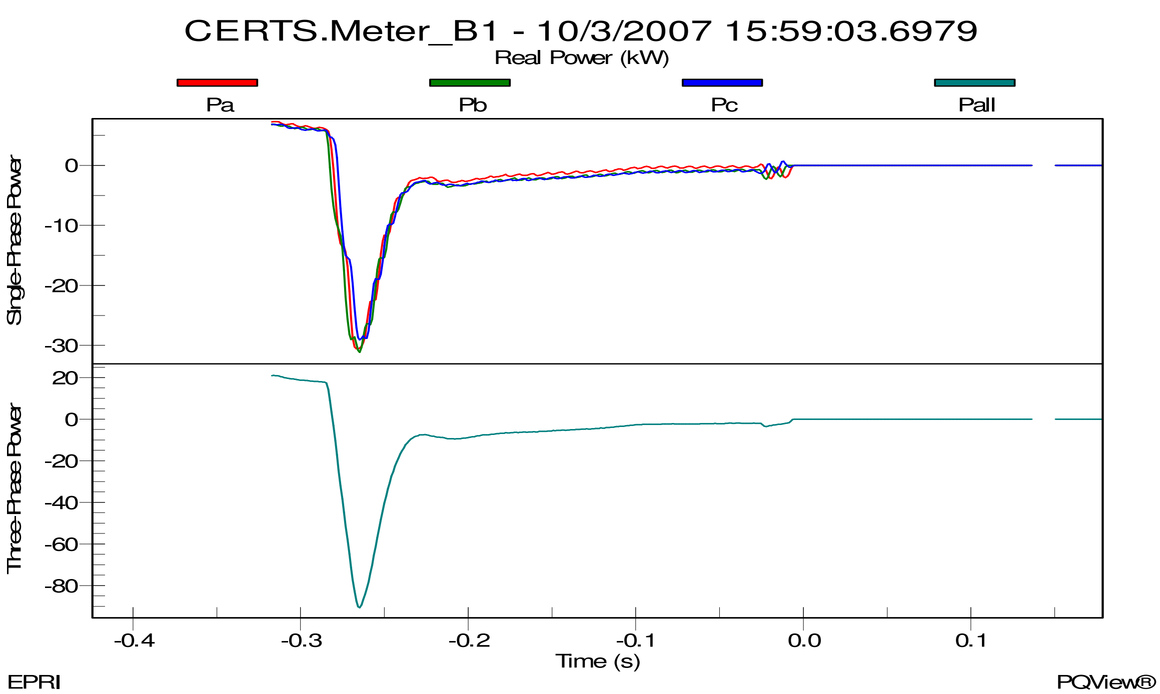

Figure 21g – Gen-set B1 shutting down due to a "Boost" fault