CERTS Microgrid
Tecogen InVerde INV100 Test Report

3/5/2012

D. Klapp, R. Zimmerly, J. Howard
AEP Dolan Technology Center
Groveport, OH

Table of Contents

1. Definitions and Acronyms

1.1. **AEP**: American Electric Power
1.2. **CB1**: Safety circuit breaker for test bed 1
1.3. **CERTS**: Consortium for Electrical Reliability Technology Solutions
1.4. **CHP**: Combined heat and power
1.5. **DR:** Distributed resource
1.6. **EMS**: Energy Management System
1.7. **Genset A1**: Number assignment to the InVerde INV 100 within the test bed environment
1.8. **Genset A2**: Number assignment to one of the 60kW Tecogen prototype units within the test bed environment
1.9. **Genset B1**: Number assignment to one of the 60kW Tecogen prototype units within the test bed environment
1.10. **LB3**: Load bank 3, capable of 95kW and 60kVAR output
1.11. **LB4**: Load bank 4, capable of 95kW and 60kVAR output
1.12. **LB5**: Load bank 5, capable of 95kW and 60kVAR output
1.13. **PCS:** Power Conditioning System
1.14. **PMG:** Permanent Magnet Generator
1.15. **Tecogen**: Genset manufacturer and provider of three 60kW rated prototype units, and the 100kW rated InVerde INV100 unit for the Walnut Site test bed

2. Executive Summary

The CERTS microgrid project at AEP is now in its third phase. One of the milestones of this phase is to install and commission a Tecogen InVerde INV100 genset. This is a natural gas fueled, combined heat and power "CHP" genset capable of producing 100kW of electrical load. Previous phases of the project included functional testing of Tecogen 60kW prototype units, and sufficient results were gained. During that period, Tecogen developed the commercially available InVerde INV100. This new unit diverged enough from the prototype units to warrant the replacement of a prototype in the test bed with one of these commercial units.

The installation process for the InVerde INV100 utilized some of the existing connection points that belonged to the prototype unit. However, some conductor upgrades were required as well as an additional cooling tower to account for the increased electrical capacity. The associated circuit breaker, fused disconnect, and bus transformer were also replaced with larger sized equipment rated for the larger load.

With the InVerde INV100 installed in the test bed, testing was performed on the unit. This procedure was modeled after that developed for the Tecogen prototype units. For these tests, data was to be gathered on black start capacity, frequency droop, voltage droop, emergency shutdown functionality, load step response, load sharing capability, and pmax controller. Since continuous run tests were completed on the prototype units, that portion was omitted from the InVerde INV100 testing.

After the initial round of testing was complete, it was determined that the unit had voltage instability issues. In order to fix this issue, the bus transformer was taken out of service and replaced with a reactance panel. The unit was then changed from a 3 wire to a 4 wire configuration. The same run of tests was then performed, and more satisfactory results were obtained.

3. Introduction

In phases 1 & 2 of the CERTS microgrid project at AEP's Dolan Technology Center, the test bed included three 60kW prototype induction gensets. These prime movers, manufactured by Tecogen, made up the whole of the project's generating capacity within the microgrid. Exhaustive testing has been performed on the prototypes to assess the integration of the CERTS controls in their power electronics that interface with the microgrid bus. Over the course of this testing, Tecogen developed the commercially available InVerde INV100 product. This new genset improves upon the prototype with the addition of a more organized power electronics cabinet, sound reduction encasing, and increased generating capacity. Since Tecogen has adopted the CERTS controls into a readily available product line, a need was identified to test its capability within the test bed environment. Also, the test results can show how much the commercial unit has diverged from the prototypes.

The InVerde INV100 replaced one of the existing prototype units within the genset enclosure at the test site, and utilized existing connections to the electrical bus and the natural gas line. After the installation, the InVerde INV100 was referred to as genset A1 within the test bed, which was the previously assigned to the prototype that it replaced. The main CERTS controls, such as frequency droop, voltage droop, and pmax limiter were tested for proper implementation in the inverter control. It was then put through the same set of functional tests as the prototypes, in order to produce comparable results to the previous phase of testing.

4. Equipment under Test

4.1. Tecogen InVerde INV100

The Equipment under test is an InVerde INV100 unit referred to as “A1”. It is a natural-gas engine driven, inverter-based “CHP” module that is capable of producing 100kW of continuous power as well as 230 °F hot water at a rate of 7.0 therms per hour. The low emissions engine drives a water cooled “PMG” at variable speed. The engine is operated over a wide speed range depending on the load requirement, resulting in a highly variable frequency output from the PMG. The “PCS”, which includes an inverter and a rectifier, was designed into the unit to convert the “PMG” output power to a stable high quality 60Hz. The use of the variable speed greatly increases fuel efficiency at partial load, as well as allowing a short term one hundred hour 125kW “peaking” mode per year. The Inverde INV 100 was designed to be grid tied as well as a standalone power generation unit in the event of a potential blackout condition.

5. Equipment Used in Testing

5.1. Tecogen 60kW Prototypes “A2” and “B1”

The Tecogen prototype serial number 200836 genset is known in the test bed as “A2”. Manufactured by Tecogen and originally installed at the AEP CERTS Microgrid test site in 2006, this is a 60kW co-generation combined heat and power (CHP), natural-gas engine driven, inverter based unit. Along with prototype B1, this unit has undergone several hours of operation and rigorous testing and has proved to be a reliable genset to use in these continued tests. (http://certs.lbl.gov/pdf/certs-mgtb-report.pdf).

5.2. Static Switch

The paralleling device used in this series of tests is a S&C PureWave Power Electronic Switch. This consists of an SCR-based switch (Semicron SKKT 250/16E 250amp 1600V, Dual SCR modes) with input, output, and bypass breakers. Along with a DSP controller, this switch is capable of sub-cycle performance while operating within the confines of IEEE 1547. In addition to isolating the microgrid during protection events, the static switch also performs synchronized closing when the proper conditions are met.

5.3. Load Banks

The load banks used during these test are LB3, LB4, LB5, LB6 which are capable of consuming 100kW as well as 60kVar each for a total potential maximum load of 400kW and 240kVar.

5.4. Test Meters

There are twelve PowerLogic® ION7650 meters placed through out the microgrid which monitor electrical system conditions during testing.

The power quality analysis & compliance monitoring enables the PowerLogic® ION7650 meter to summarize power quality measurements into simple pass/fail indicators and includes anti-aliasing and flicker features. Trending and forecasting, adaptive waveform capture (events up to 60 seconds), transient capture (16 µs @ 60 Hz), up to 1024 samples per cycle, sag/swell monitoring, harmonics (up to 63rd), symmetrical components and disturbance direction detection.

The meters also comply with ANSI C12.20-1998, class 10 & class 20 on time-of-use, interval data, bi-directional, 4-quadrant energy, demand and TLC, Transformer/Line loss compensation.

Communications and integration capabilities of the meters include up to 5 communications ports and multi-protocol support for Modbus RTU, slave/master, DNP 3.0., Modbus TCP and Ethernet and modem gateways to 31 devices on RS-485 port simplifies integration with SCADA and energy management systems.

Logging, I/O and setpoints - enable the ION7650 to perform sequence-of-events, coincident minimum/maximum, historical trend, and high-speed snapshot recording, 1 ms resolution time stamping and GPS time synchronization allowing us to pinpoint event capture with greater accuracy.

5.5. Ethernet Network

An Ethernet network was utilized for communications to interlink all meters, load control PLCs, and the Data Acquisition System (DAS) computer, using fiber-optic links and switches within the microgrid to allow for real time data collection.

6. Installation of the InVerde INV100

Preparation for the installation of the InVerde INV100 began with disconnecting the existing electrical, communications, water, and gas connections to the prototype Genset A1. The existing prototype 60kW genset A1 was then removed and prepared for storage, and the InVerde INV100 was placed in the vacant location. Since the physical size of the InVerde INV100 is similar to the prototype, the external utility connections for electrical, communications, water, and gas were re-connected. Slight modifications were made since the InVerde INV100 has a sound attenuating enclosure, which the prototypes lack. The exhaust column for the original prototype was replaced with a larger one for the InVerde INV100, since it's capable of a larger thermal output.

The transformer that lies between the genset and the microgrid bus was replaced by a larger one to provide more impedance, but was later taken out of service and replaced with a reactance panel. This panel was mounted on the interior of the InVerde INV100 inverter cabinet, essentially replacing the transformer as a source of impedance. The genset's firmware was then changed from a 3-wire configuration to 4-wire, since the transformer provided a wye connection to the microgrid bus. The existing fuse disconnect switch and circuit breaker were replaced with similar types of equipment that have a greater interrupting capability. Additionally, the conductor cables that ran between all of this equipment were upgraded to a larger size.

To account for the need for extra cooling capacity, a Cancoil cooling tower was added to the test bed. Running in parallel with the existing cooling loop, this is a single fan tower that will run once the larger cooling tower has reached its rated capacity.

Additionally, a water line in the test bed was relocated from above ground to underground. This was done during the installation of the InVerde INV100 to take advantage of the test bed outage. However, in order to perform this work the natural gas delivery manifold needed to be dismantled. Once the water line was buried, the gas manifold was reassembled with new seals and a more robust support structure.

Figures 1-4 display the InVerde INV100 100 installation in the test bed.

Figure 1 - Front view of the InVerde INV100 inside the genset enclosure

Figure 2 - Natural gas, water, and network connections to the InVerde INV100

Figure 3 – Rear view of the InVerde INV100 inside the genset enclosure

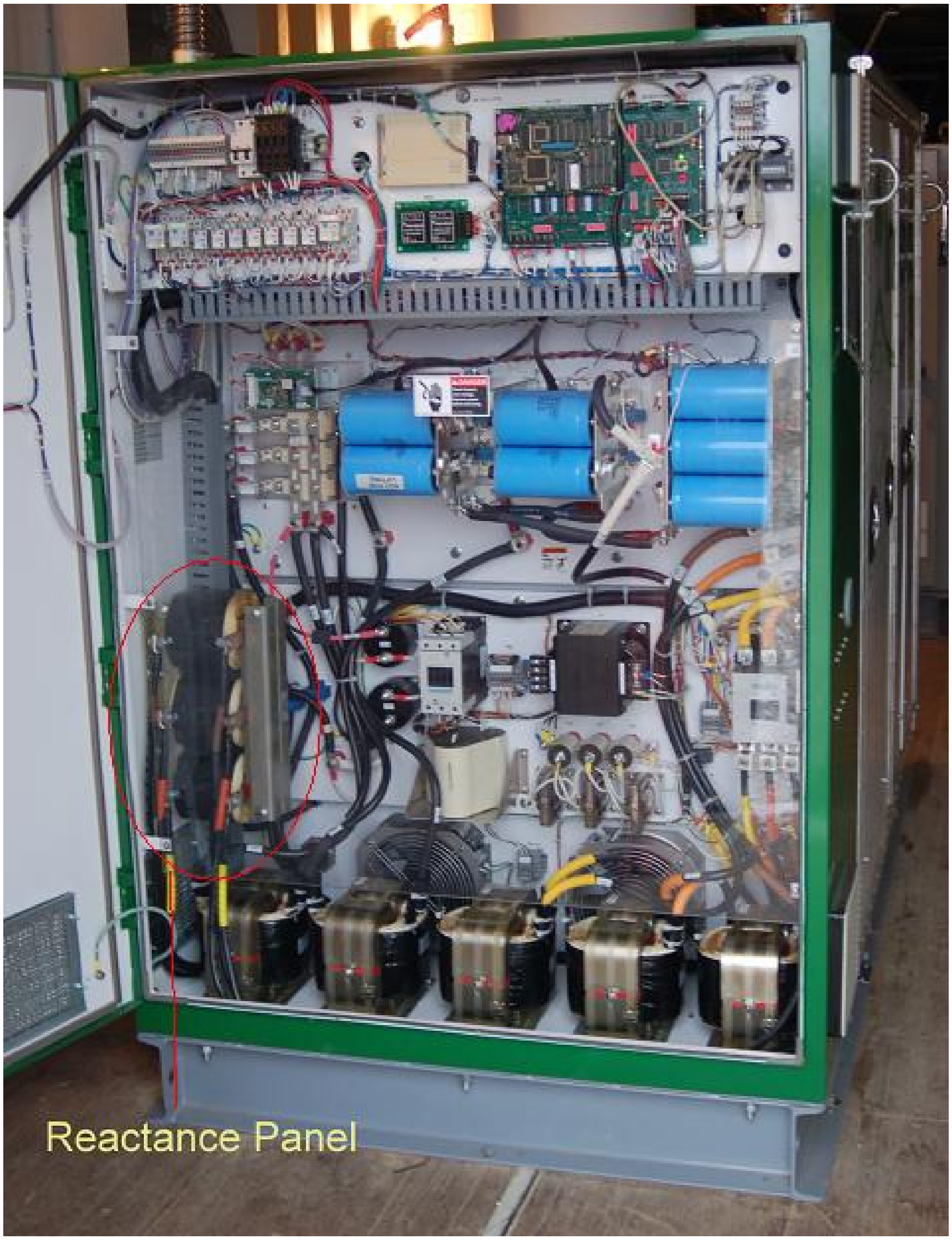

Figure 4 - InVerde INV100 power electronics interface

7. Testing and Results

The following set of tests was designed to ensure the InVerde INV100 inverter controls are implemented correctly. This includes unit control in conjunction with limit controls and synchronized closing of the static switch. Testing was conducted with supervisory control from the operations trailer in the test bed. This EMS interface adds a layer of optimization on top of the native CERTS controls.

Prior to each test point, a data capture trigger was set that would record 5 seconds of data once the chosen piece of equipment operated or changed condition. Once all testing was complete, the data was migrated to a different server and uploaded to be viewed in a web interface (WebPQView). This provides waveform, RMS, frequency, and power data for each event that was triggered.

The tests were performed in the following sequence:

7.1. Emergency Shutdown

To verify the emergency shut down user command is functional, first genset A1 was started and dispatched to 50kW, and then 50kW of load was added to the bus. Also, the microgrid bus was isolated from the utility grid. Next, the 'emergency shut down' command was issued from EMS. As a result, genset A1 shut down and all microgrid protection breakers opened as expected. This function emulates the manual emergency stop that is located on the exterior of the InVerde INV100. Fig. 5 displays genset A1's current waveform as a response to the shut down.

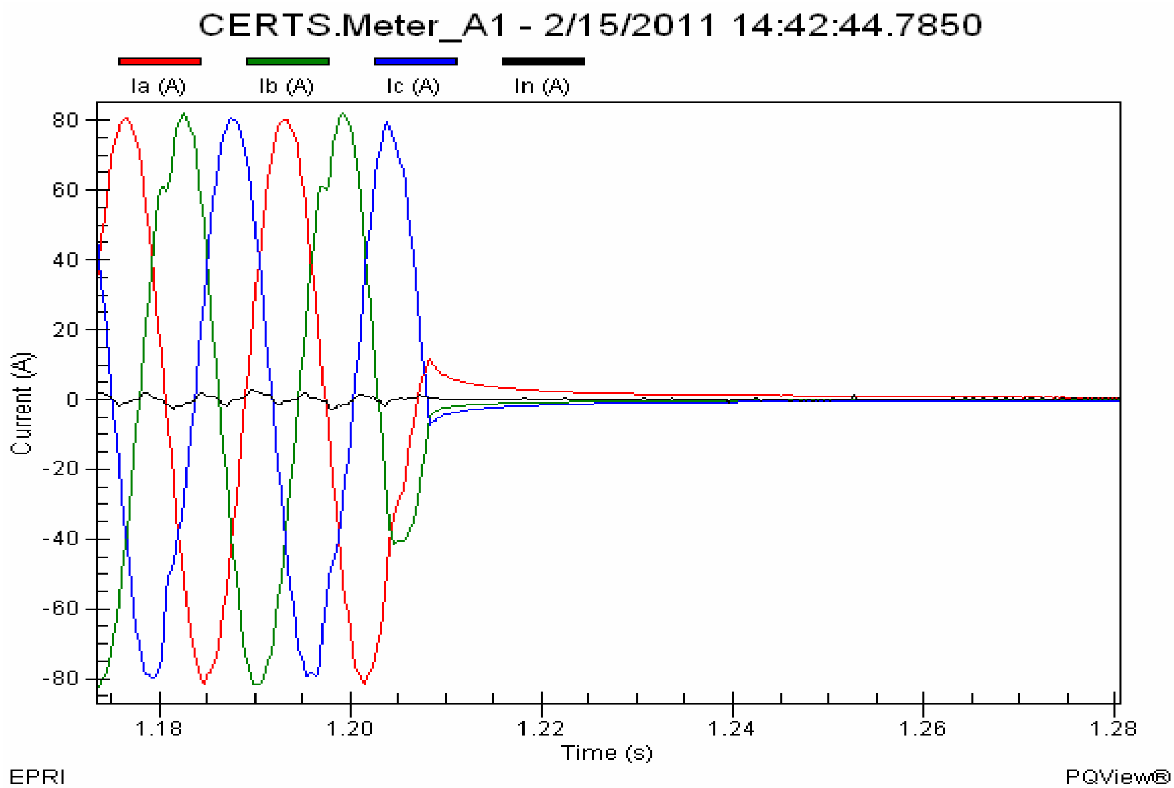

Figure 5 - Genset A1 current waveform as a response to emergency shutdown

7.2. Frequency vs. Real Power Droop

This sequence of tests was performed to ensure the CERTS frequency vs. real power droop control was properly implemented into the InVerde INV100's inverter. To begin, genset A1 was started and dispatched to 0kW and 277V. With the microgrid isolated from the utility grid, load was added to the microgrid bus in the following steps:

- 20kW
- 40kW
- 60kW
- 80kW
- 95kW (maximum)

A data capture trigger was set to record on the addition of load for all of the steps, and once genset A1's maximum power was reached all load was removed from the microgrid bus. The power dispatch point for genset A1 was then changed in EMS from 0kW to 100kW and the same load step procedure was repeated. The functionality of the frequency vs. droop control could then be compared at different real power dispatch points.

Figures 6-10 display genset A1 frequency after each load step was applied, with the genset dispatched to 0kW. Since the load on the bus was greater than the genset dispatched load, the genset frequency remained below the nominal 60Hz throughout this set of tests.

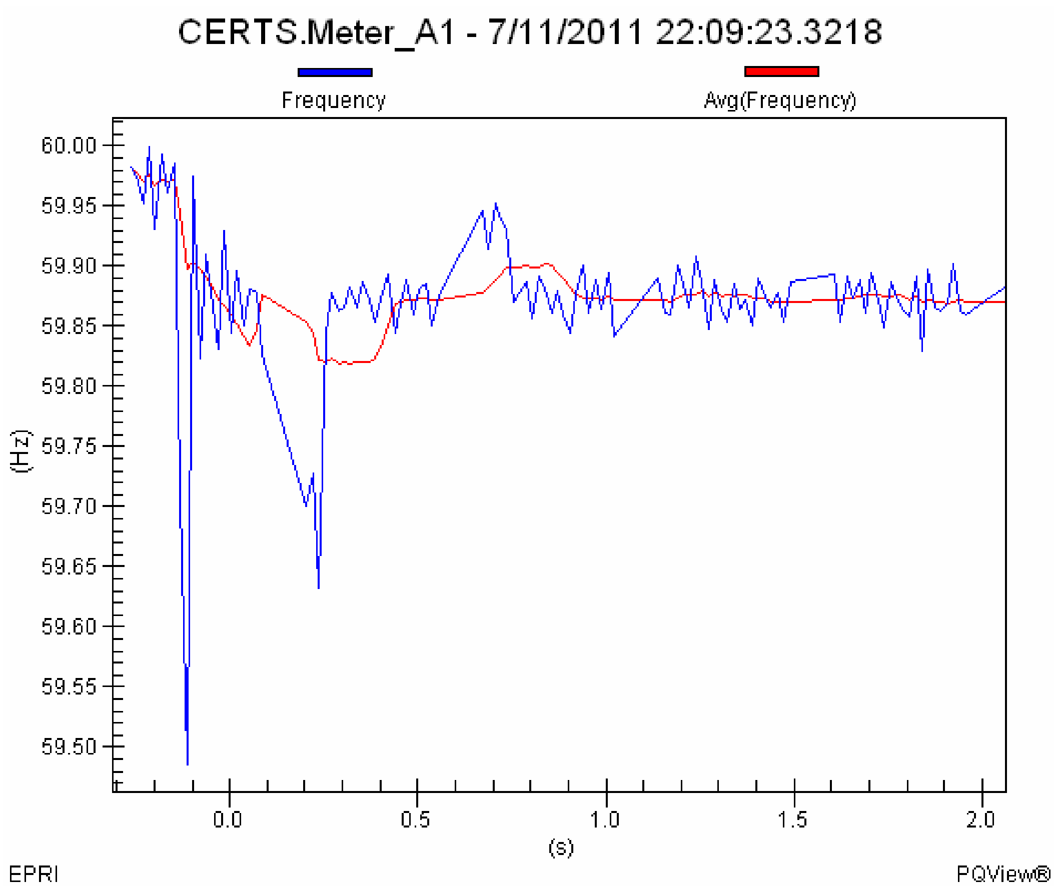

Figure 6 - Genset A1 (0kW dispatch) frequency after 20kW load is added (19.5kW ouput from genset A1)

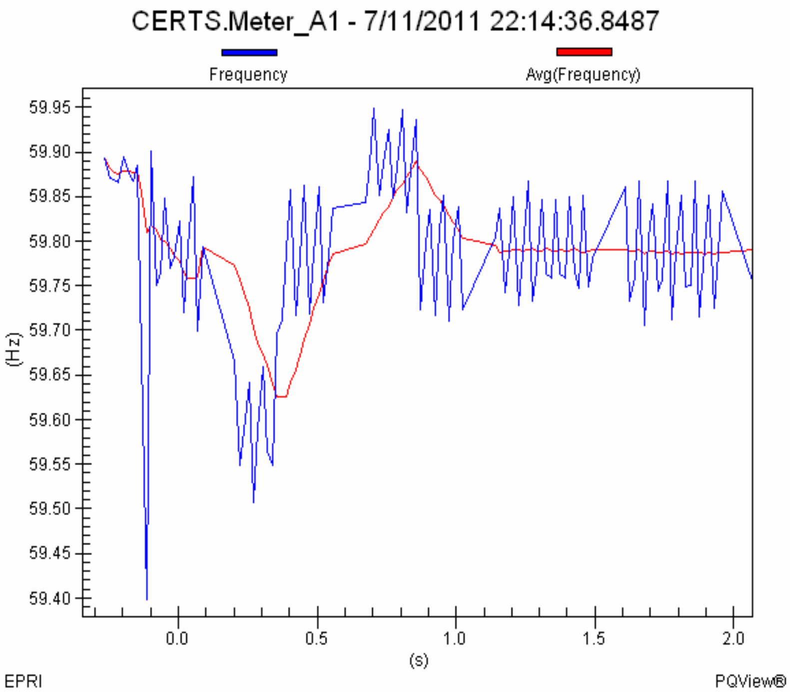

Figure 7 - Genset A1 (0kW dispatch) frequency after 40kW load is added (37kW output from genset A1)

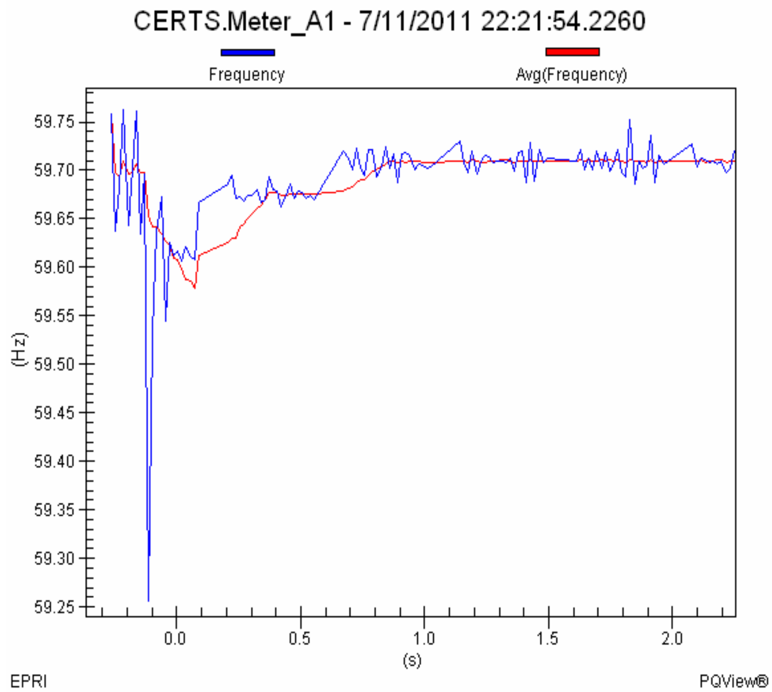

Figure 8 - Genset A1 (0kW dispatch) frequency after 60kW load is added (53kW output from genset A1)

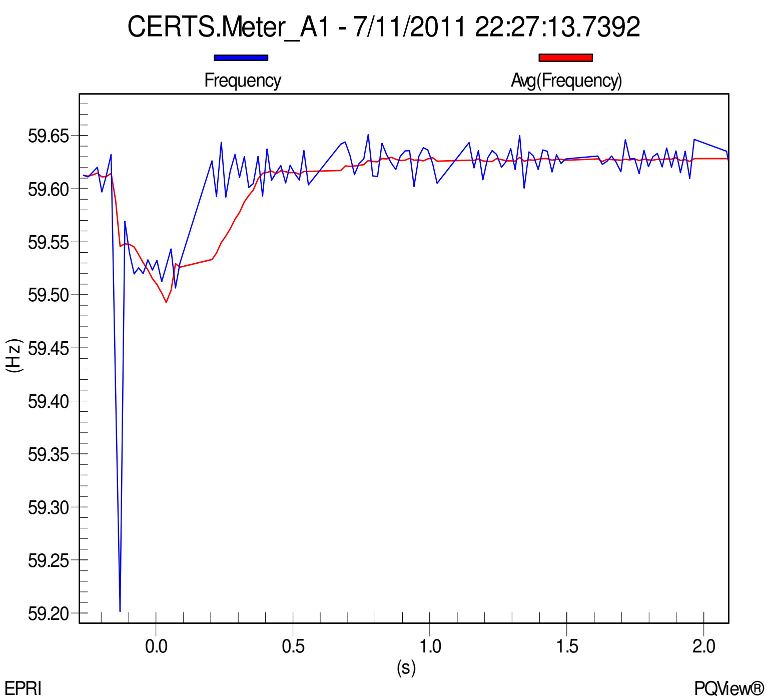

Figure 9 - Genset A1 (0kW dispatch) frequency after 80kW load is added (70kW output from genset A1)

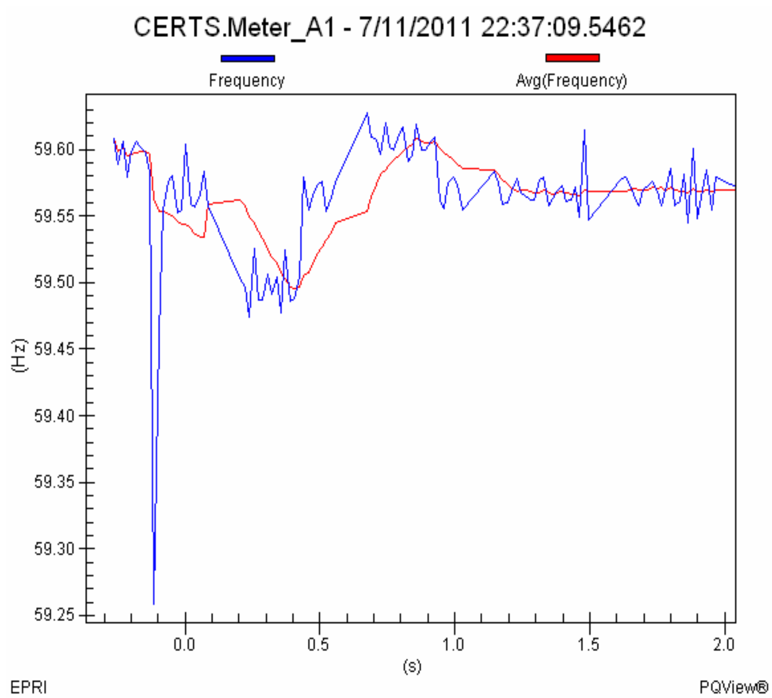

Figure 10 - Genset A1 (0kW dispatch) frequency after 95kW load is added (81.5kW output from genset A1)

The InVerde INV100's expected frequency vs. real power droop is -0.005 Hz/kW. Figure 11 is a plot of the frequency and real power data points gathered at each load step. The slope of the added trend line reflects the actual value of -0.0048Hz/kW droop.

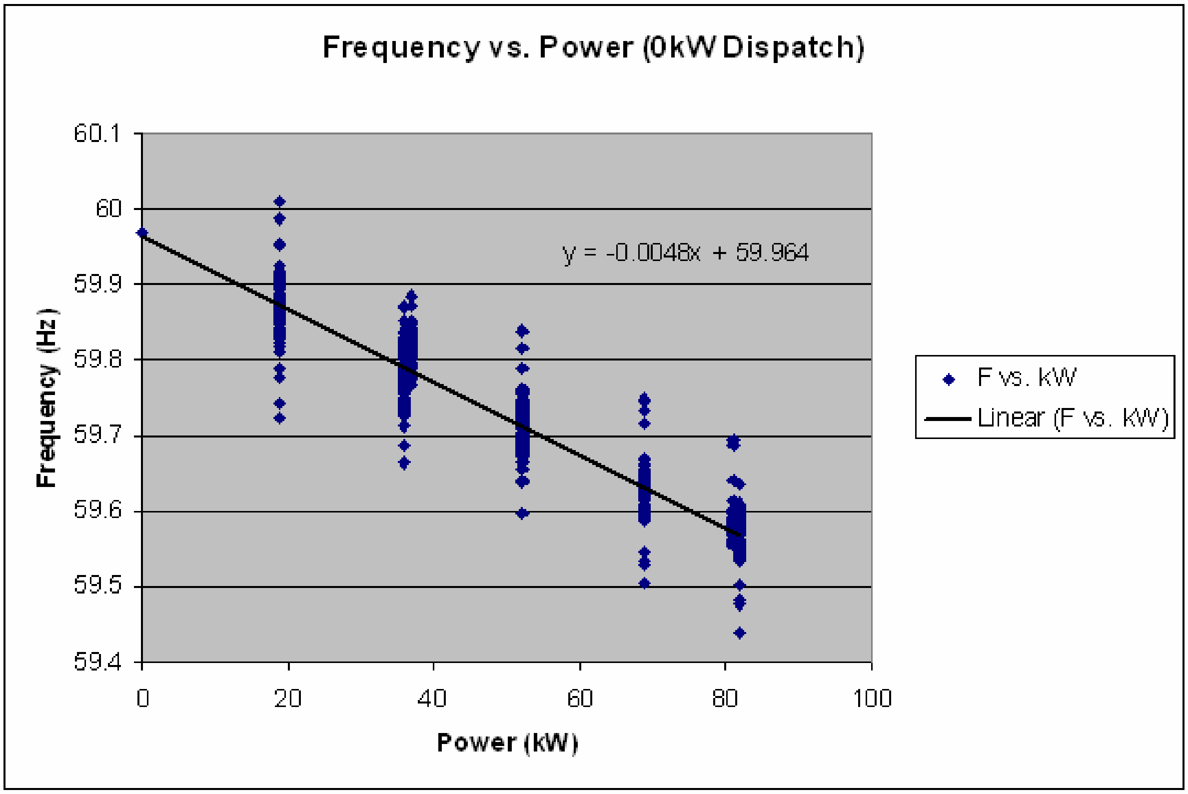

Figure 11 - Frequency vs. real power droop at 0kW genset dispatch

Figures 12-16 display the genset A1 frequency after the same load steps were applied, but now with the genset dispatched to 100kW. Since the load on the bus was less than the genset dispatched load, the genset frequency remained above the nominal 60Hz throughout this set of tests.

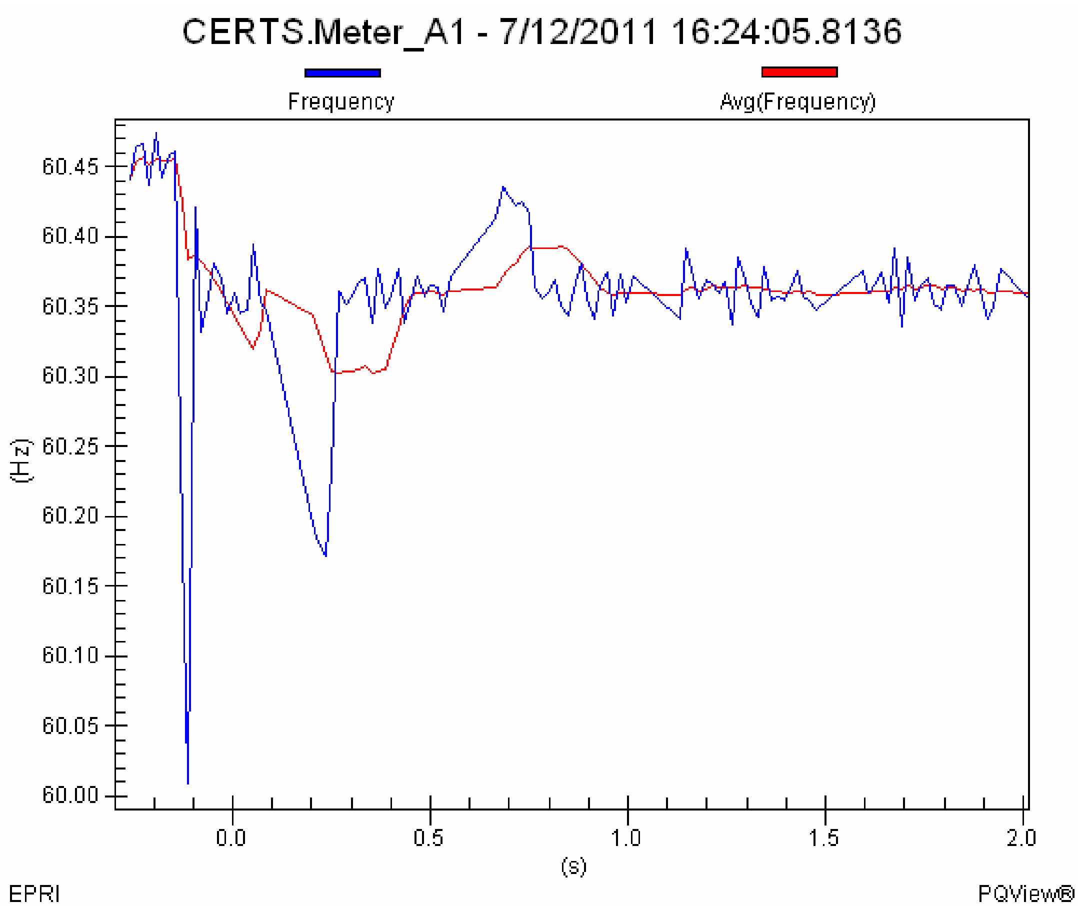

Figure 12 - Genset A1 (100kW dispatch) frequency after 20kW load is added (19.5kW output from genset A1)

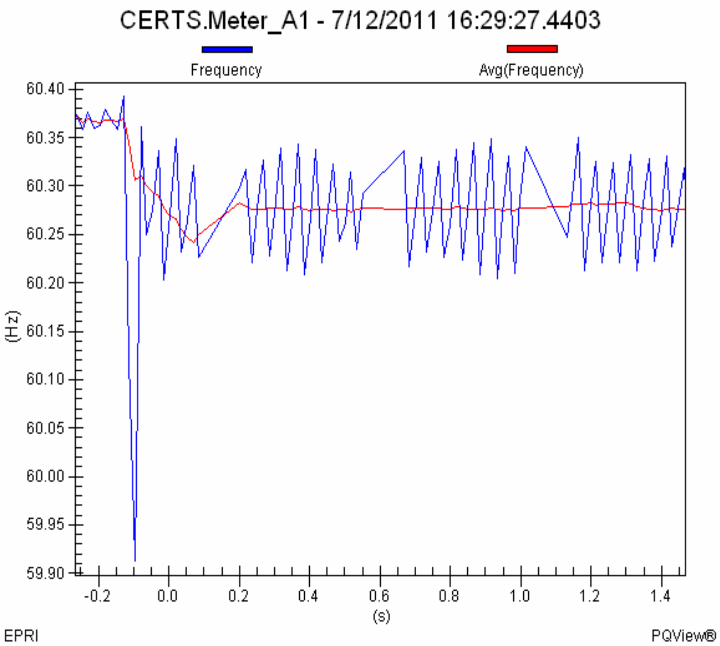

Figure 13 - Genset A1 (100kW dispatch) frequency after 40kW load is added (37kW output from genset A1)

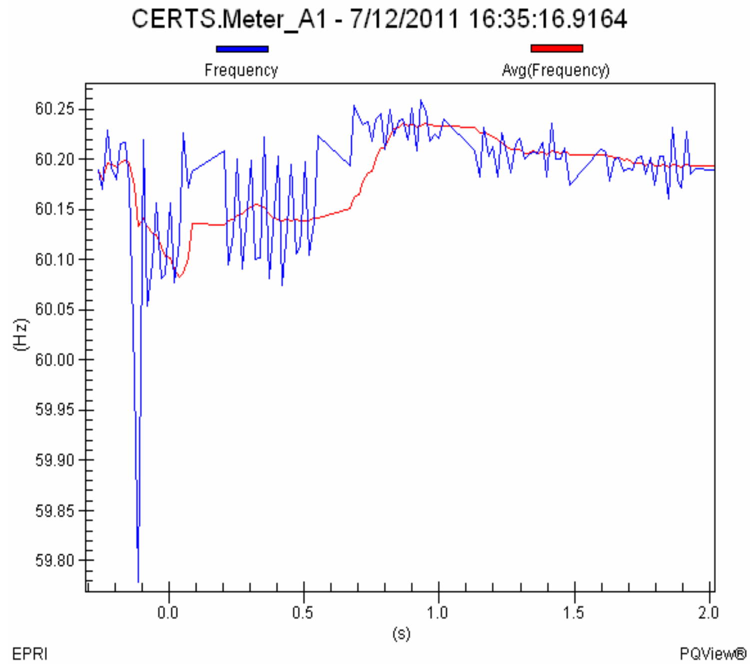

Figure 14 - Genset A1 (100kW dispatch) frequency after 60kW load is added (53.5kW output from genset A1)

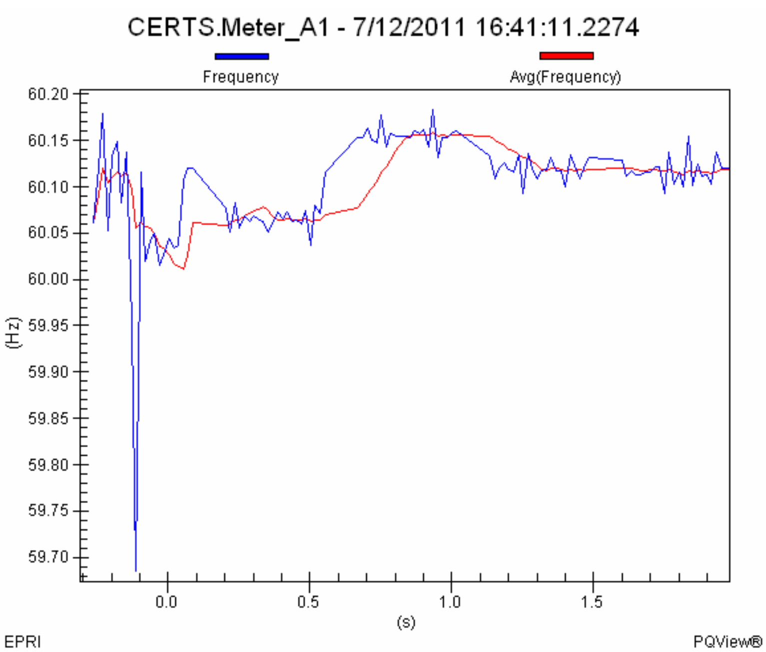

Figure 15 - Genset A1 (100kW dispatch) frequency after 80kW load is added (69.5kW output from genset A1)

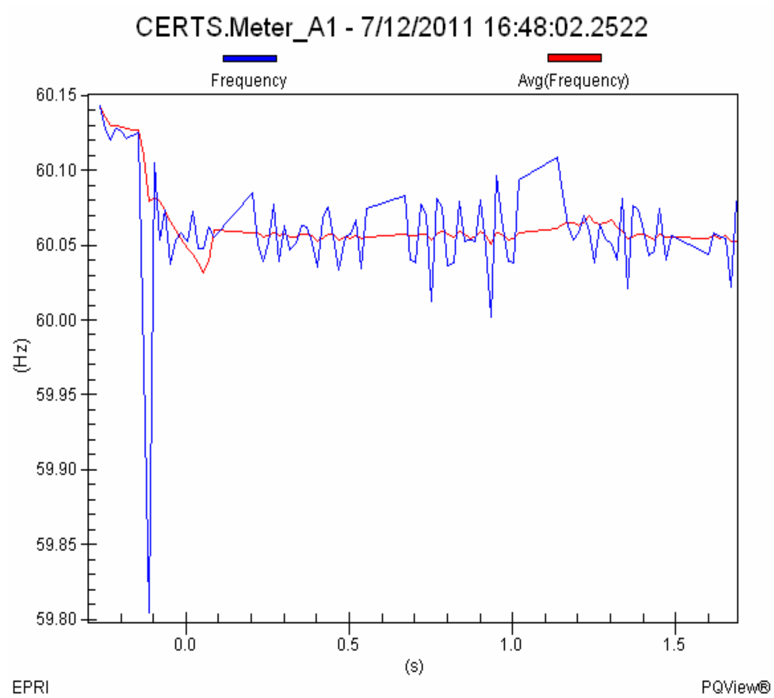

Figure 16 - Genset A1 (100kW dispatch) frequency after 95kW load is added (83.5kW output from genset A1)

Figure 17 is a plot of the frequency and power measurements taken at each load step, with genset A1 dispatched to 100kW. The slope of the added trend line is -0.0049 Hz/kW, which is nearly the same value as when genset A1 was dispatched to 0kW. Therefore, CERTS frequency vs. real power droop was properly implemented in the InVerde INV100's inverter controls. Also, the genset will operate on the same droop curve regardless of the real power dispatch point.

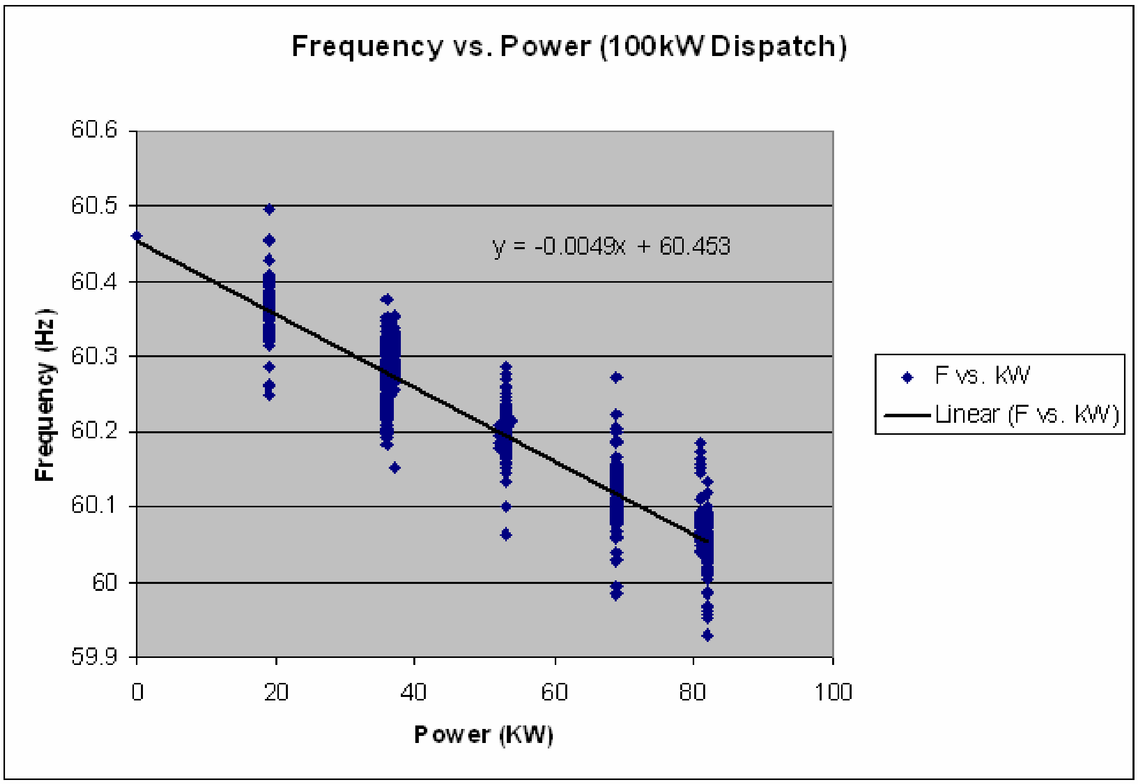

Figure 17 - Frequency vs. real power droop at 100kW genset dispatch

7.3. Voltage vs. Reactive Power Droop

The next sequence of tests was performed to ensure the CERTS voltage vs. reactive power droop control was properly implemented into the InVerde INV100's inverter. To begin, genset A1 was started and dispatched in EMS to 0kW and 277V. With the microgrid isolated from the utility grid, reactive load was added to the microgrid bus in the following steps:

- 20kVAR
- 40kVAR
- 60kVAR

The InVerde INV100 has a nameplate capacity of 100kVAR, but 60kVAR is the maximum reactive capability of a single load bank in the test bed. Data triggers were set to record as each reactive load step was added to the microgrid bus.

Once the testing sequence was complete, all reactive load was removed from the microgrid bus and genset A1 was dispatched to 290V (+105% of nominal). The same reactive load steps were applied and the process was repeated again with the genset dispatched to 263V (95% of nominal). Adjusting the nominal voltage to +/- 5% provided a comparison of the functionality of the voltage vs. reactive power droop control at different genset dispatch points.

Figures 18-23 display the RMS voltage as each reactive load step is added to the microgrid bus, as well as the reactive output of genset A1. The nominal voltage dispatch during this sequence was 277V.

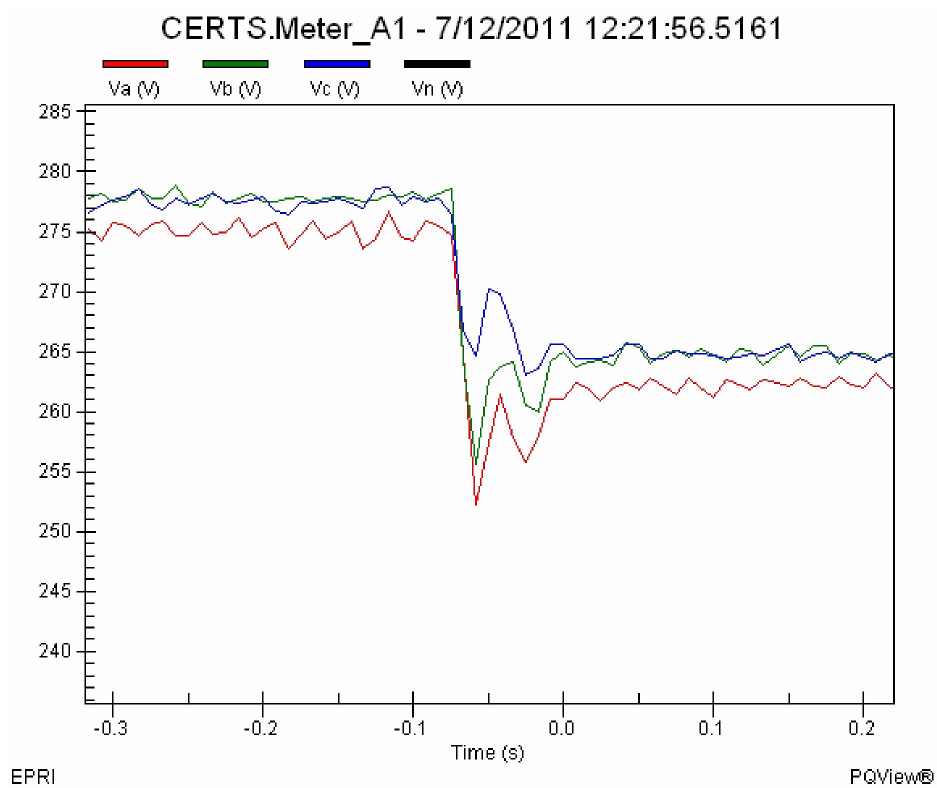

Figure 18 - RMS voltage after 20kVAR load step at 277V genset dispatch

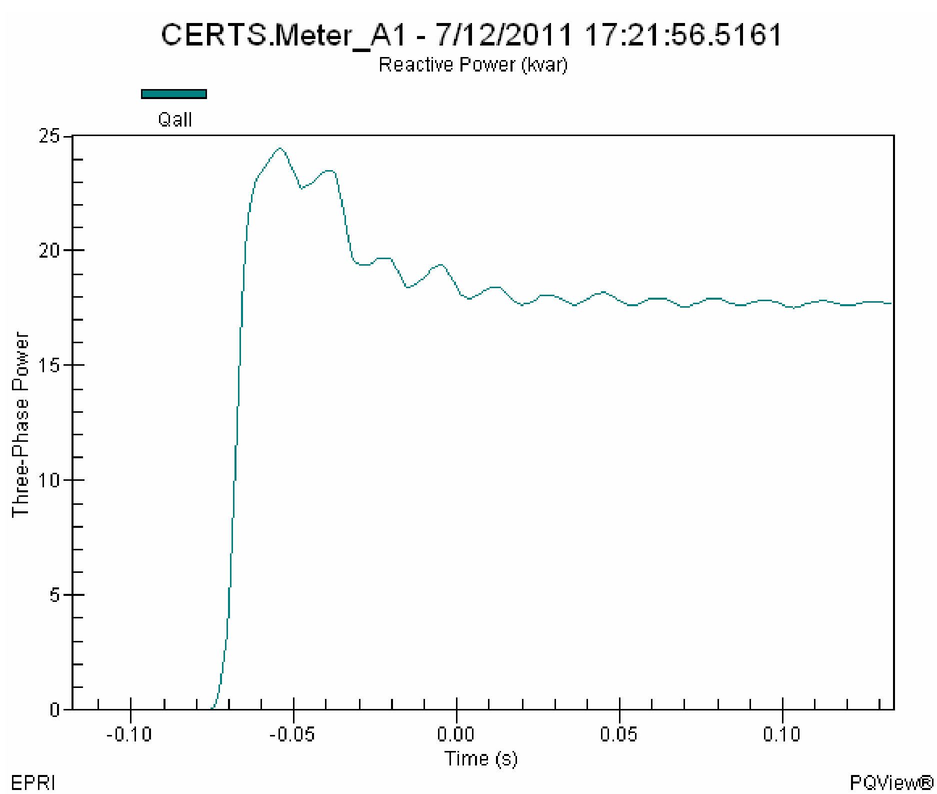

Figure 19 - Reactive power after 20kVAR load step at 277V genset dispatch

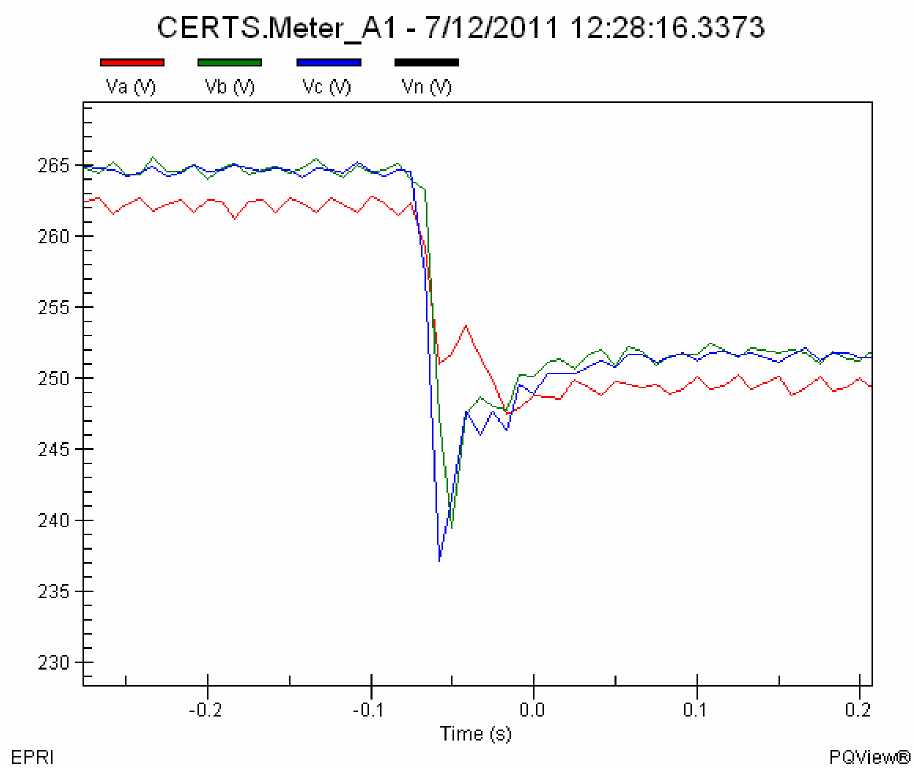

Figure 20 - RMS voltage after 40kVAR load step at 277V genset dispatch

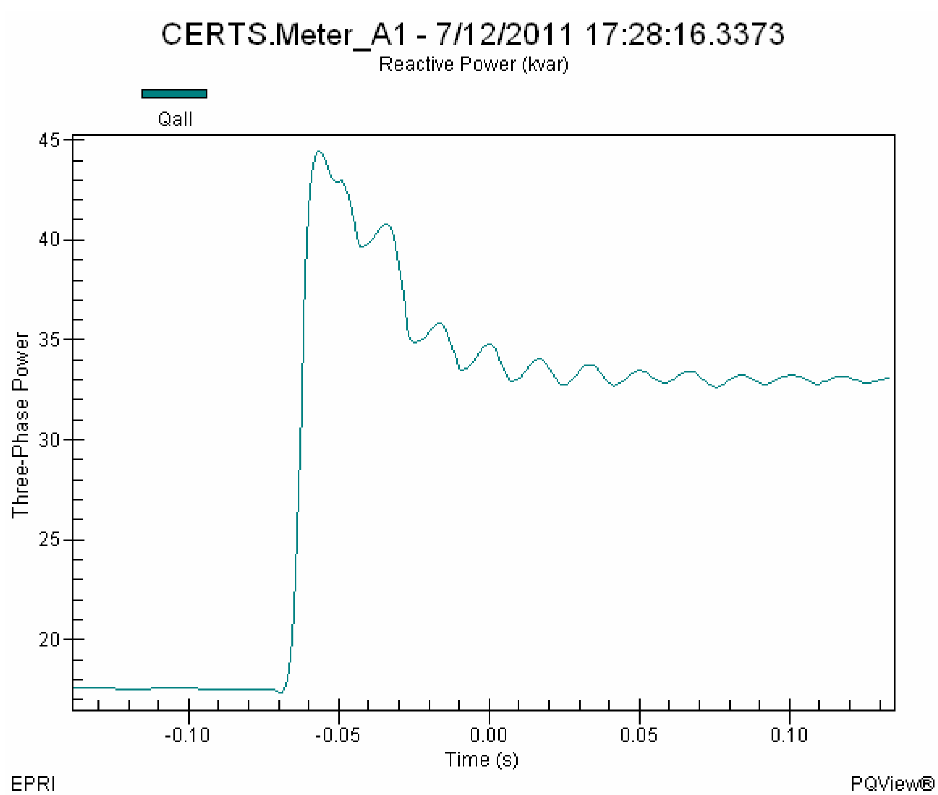

Figure 21 - Reactive power after 40kVAR load step at 277V genset dispatch

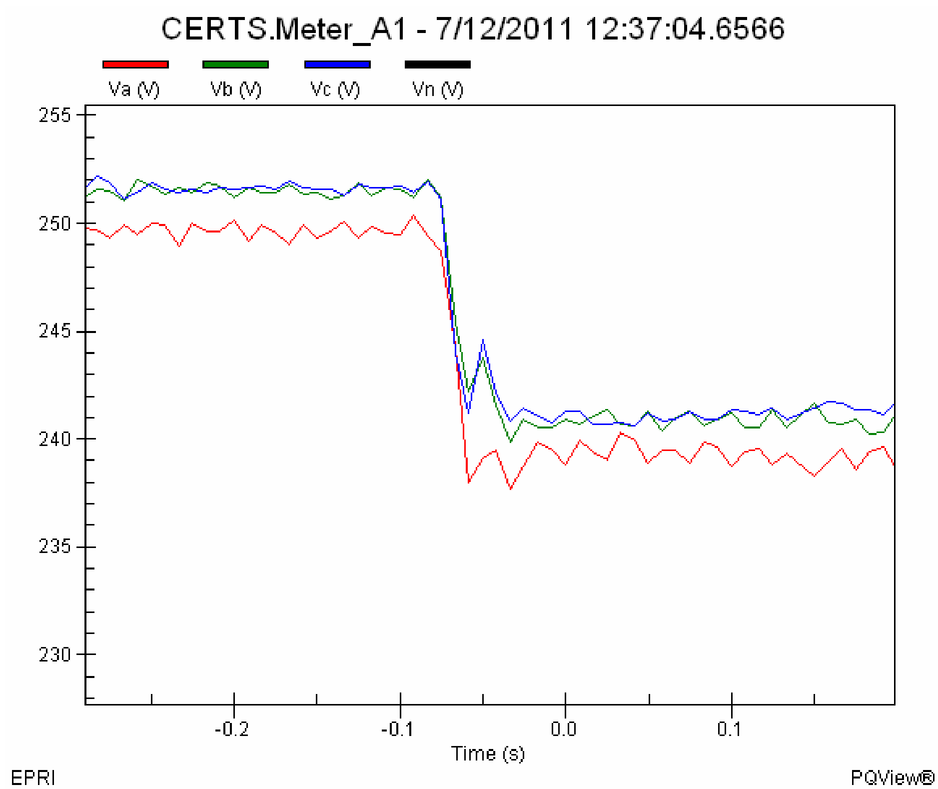

Figure 22 - RMS voltage after 60kVAR load step at 277V genset dispatch

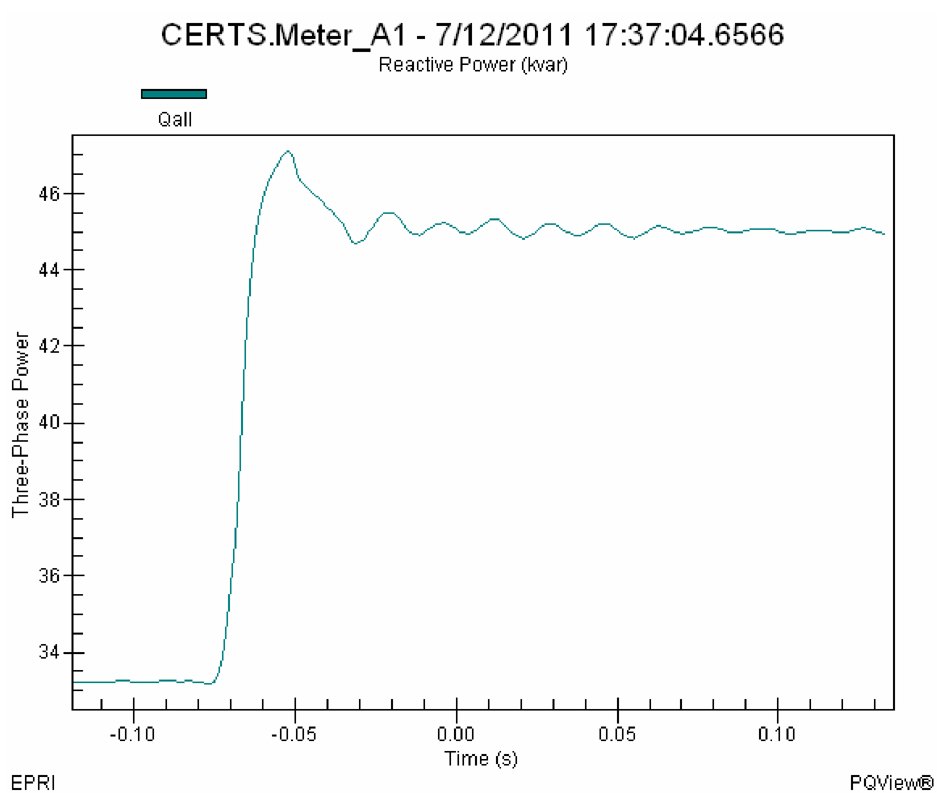

Figure 23 - Reactive power after 60kVAR load step at 277V genset dispatch

Figure 24 is a plot of voltage and reactive power measurements taken at each reactive load step, with genset A1 dispatched to 277V. The expected voltage vs. reactive power slope is 0.47 V/kVAR. The slope of the added trend line reflects the actual droop of 0.83 V/kVAR, indicating improper implementation of the voltage droop in the inverter controls.

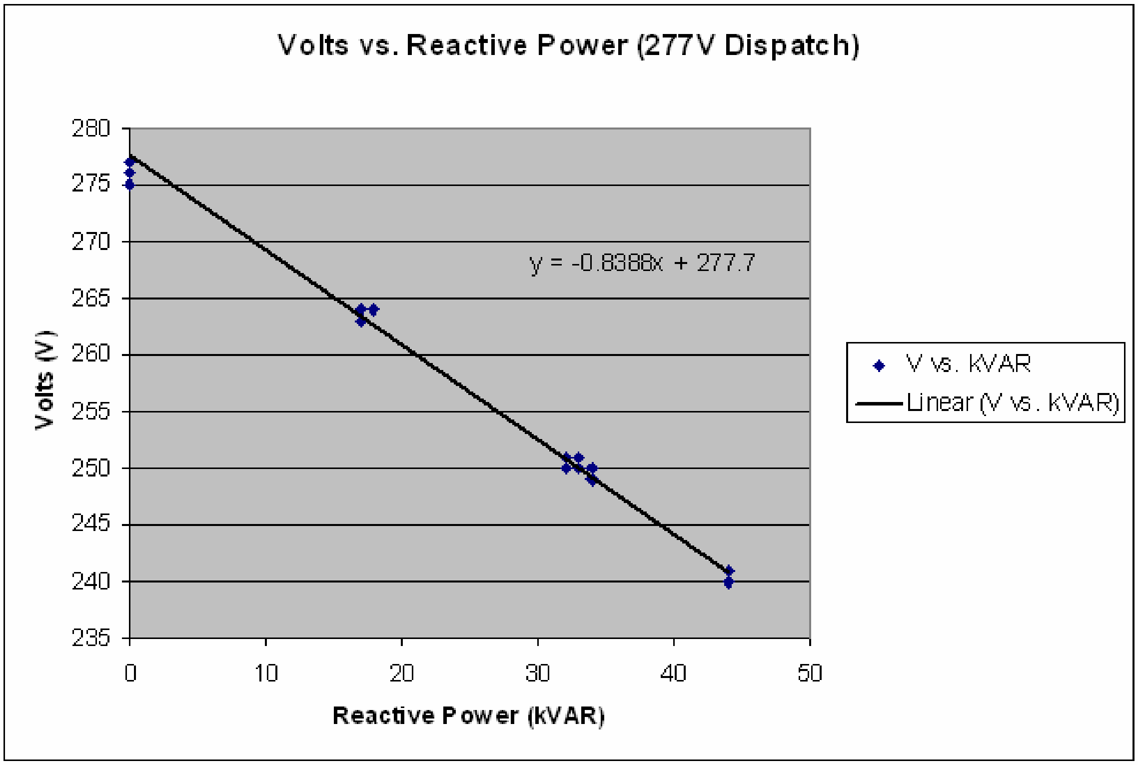

Figure 24 - Voltage vs. reactive power droop at 277V genset dispatch

Figures 25-30 display the RMS voltage as each reactive load step is added to the microgrid bus, as well as the reactive output of genset A1. The nominal voltage dispatch during this sequence was 290V.

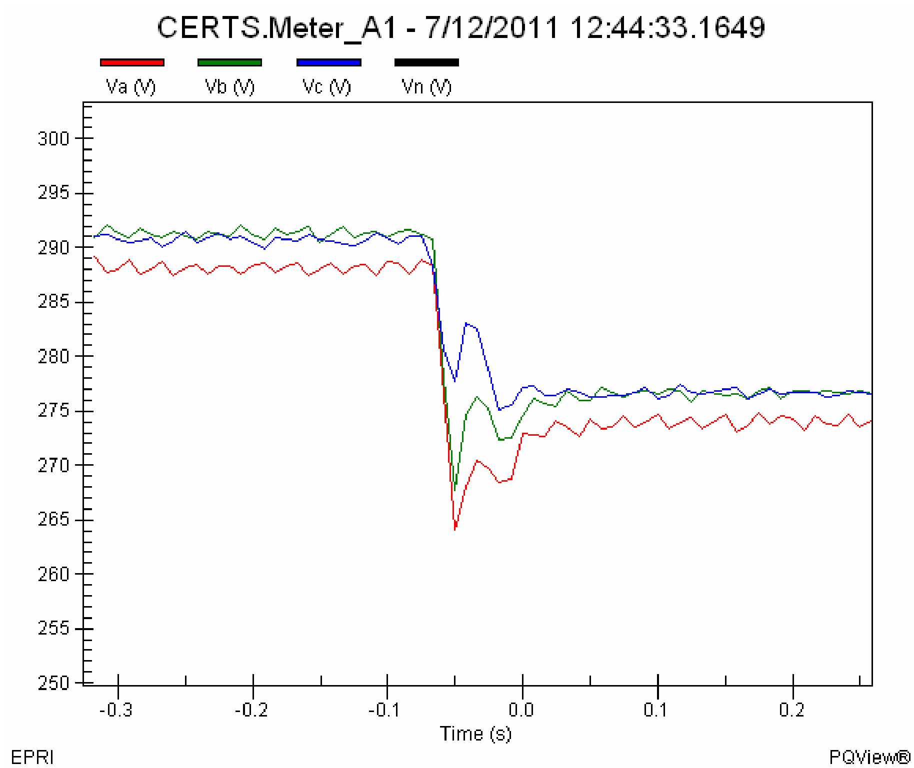

Figure 25 - RMS voltage after 20kVAR load step at 290V genset dispatch

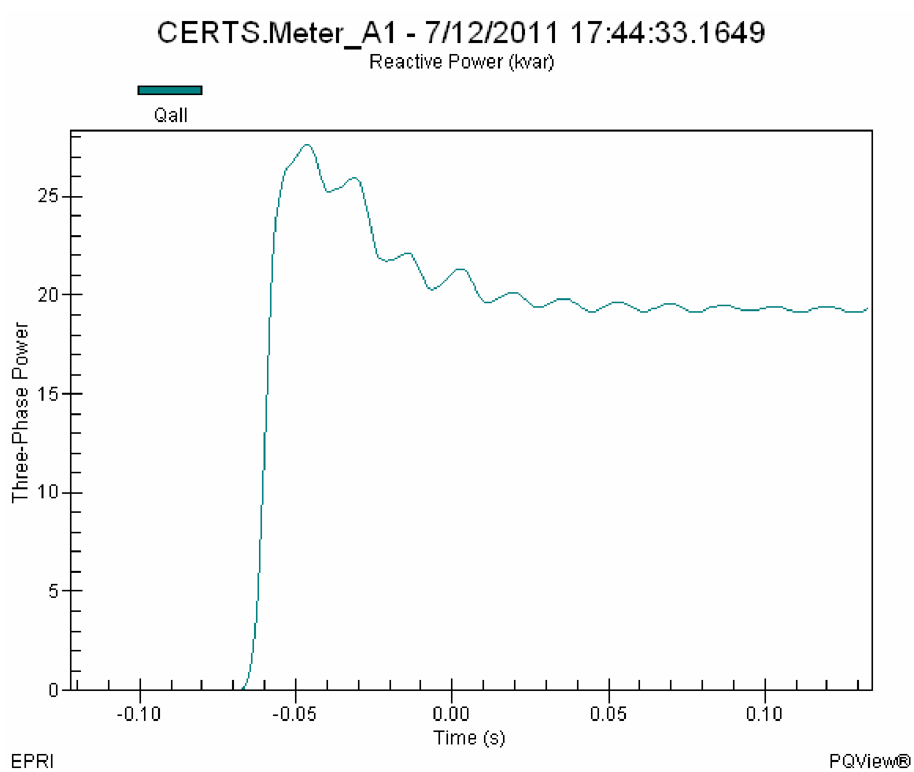

Figure 26 - Reactive power after 20kVAR load step at 290V genset dispatch

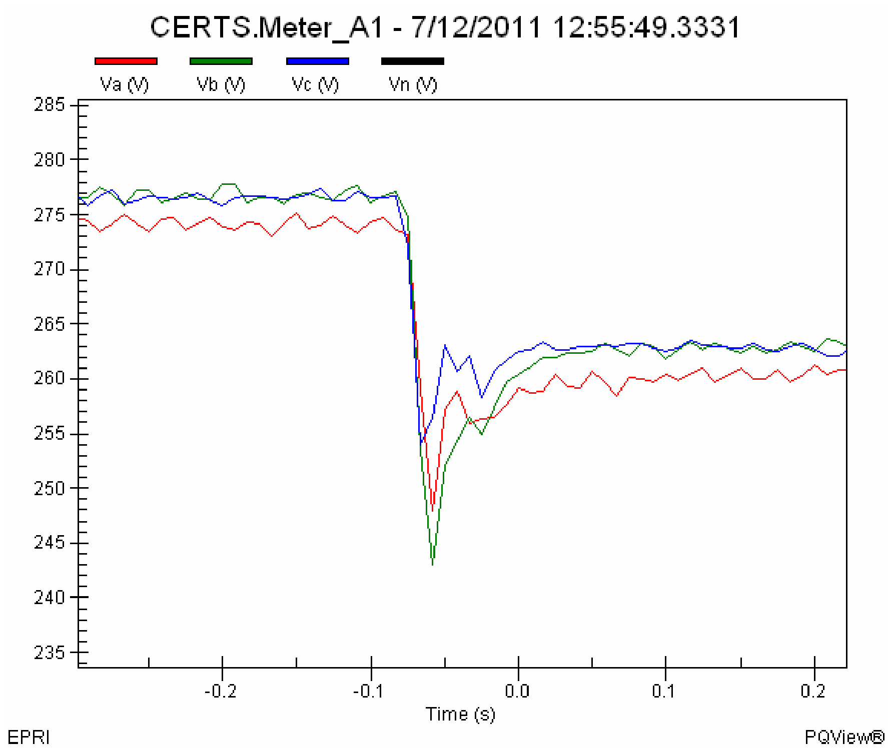

Figure 27 - RMS voltage after 40kVAR load step at 290V genset dispatch

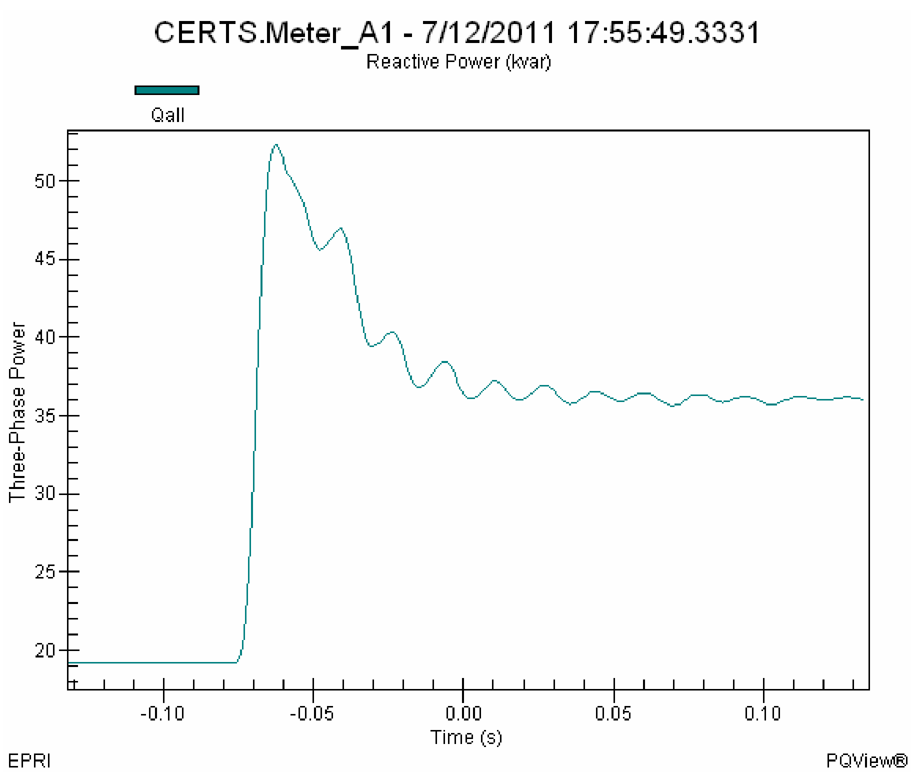

Figure 28 - Reactive power after 40kVAR load step at 290V genset dispatch

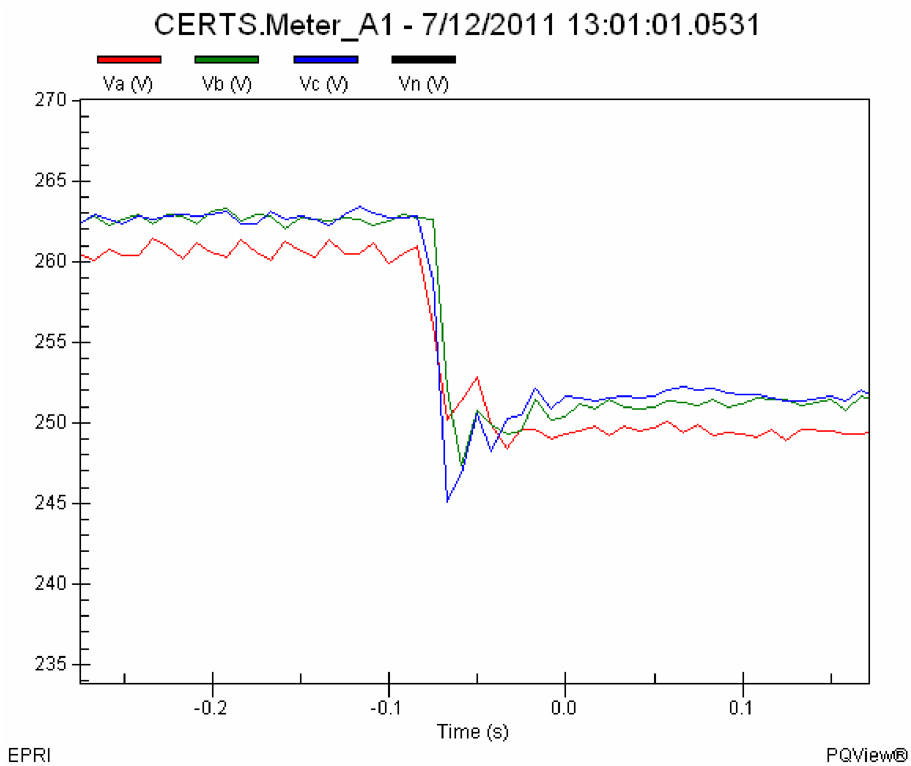

Figure 29 - RMS voltage after 60kVAR load step at 290V genset dispatch

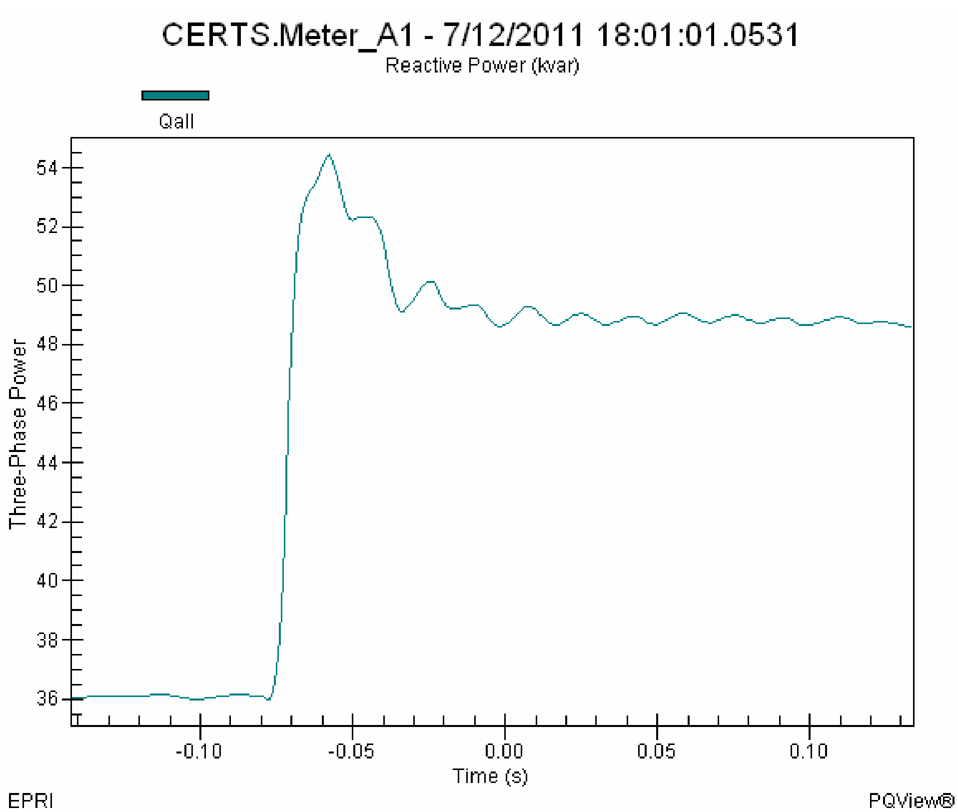

Figure 30 - Reactive power after 60kVAR load step at 290V genset dispatch

Figure 31 is a plot of voltage and reactive power measurements taken at each reactive load step, with genset A1 dispatched to 290V. The expected voltage vs. reactive power slope is 0.47 V/kVAR. The slope of the added trend line reflects the actual droop of 0.86 V/kVAR, again indicating improper droop control or prompting further investigation into the discrepancy.

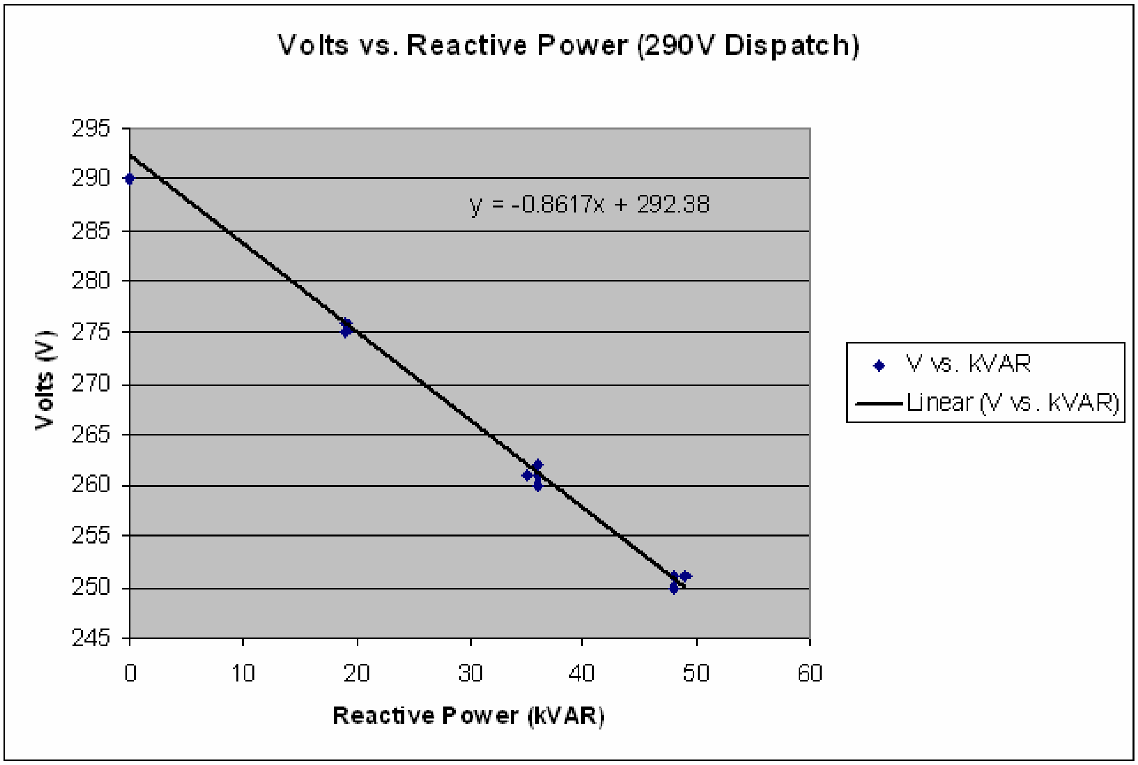

Figure 31 - Voltage vs. reactive power droop at 290V genset dispatch

Figures 33-37 display the RMS voltage as each reactive load step is added to the microgrid bus, as well as the reactive output of genset A1. The nominal voltage dispatch during this sequence was 263V.

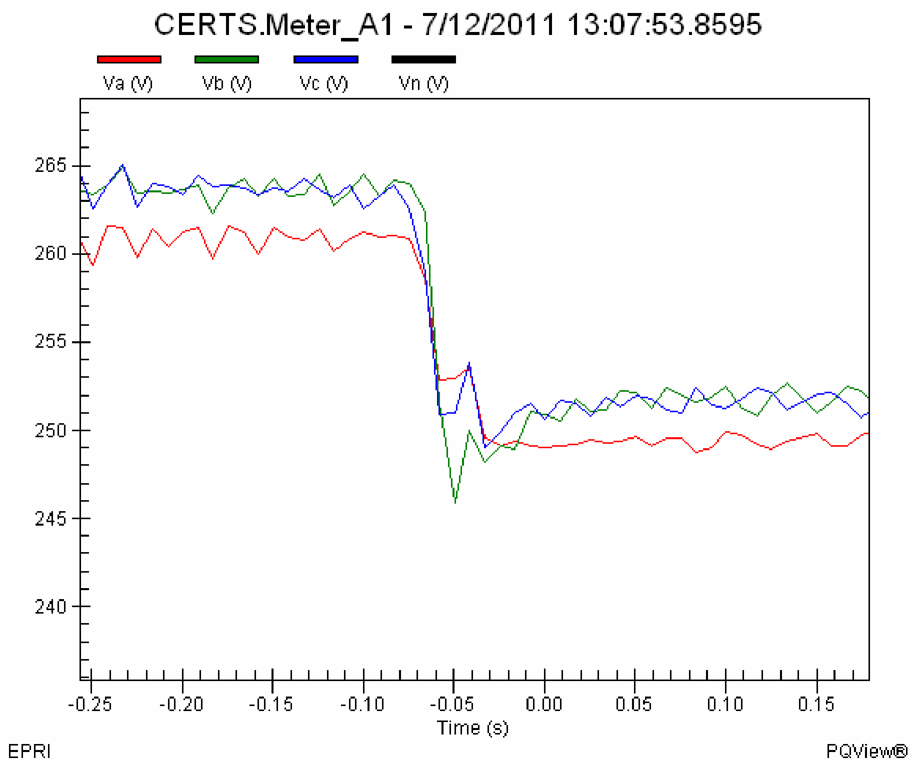

Figure 32 - RMS voltage after 20kVAR load step at 263V genset dispatch

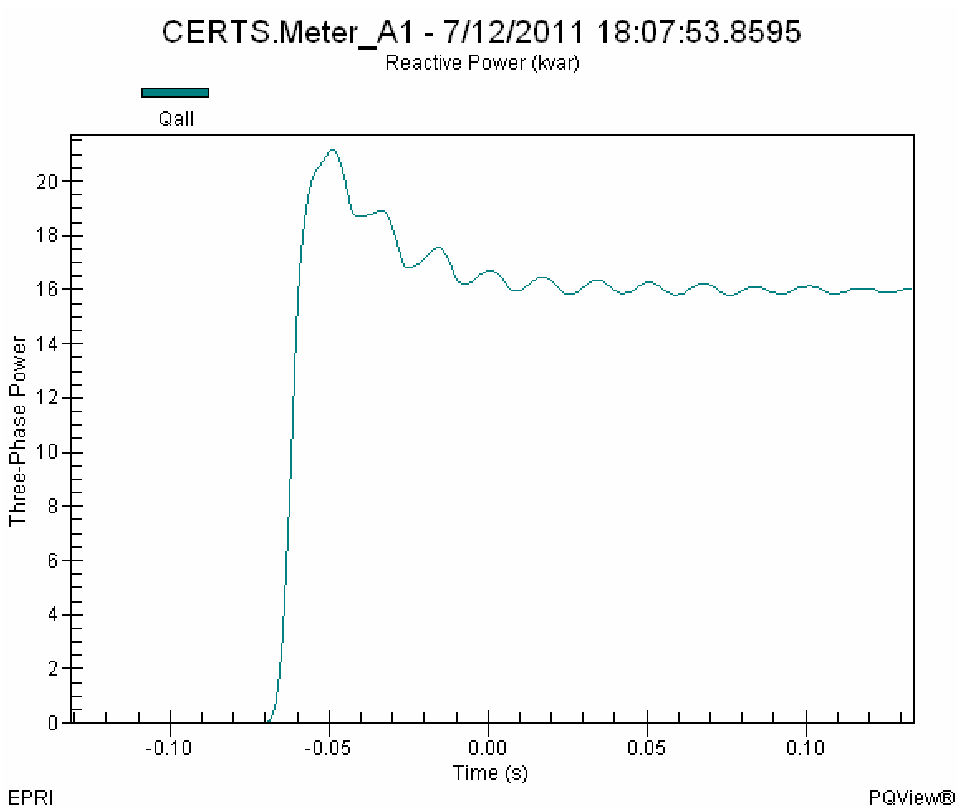

Figure 33 - Reactive power after 20kVAR load step at 263V genset dispatch

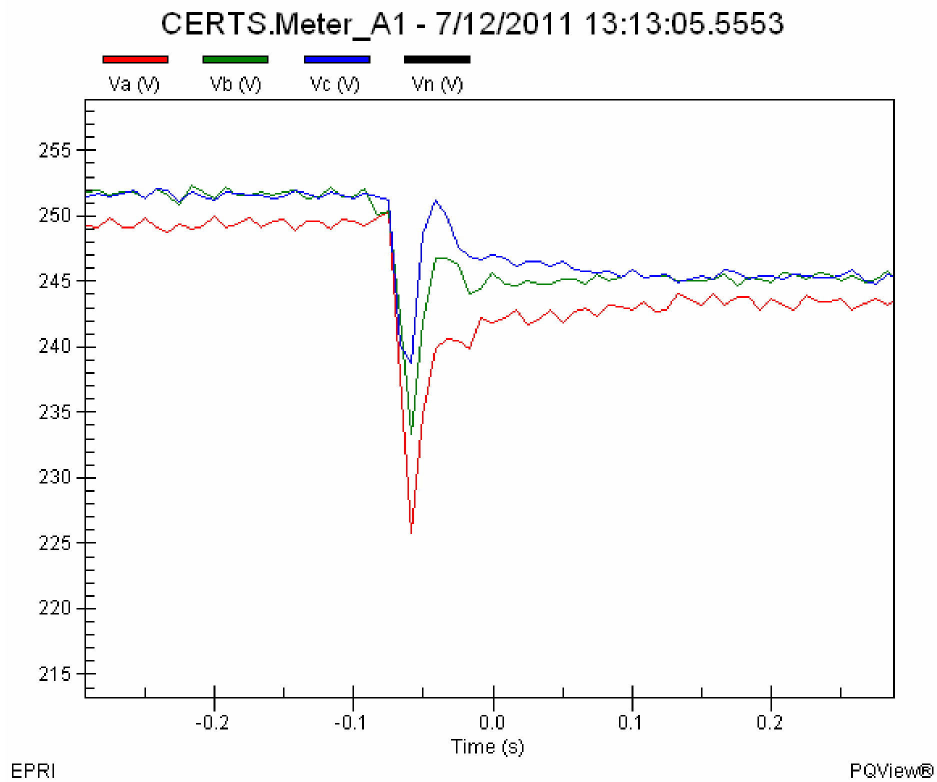

Figure 34 - RMS voltage after 40kVAR load step at 263V genset dispatch

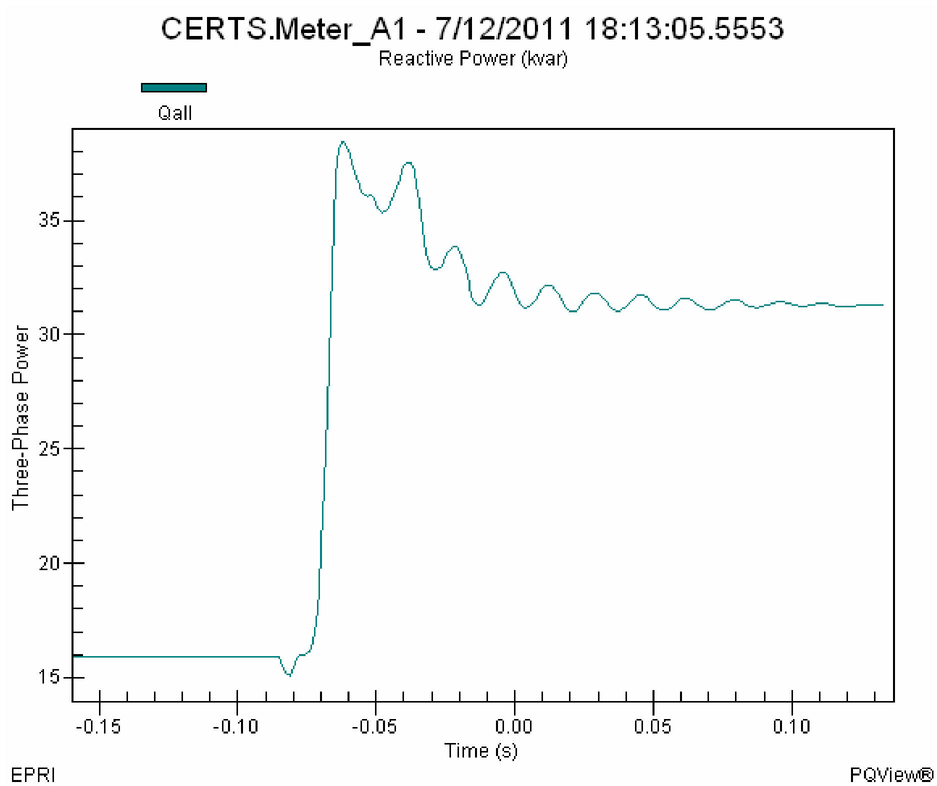

Figure 35 - Reactive power after 40kVAR load step at 263V genset dispatch

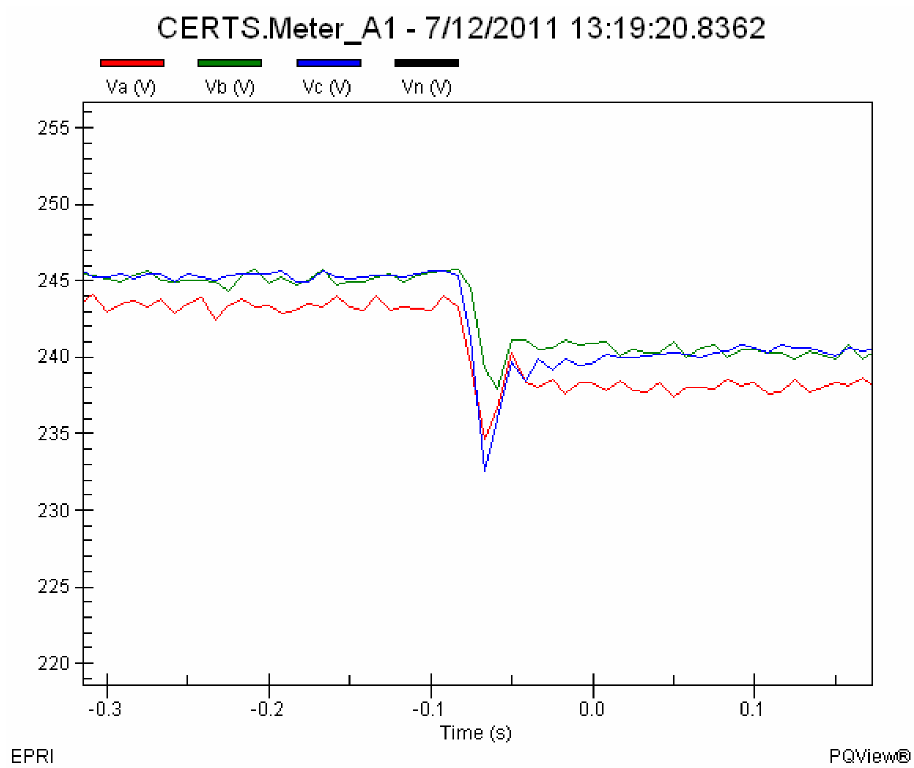

Figure 36 - RMS voltage after 60kVAR load step at 263V genset dispatch

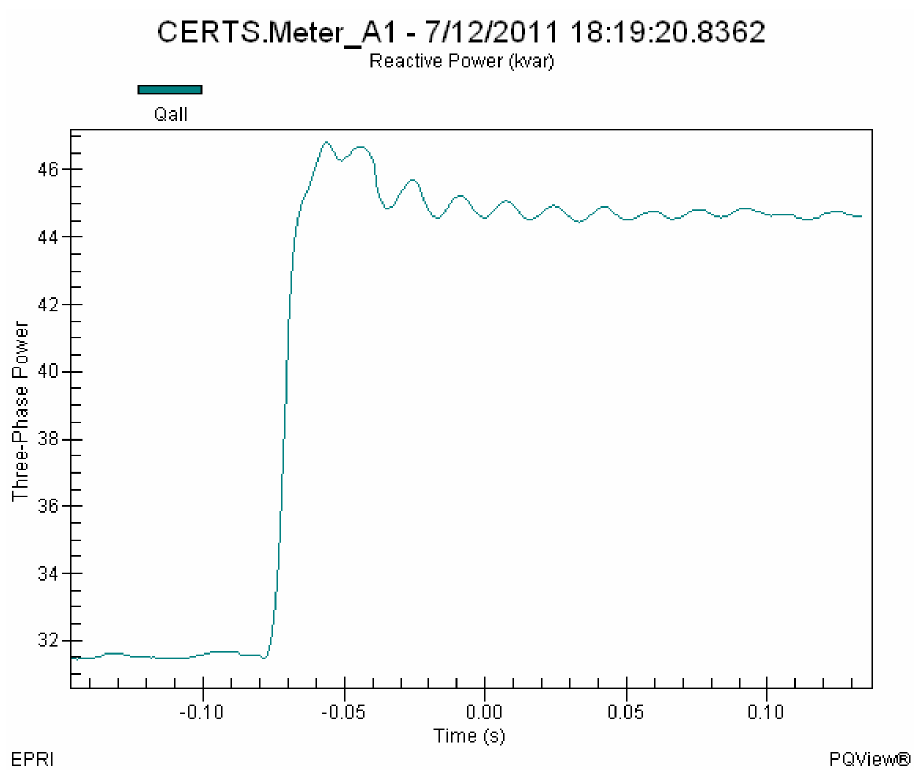

Figure 37 - Reactive power after 60kVAR load step at 263V genset dispatch

Figure 38 is a plot of voltage and reactive power measurements taken at each reactive load step, with genset A1 dispatched to 263V. The expected voltage vs. reactive power slope is 0.47 V/kVAR. The slope of the added trend line reflects the actual droop of 0.4 V/kVAR, which indicates the droop control operates closer to the expected value at a lower voltage dispatch.

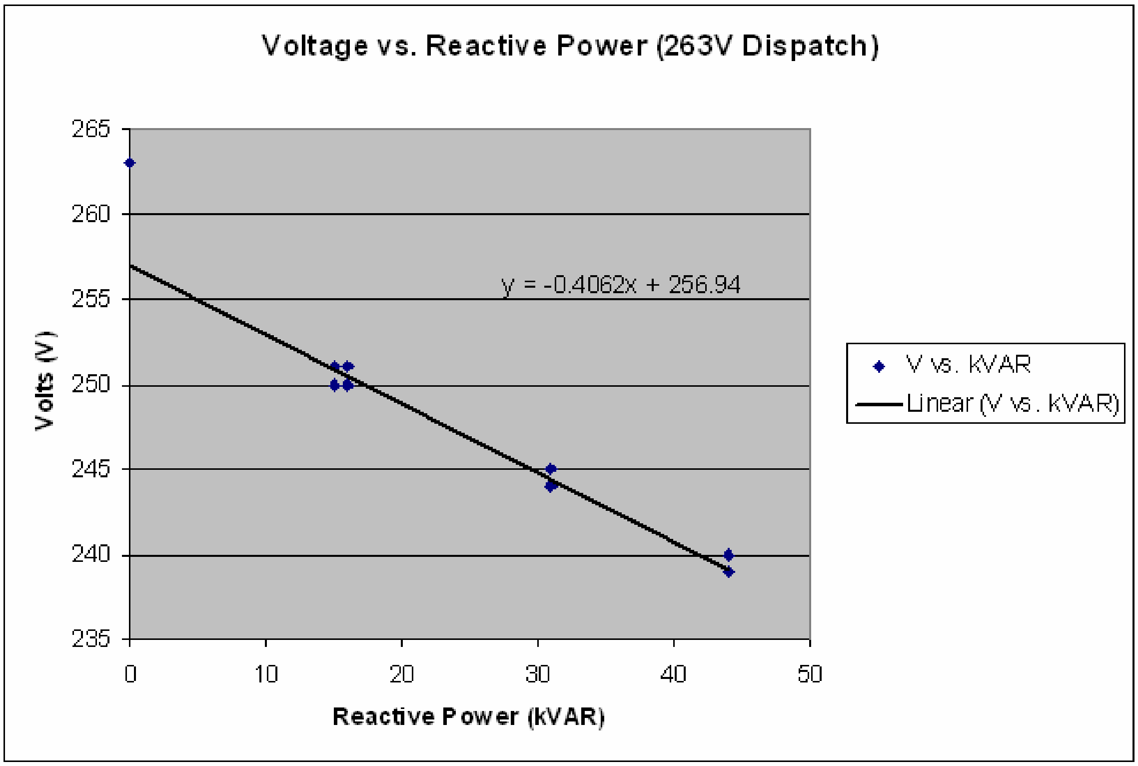

Figure 38 - Votlage vs. reactive power droop at 263V genset dispatch

The results of this sequence of testing showed variance in the voltage vs. reactive power droop at different levels of genset voltage dispatch. The cause of the discrepancy is yet to be determined, but it should be noted that the metered data at the test site does not account for wiring between the genset and metering point. Thus, additional voltage potential must be added to the calculation of voltage vs. reactive power droop.

7.4. Initial Voltage Regulation

This sequence of tests was performed to verify smooth transitions of genset A1's response to different load step conditions. During all tests in this section, the microgrid was isolated from the utility grid. Real load was applied in the following steps:

- 30kW
- 60kW
- 95kW (maximum)

Genset A1 was then started and dispatched to 0kW and 277V. As the real load was added to the microgrid bus, the voltage magnitude of genset A1 was monitored. This process was then repeated with genset A1 dispatched to +5% of nominal voltage (290V), and then dispatched to -5% nominal (264V).

This test sequence was initially performed with a transformer between genset A1 and the microgrid bus. However, the genset voltage output was increasing as real load was applied. The voltage was expected to decrease slightly beyond its nominal value, not increase. The original round of testing continued from this point, but the voltage rise was flagged as an area of concern that needed to be addressed.

As mentioned above, a reactance panel was installed in the place of the bus transformer. After this modification was made, the test results showed no transients in voltage waveforms for each load step. Also, the voltage was no longer rising as load was added. With load near genset A1's capacity, the output voltage of the genset only deviated -2% of nominal. The same percentage occurred with the genset dispatched to both + and – 5% of nominal voltage.

Figures 39-56 display genset A1's voltage and current waveforms as well as RMS voltage output for 277V, 290V, and 264V dispatch points.

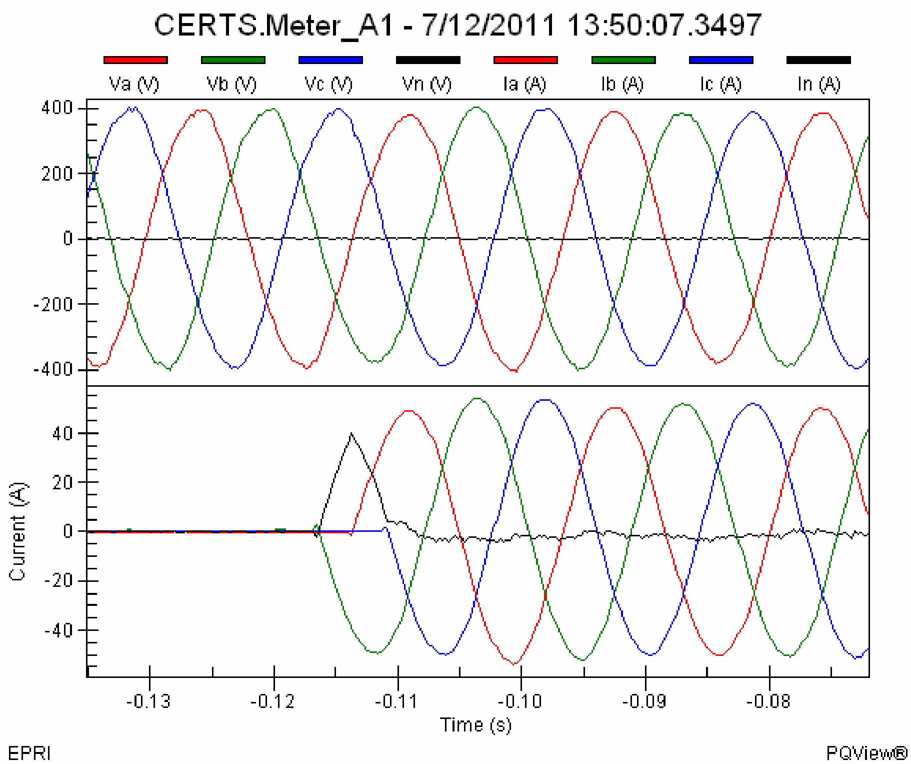

Figure 39 - Voltage and current waveforms after a 30kW load step (277V dispatch)

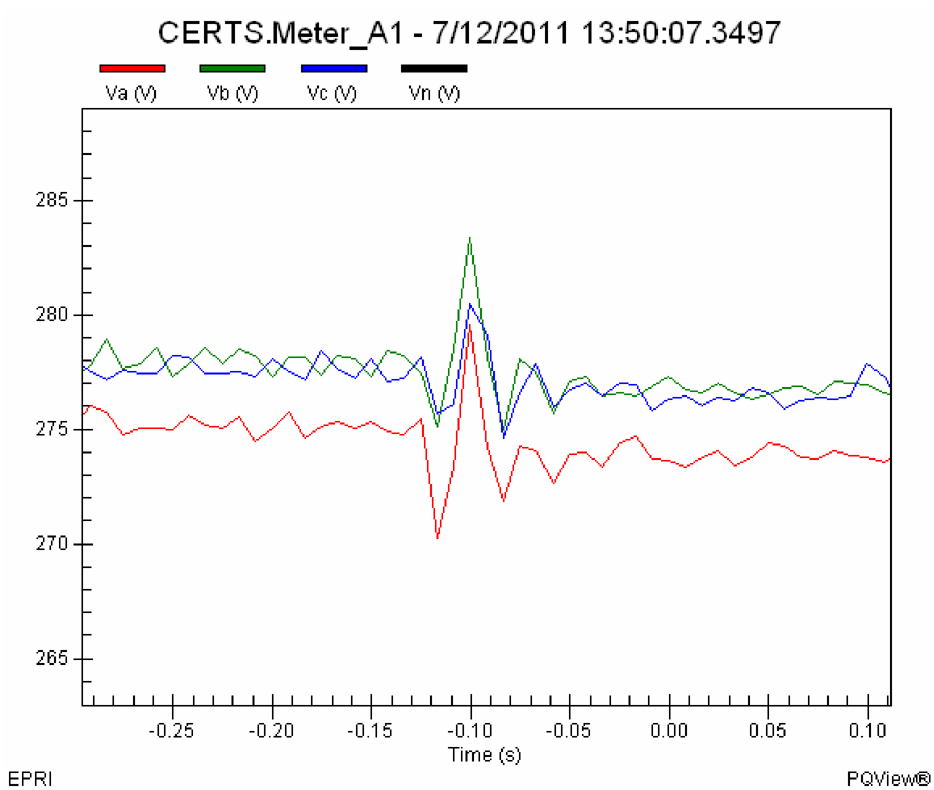

Figure 40 - RMS voltage after a 30kW load step (277V dispatch)

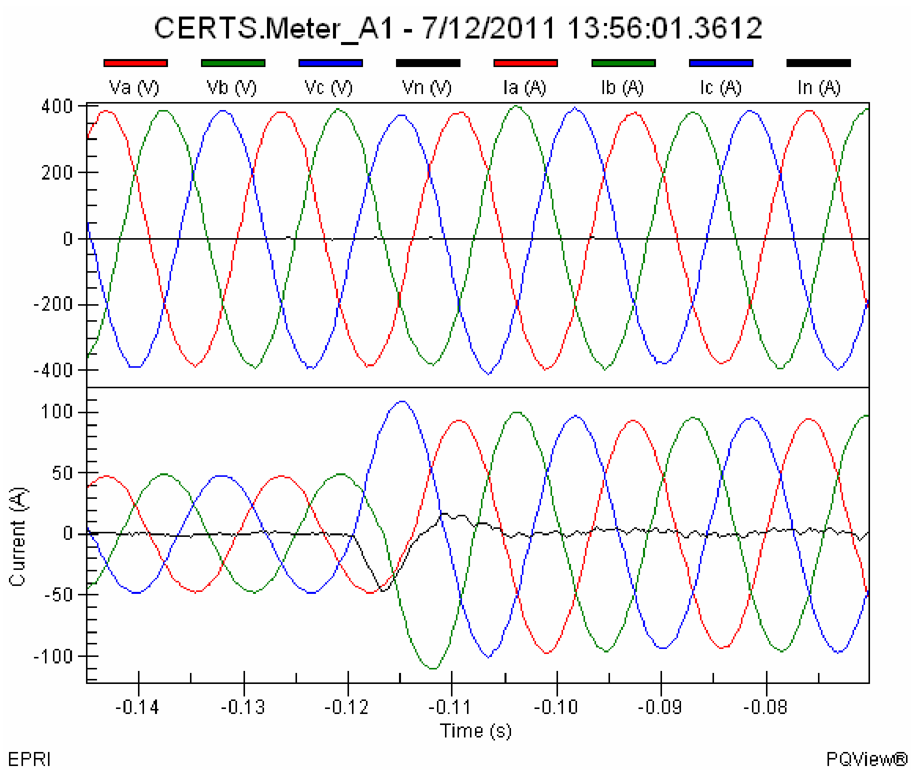

Figure 41 - Voltage and current waveforms after a 60kW load step (277V dispatch)

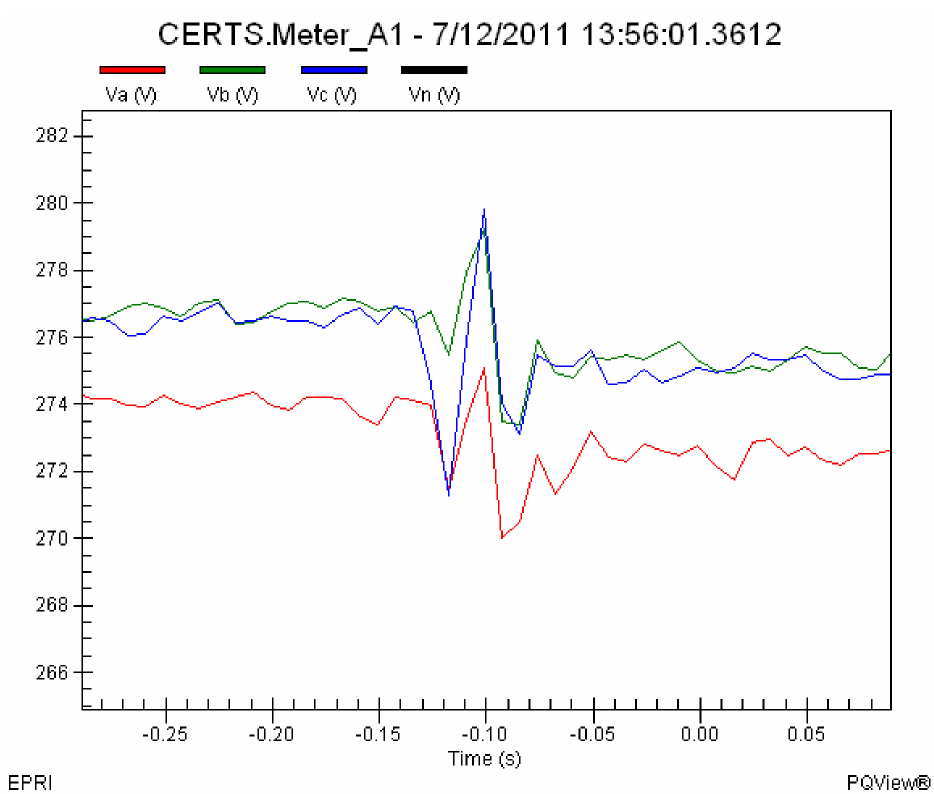

Figure 42 - RMS voltage after a 60kW load step (277V dispatch)

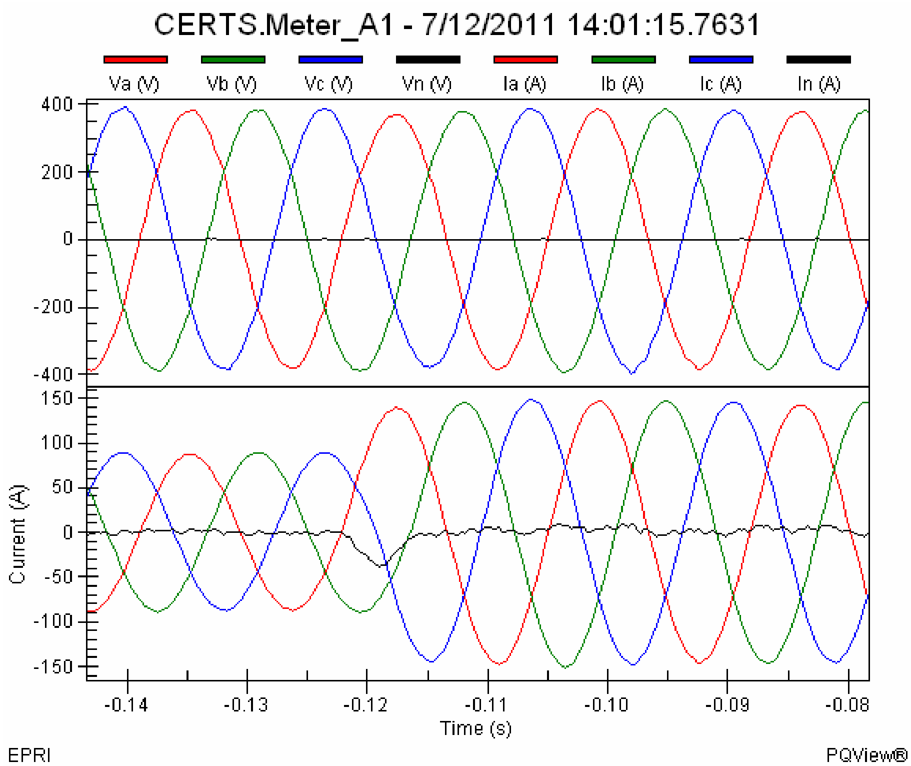

Figure 43 - Voltage and current waveforms after a 95kW load step (277V dispatch)

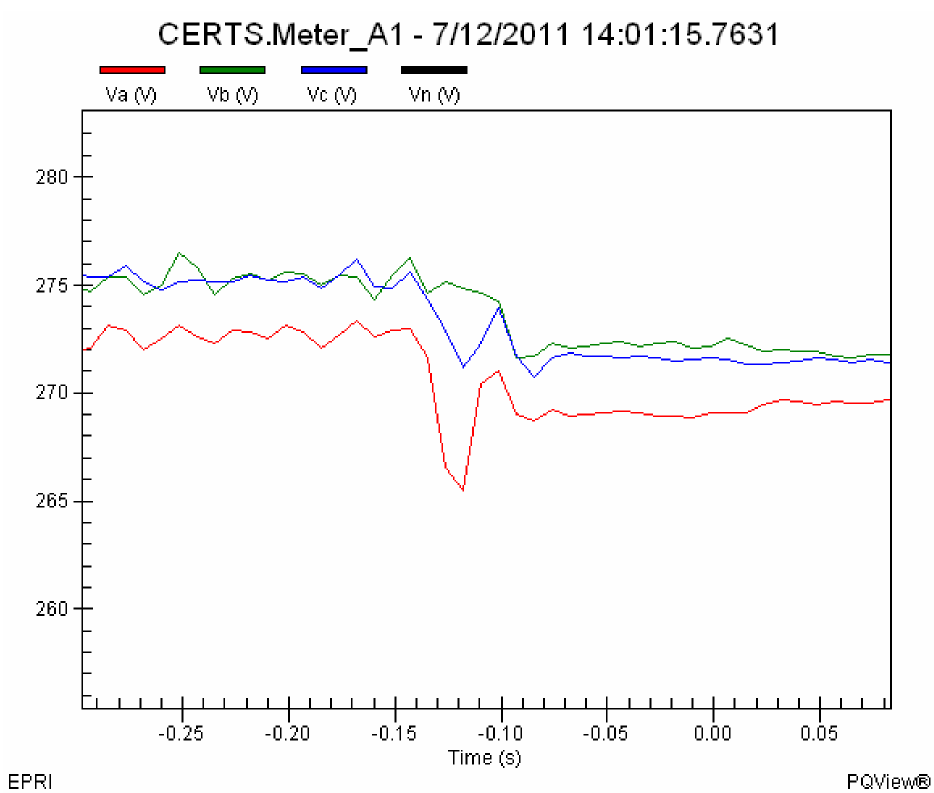

Figure 44 - RMS voltage after a 95kW load step (277V dispatch)

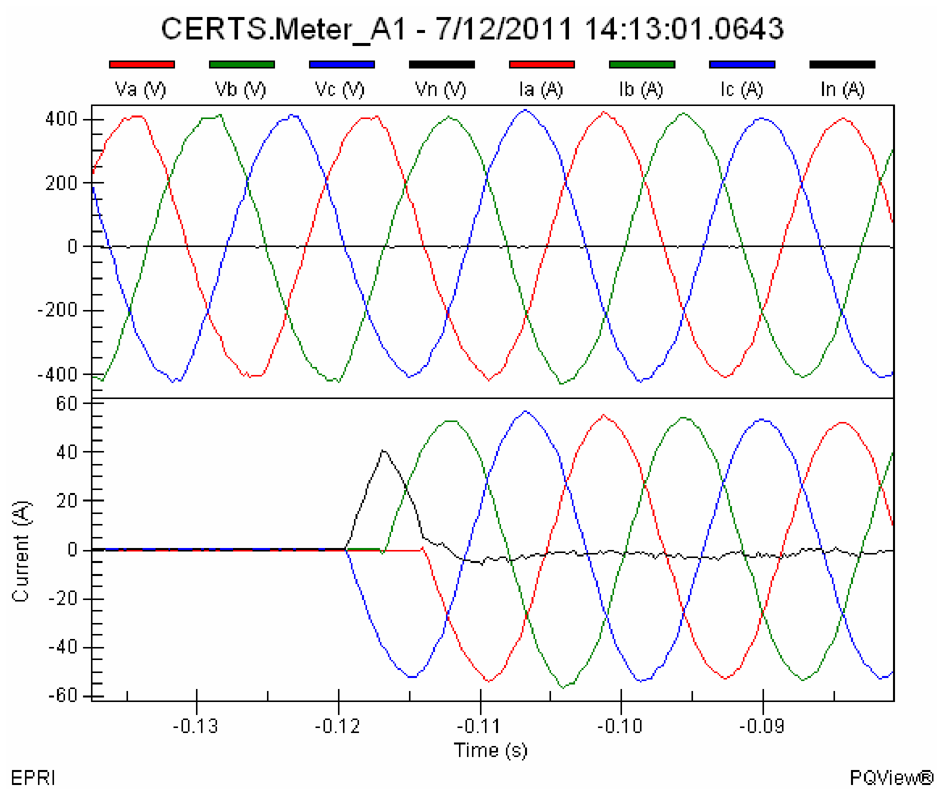

Figure 45 - Voltage and current waveforms after a 30kW load step (290V dispatch)

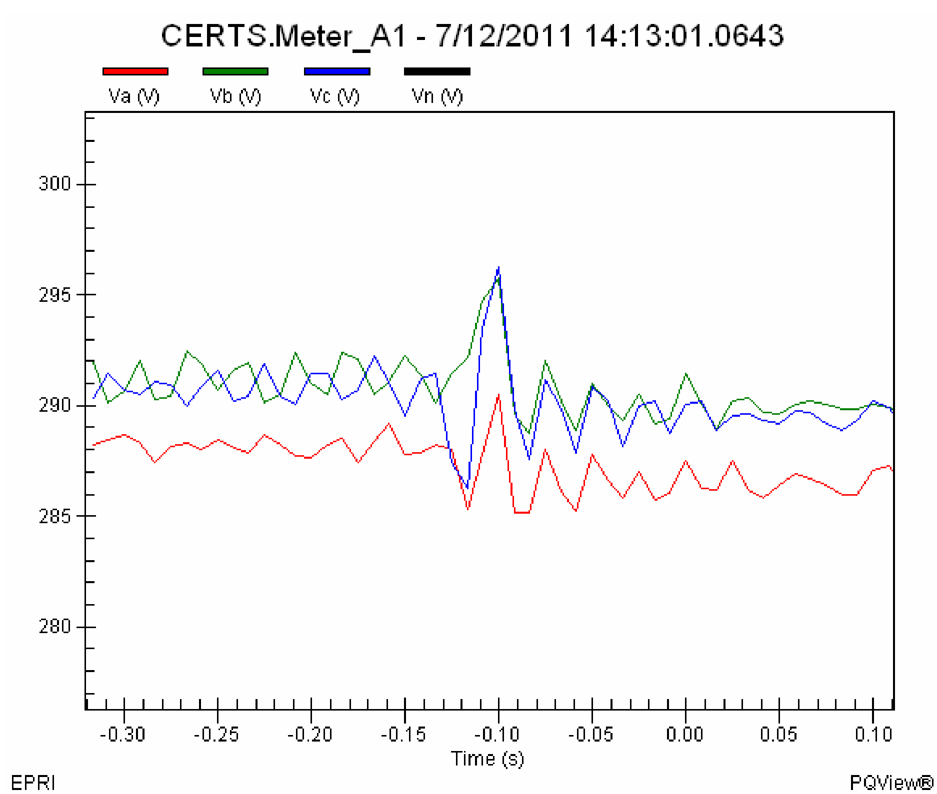

Figure 46 - RMS voltage after a 30kW load step (290V dispatch)

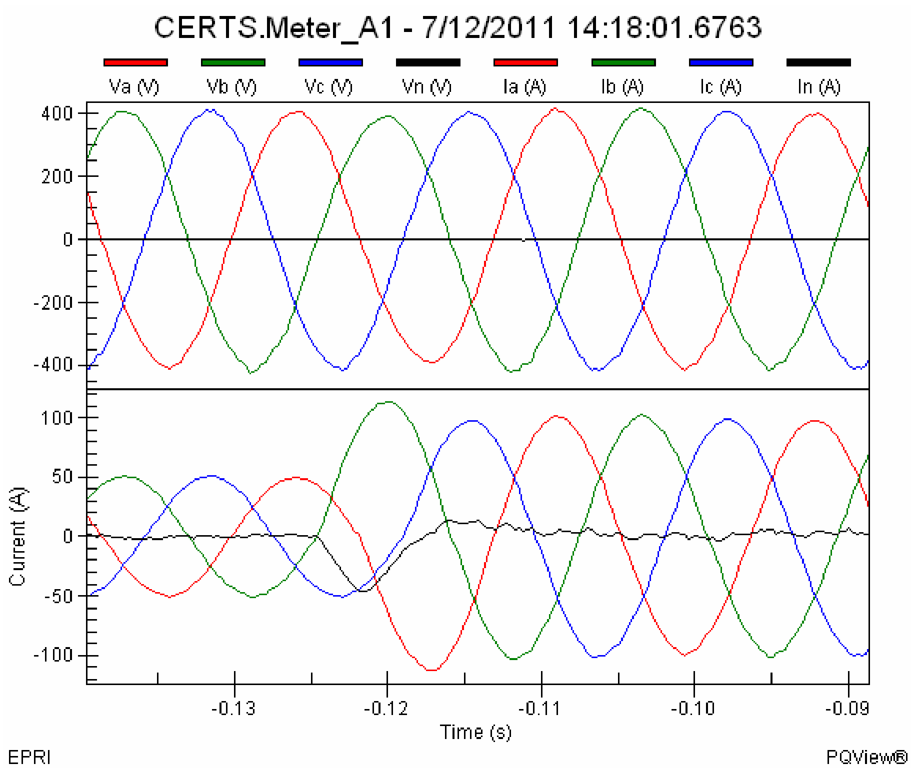

Figure 47 - Voltage and current waveforms after a 60kW load step (290V dispatch)

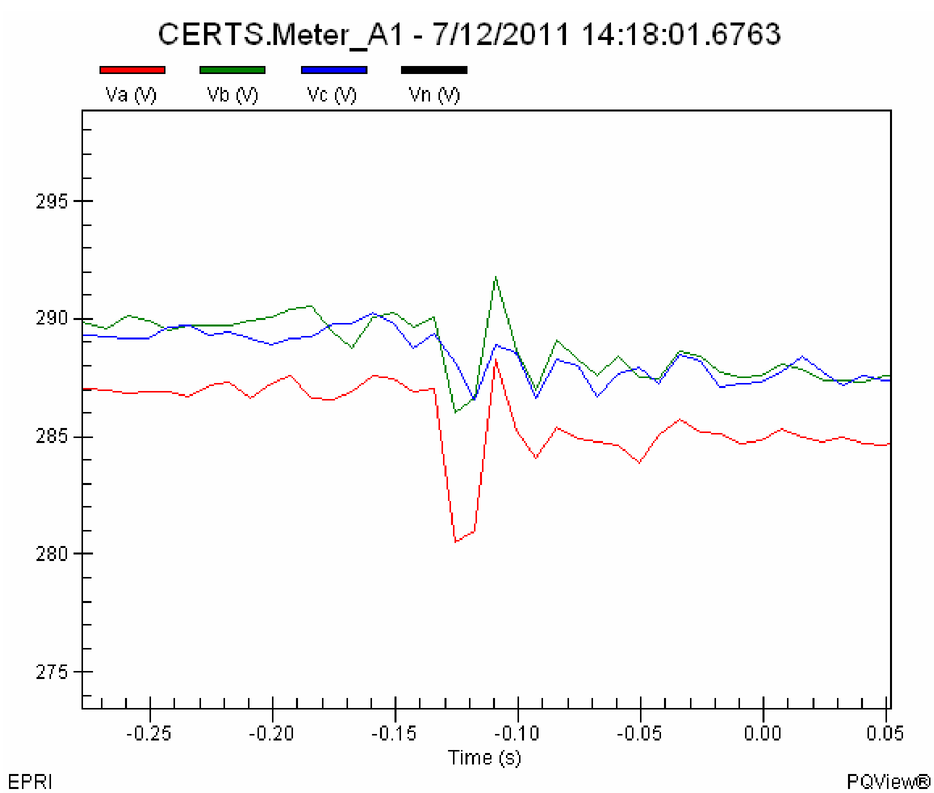

Figure 48 - RMS voltage after a 60kW load step (290V dispatch)

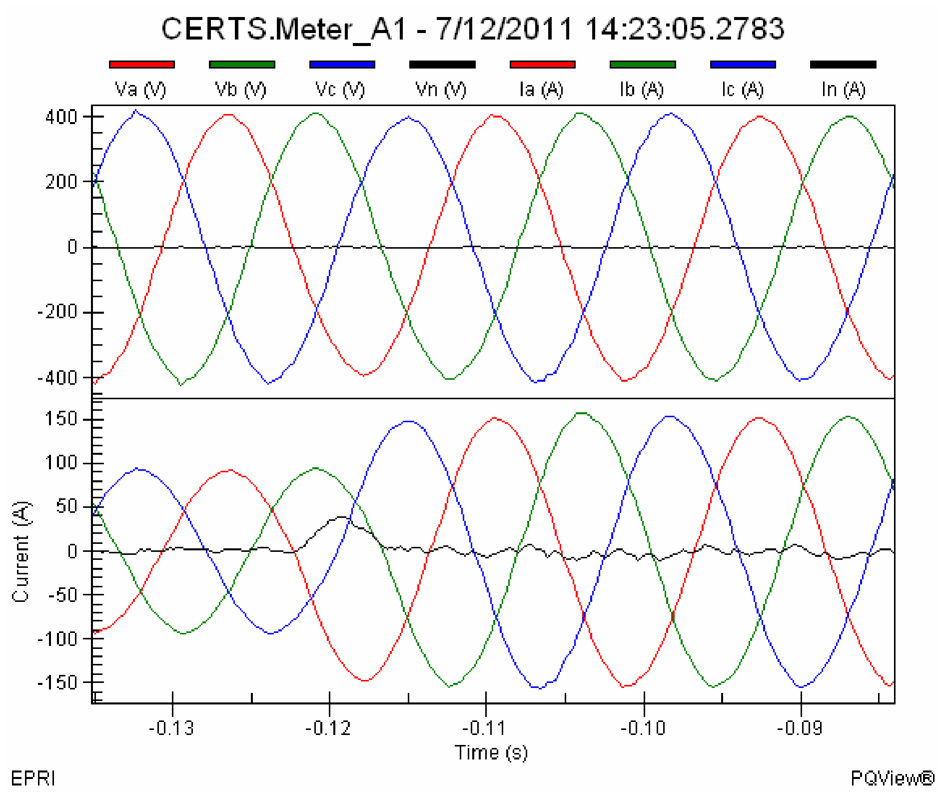

Figure 49 - Voltage and current waveforms after a 95kW load step (290V dispatch)

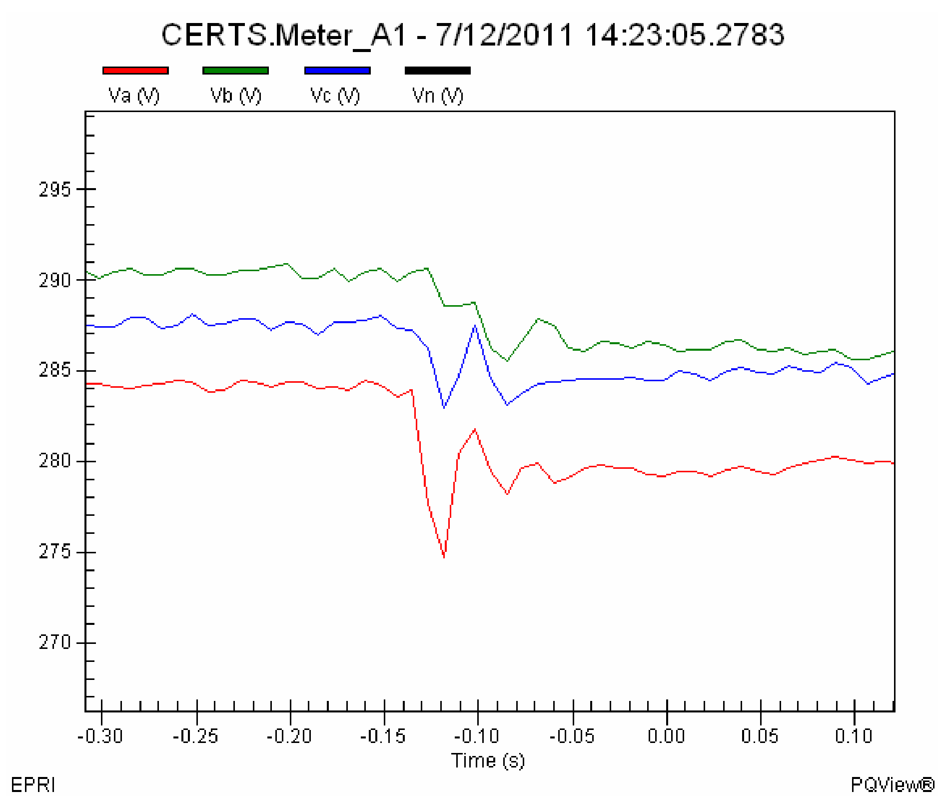

Figure 50 - RMS voltage after a 95kW load step (290V dispatch)

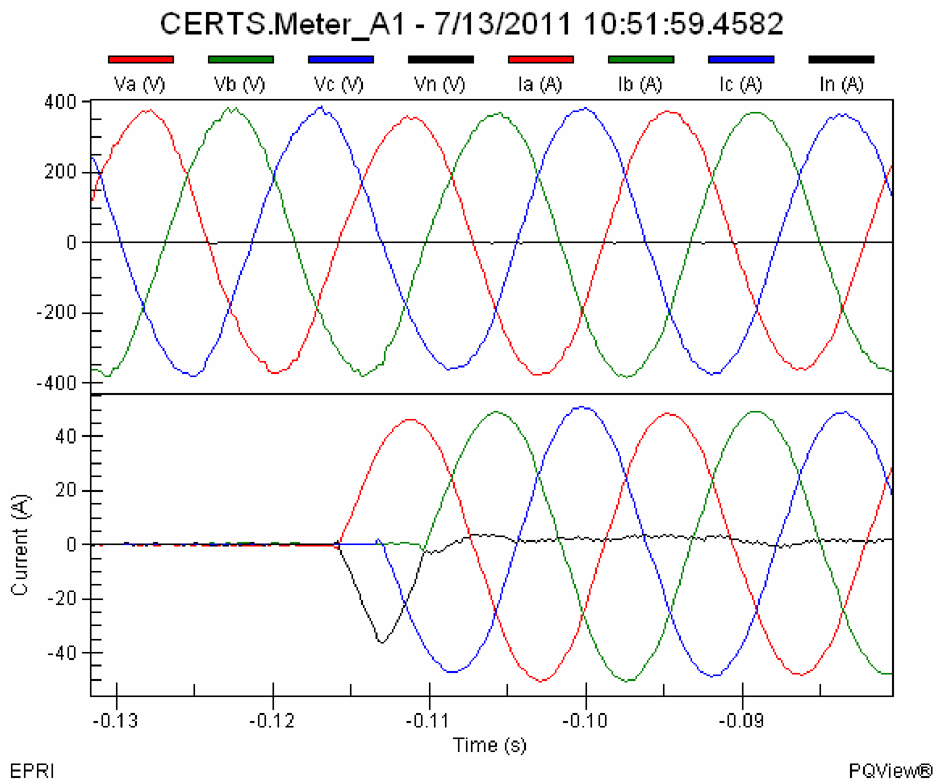

Figure 51 - Voltage and current waveforms after a 30kW load step (264V dispatch)

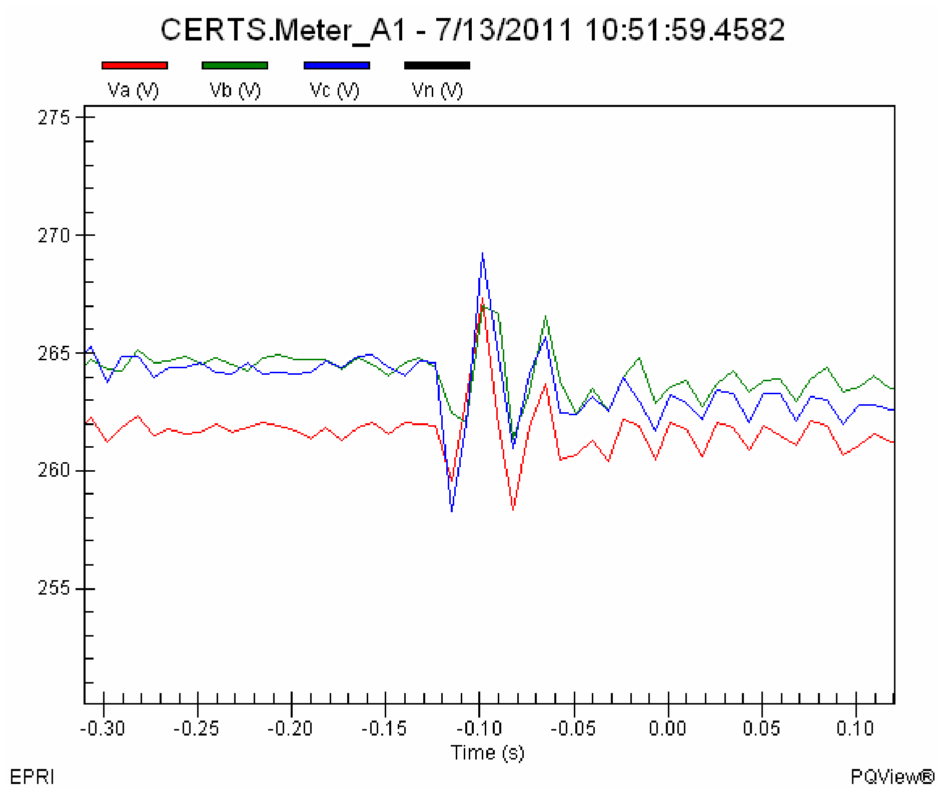

Figure 52 - RMS voltage after a 30kW load step (264V dispatch)

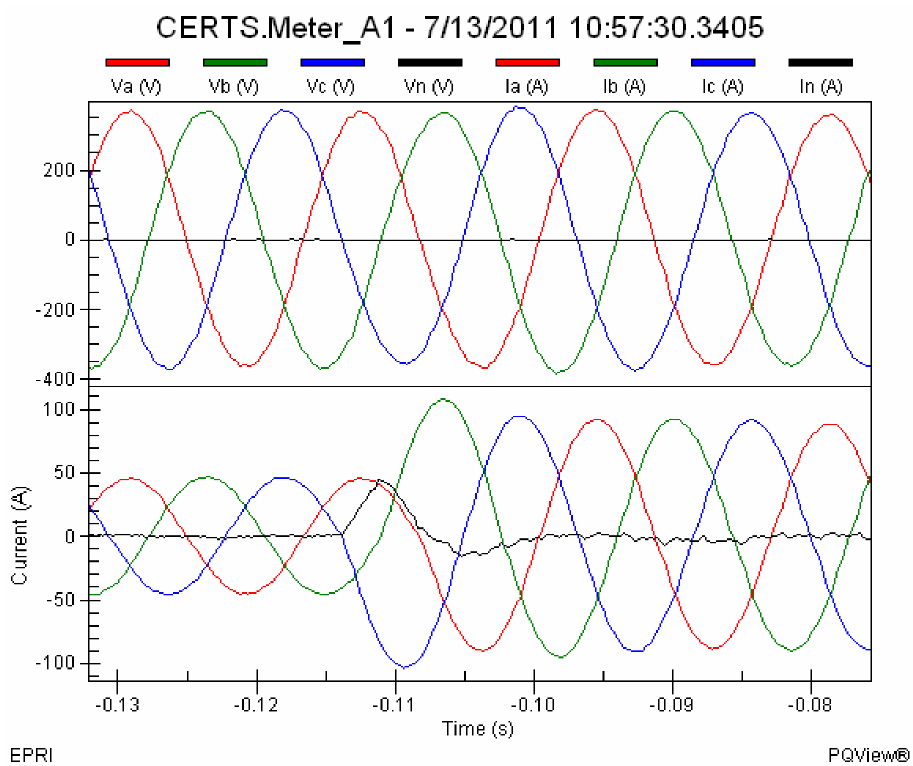

Figure 53 - Voltage and current waveforms after a 60kW load step (264V dispatch)

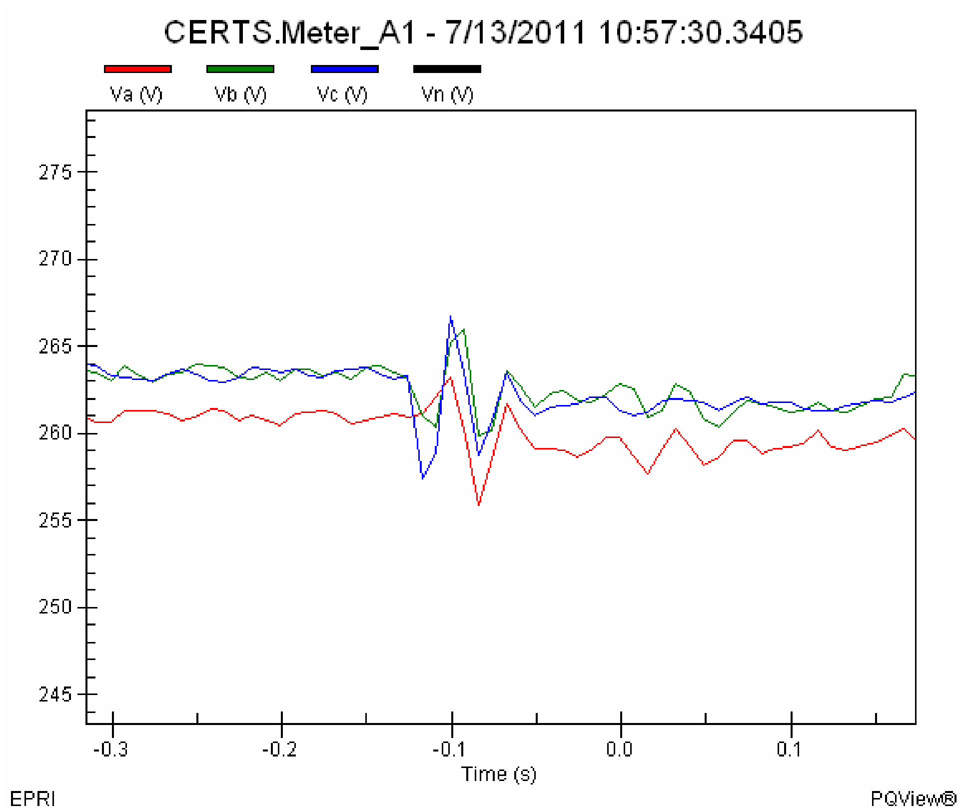

Figure 54 - RMS voltage after a 60kW load step (264V dispatch)

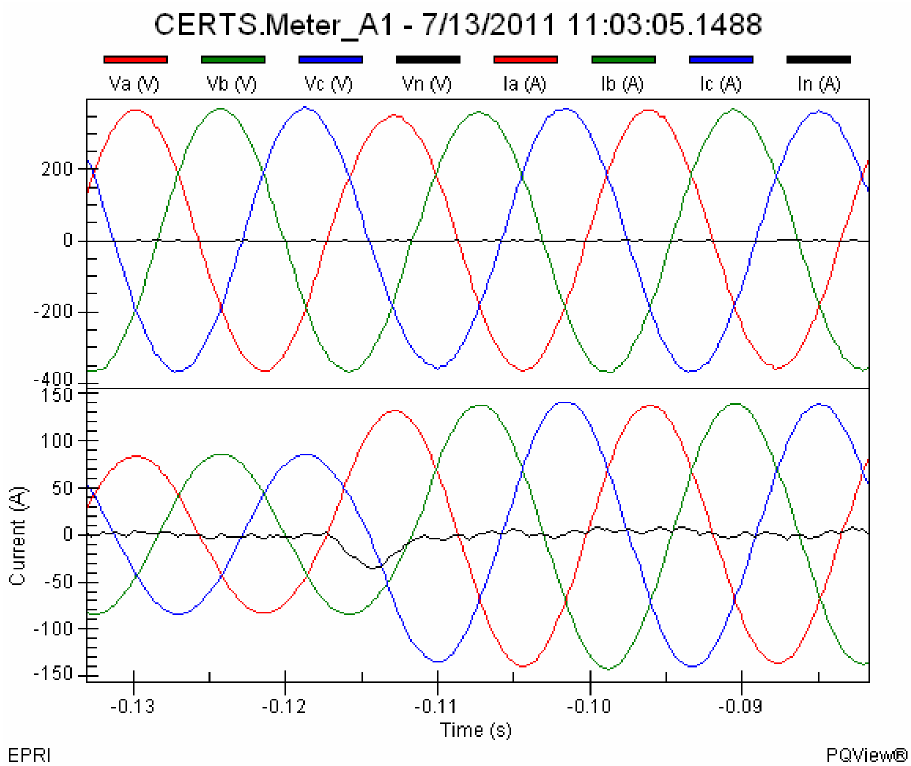

Figure 55 - Voltage and current waveforms after a 95kW load step (264V dispatch)

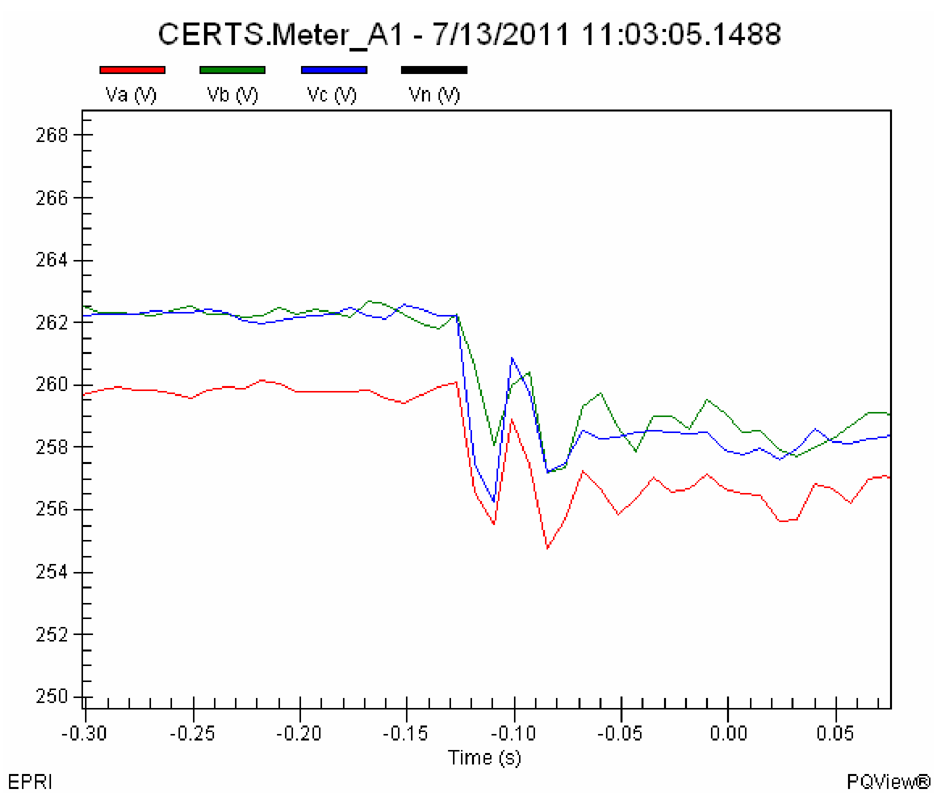

Figure 56 - RMS voltage after a 95kW load step (264V dispatch)

Figure 57 display a plot of genset A1's voltage as real power was added to the microgrid bus. The three voltage dispatch points are shown in different colors with trend lines added to show the slope at each level.

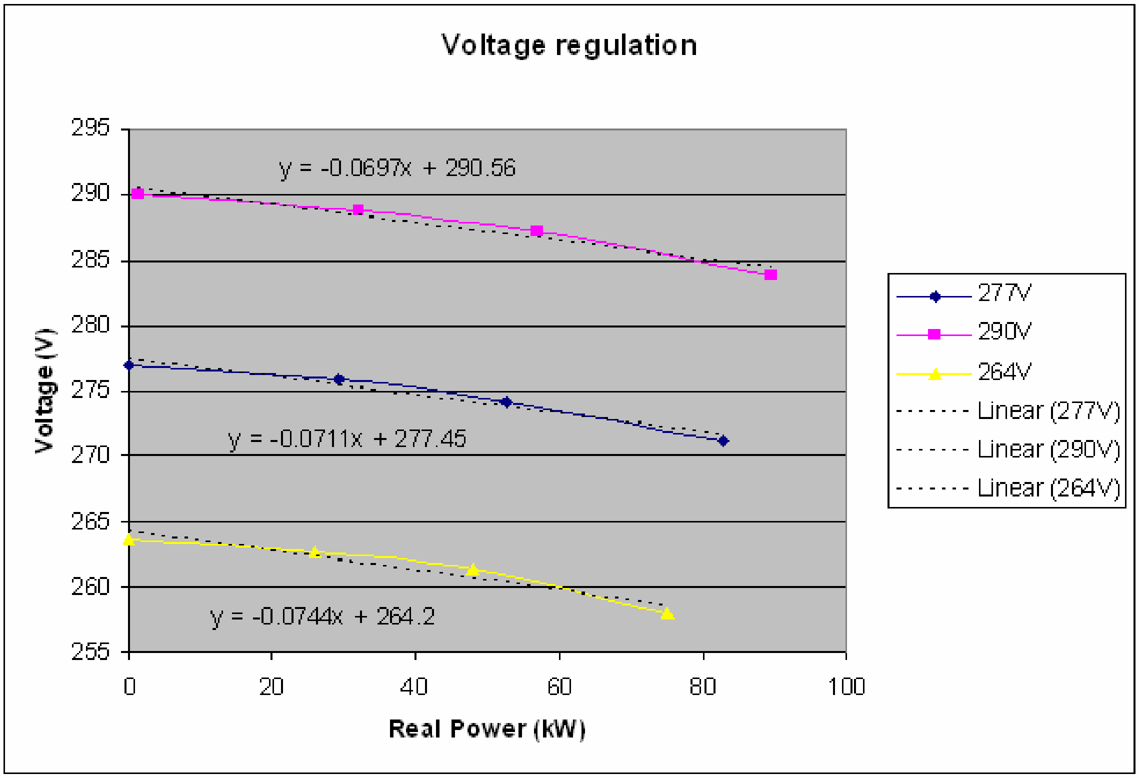

Figure 57 - Plot of voltage as real load was applied to genset A1, dispatch at 3 different voltages

7.5. Load Step Response

Similar to the previous set of tests, this sequence was run to determine the InVerde INV100's response to different levels of loading. However, this time the load steps are more numerous and severe. Two load banks (LB3 and LB4) were utilized to provide a base load prior to adding a load step. Also, instead of monitoring the genset's voltage transients and magnitude, attention was paid to its ability to take on load steps without causing any generation or protection trips. All tests were performed with the microgrid isolated from the utility grid, and data was captured as each load was applied and subsequently removed from the microgrid bus.

With genset A1 dispatched to 50kW and 277V, LB3 was used to add a 20kW load step to the microgrid bus and then remove the load to observe genset A1's response to both conditions. Then, LB4 was used to add an additional 20kW to the microgrid bus and LB3 was used to apply a 20kW to 40kW load step. LB3 was then reduced to 0kW for a total bus load of 20kW. Using both LB3 and LB4 load banks, this process was repeated in 20kW steps until the rated capacity of genset A1 was reached. Within the test bed the true maximum capacity is 95kW, since that is the highest real power output any single load bank is capable of producing.

Next, the LB3 load step size was increased to 40kW. A similar procedure was performed, as LB4 was used to provide base load on the microgrid bus in steps of 20kW. LB3 was used to add and remove 40kW of load as the base load provided by LB4 increased. This was done until the rated capacity of genset A1 was reached.

The load step size of LB3 was then increased to 60kW and the same procedure was performed as it was with the 40kW load steps. Next, the load step size of LB3 was increased to 80kW and the process was repeated.

Finally, LB3 was used to add and remove a 95kW load step to the microgrid bus. LB4 was not needed to add a base load for this sequence, since a single load bank is capable of producing near genset A1's rated capacity.

With the exception of the large 0kW-95kW load step, genset A1 was capable of remaining online during all the tests that were performed in this segment. This test was performed twice to ensure continuity. To test genset A1's ability to remain online near its rated capacity, load was added using LB3 in smaller steps until 95kW was reached. Then, the entire load was removed in a single step and genset A1 remained online.

Figures 58-61 display an example of one of the load steps performed. In this situation, LB4 provides 20kW as a base load to the bus, and LB3 was used to add an 80kW load step. Due to losses in the load banks, the microgrid bus load was not truly 100kW and genset A1 had a real power output of 91kW.

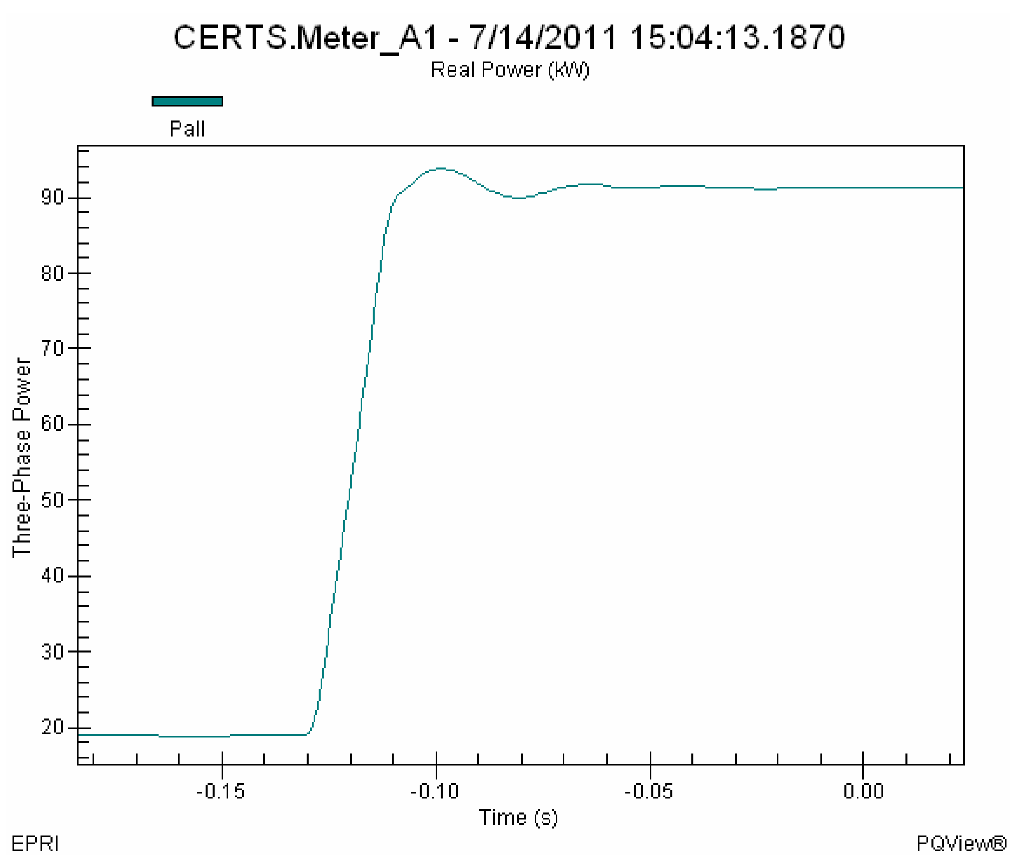

Figure 58 - Genset A1 real power output after 80kW load step (100kW total load)

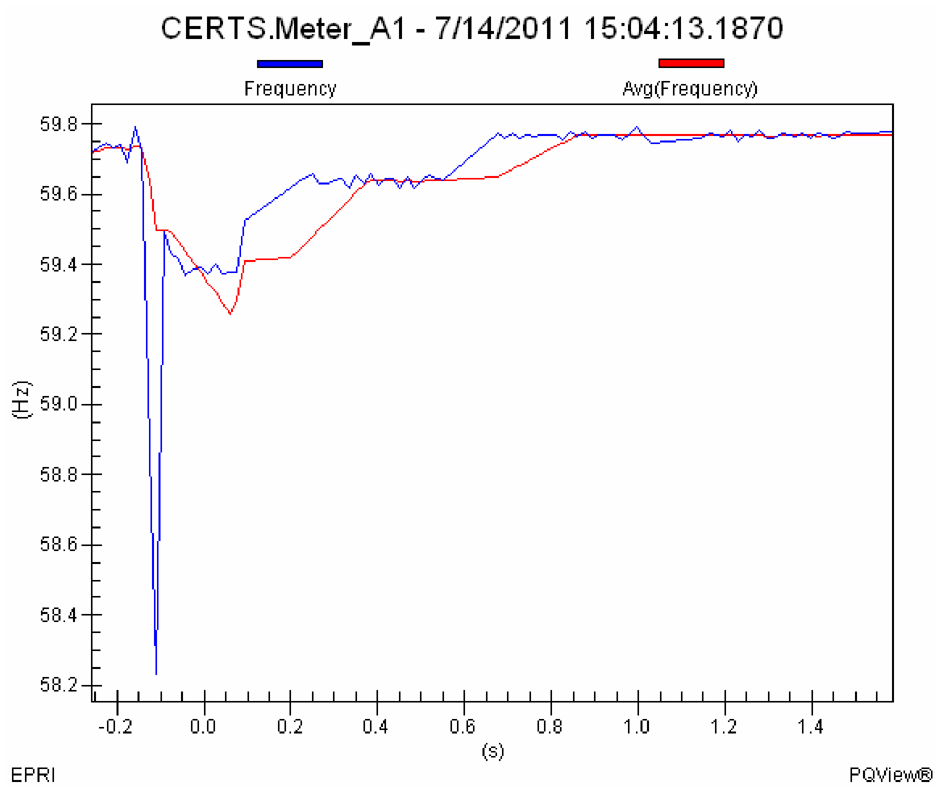

Figure 59 - Genset A1 frequency after 80kW load step (100kW total load)

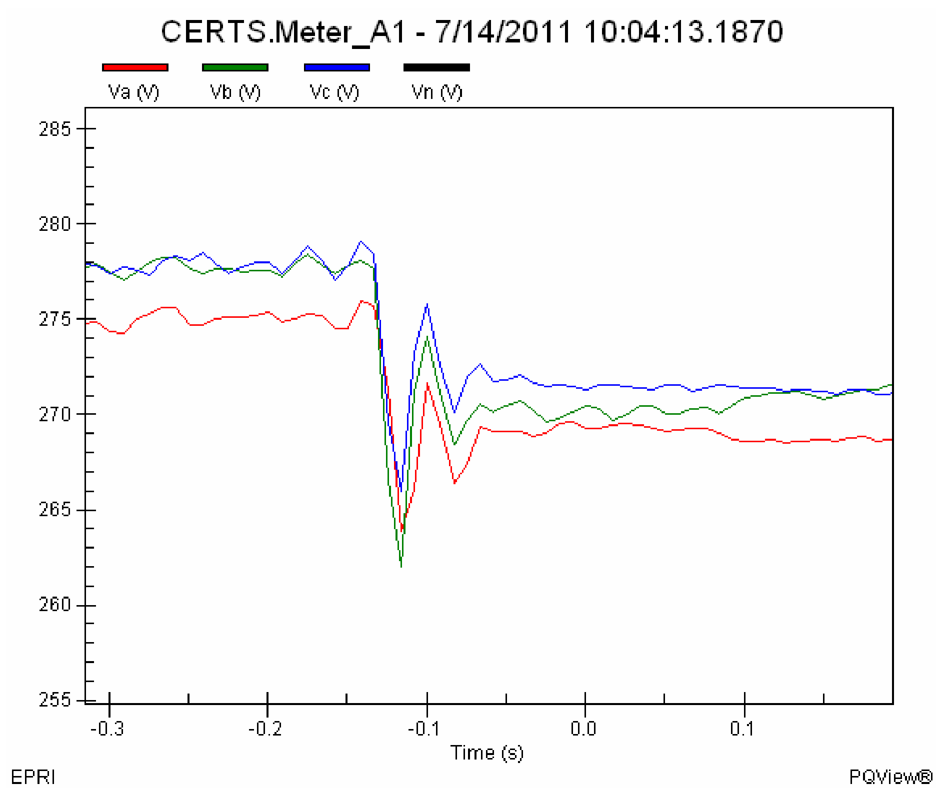

Figure 60 - Genset A1 RMS voltage after 80kW load step (100kW total load)

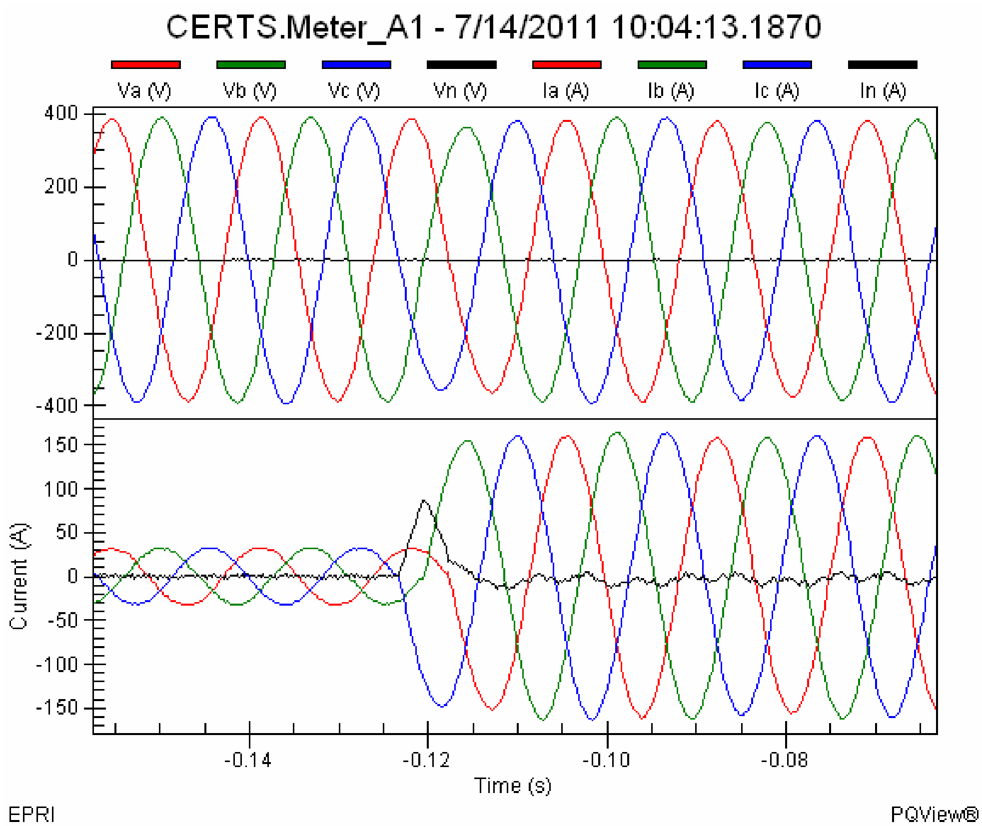

Figure 61 - Genset A1 voltage and current waveforms after 80kW load step (100kW total load)

As a comparison, figures 62-65 display a load step of 95kW. In this case genset A1 attempted to pick up the load but stalled after 1 second had passed. Adding load gradually to the rated capacity of genset A1 does not cause it to shut down, but due to limitations in the engine response to its full capacity the genset was not able to remain online. The full scale of these charts is shown as opposed to a small window at the point of loading. This was done to display genset A1's attempt to pick up the load and subsequent shut down of the genset.

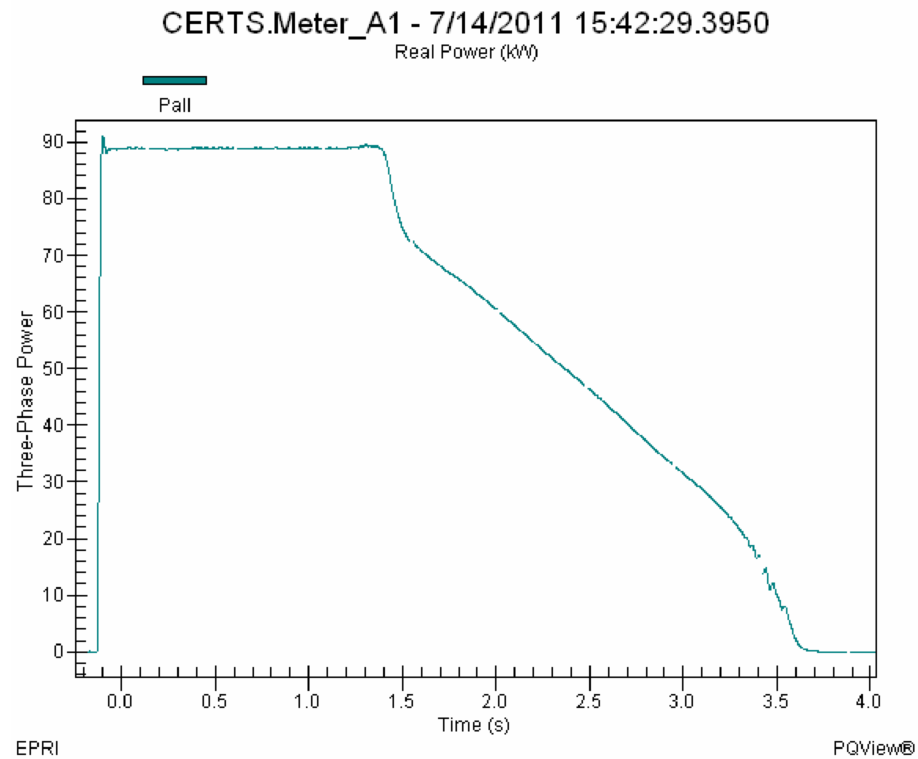

Figure 62 - Gensest A1 real power output after 95kW load step

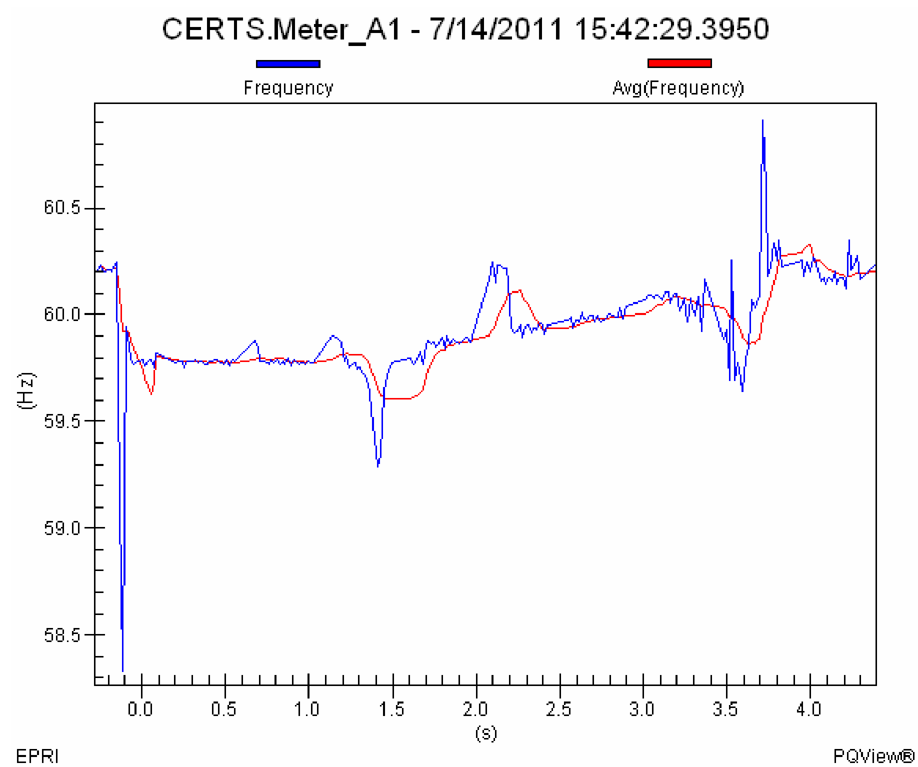

Figure 63 - Genset A1 frequency after 100kW load step

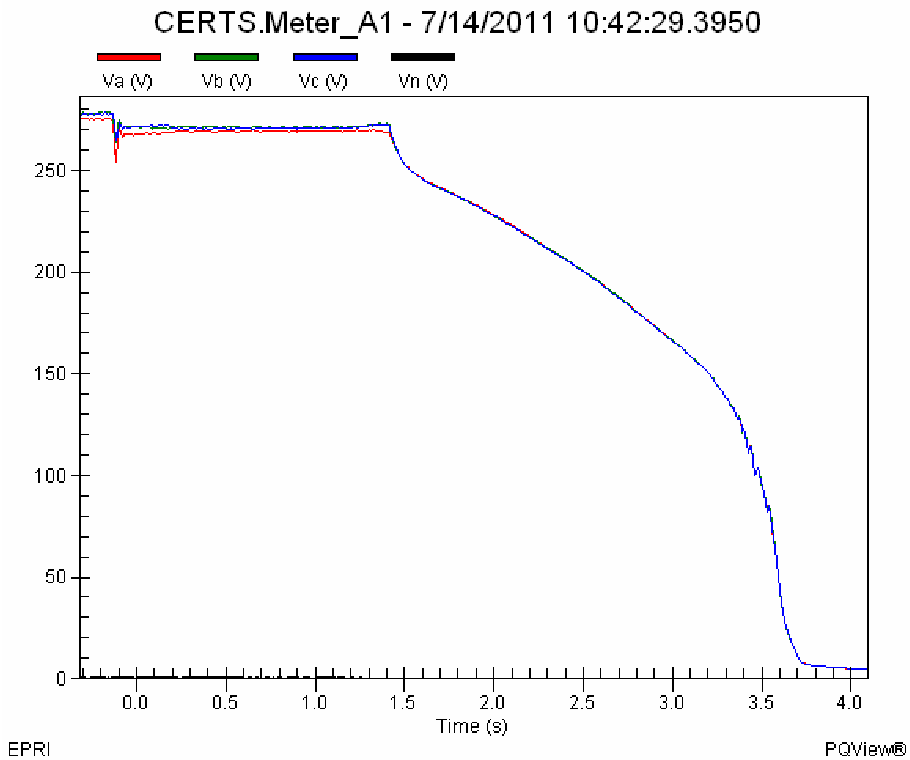

Figure 64 - Genset A1 RMS voltage after 100kW load step

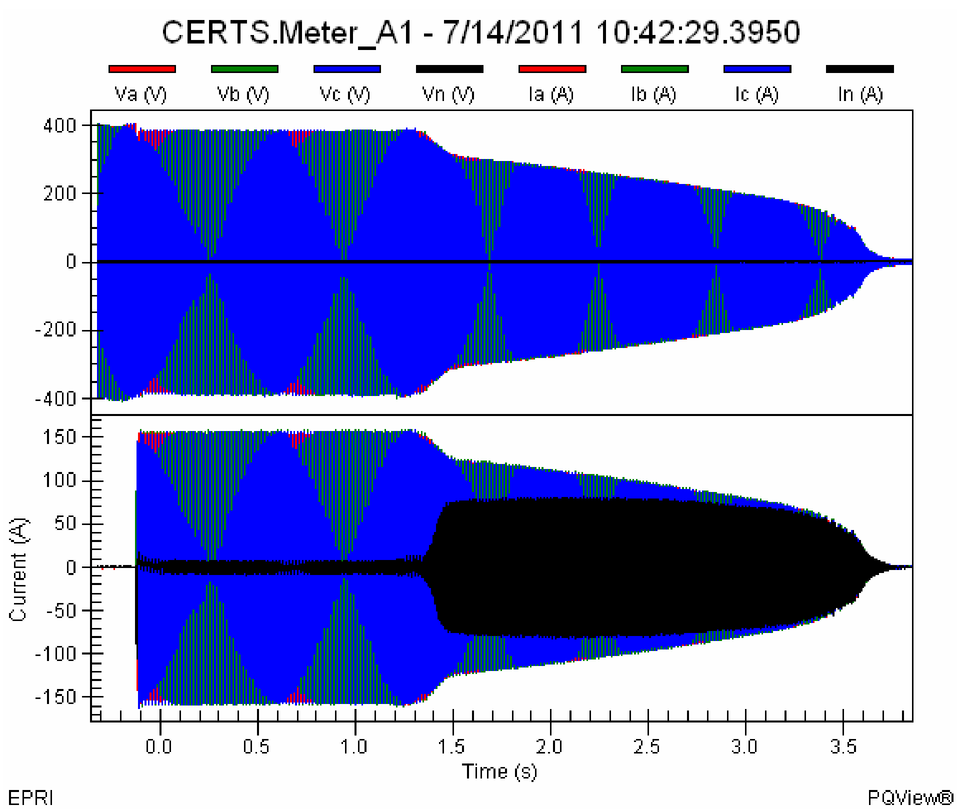

Figure 65 - Genset A1 voltage and current waveforms after 100kW load step

7.6. Open Static Switch, P=0kW

During this sequence of tests, a Tecogen 60kW prototype genset was used to test the InVerde INV100's load sharing capabilities. In the test bed environment, the prototype is referred to as genset A2. In all of the previous tests the microgrid was isolated from the utility grid, but the goal of this particular procedure is to verify smooth transitions in response to an islanding condition.

To begin, the static switch was closed to provide a connection to the utility grid. LB3 and LB4 were used to add critical or 'protected' load to the microgrid bus, and LB6 was used to add 'unprotected' load. Since the static switch is closed, load that was beyond the total genset dispatched amount was picked up by the utility grid. With genset A1 & A2 online and respectively dispatched to 5kW and 55kW, the static switch was issued a manual 'Open' command. The unprotected load is located on the utility grid side of the static switch, and was picked up in its entirety by the utility grid. In the event of a utility outage, this load would have been sacrificed. The protected load was picked up and distributed according to the dispatch levels of each genset. Table 1 displays the expected output before and after the static switch was opened.

Test Event - Open Static Switch				
	Mode	**Start**	**Event**	**End**
$A1_P$	Unit	5kW		0.0kW
$A2_P$	Unit	55kW		40kW
$B1_P$		Off		Off
Freq.		~60Hz		~60.13
L3		20kW		20kW
L4		20kW		20kW
L5		0		
L6		45kW		45kW
SS	CLOSED	-20kW	OPEN	0.0kW
Grid		25kW		45kW
Let SS to Re-close				

Table 1 – Expected output of both gensets before and after an islanding event occurred

Since genset A1 was dispatched to 5kW, it was not expected to pick up any of the load. Genset A2, dispatched to 55kW, was capable of carrying the 40kW of protected load within the microgrid. And with the load on the microgrid larger than genset A1's dispatched amount, its frequency output was above the nominal 60Hz. Once all data was captured, the manual 'Open' command was removed from the static switch allowing a synchronized close to occur. Genset A1 and A2 were then expected to return to their starting conditions.

Figures 66-68 display the transitions that occurred during this test. Meter 3 relates to the output of genset A1 and meter 4 is relates to the output of genset A2.

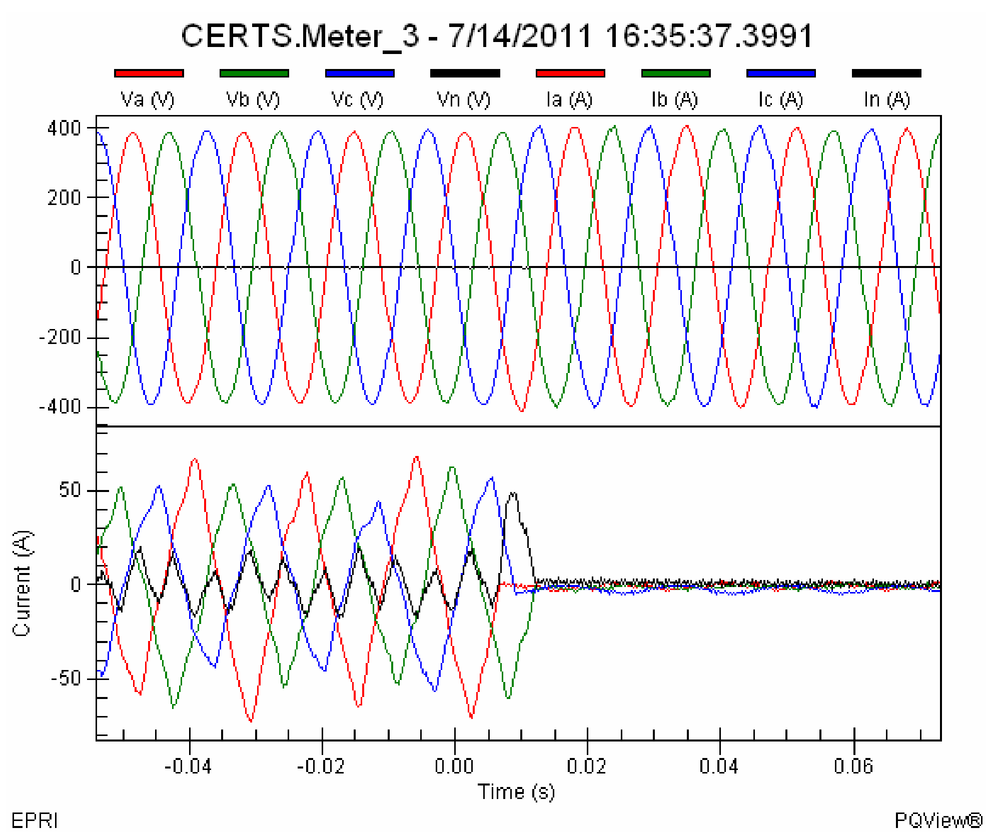

Figure 66 - Genset A1 voltage and current waveforms before and after the static switch opened

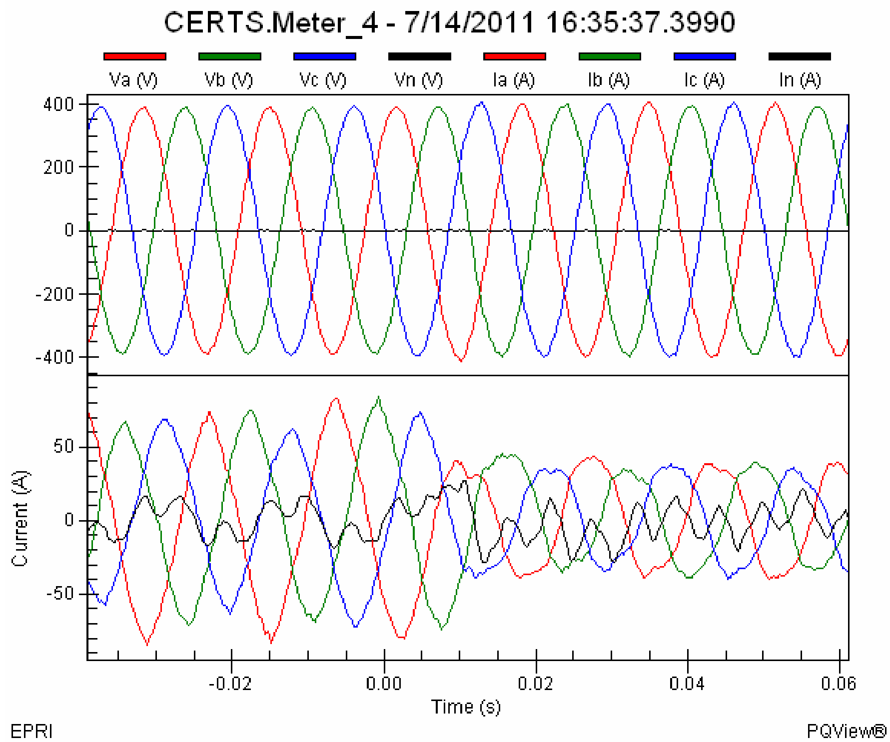

Figure 67 - Genset A2 voltage and current waveforms before and after the static switch opened

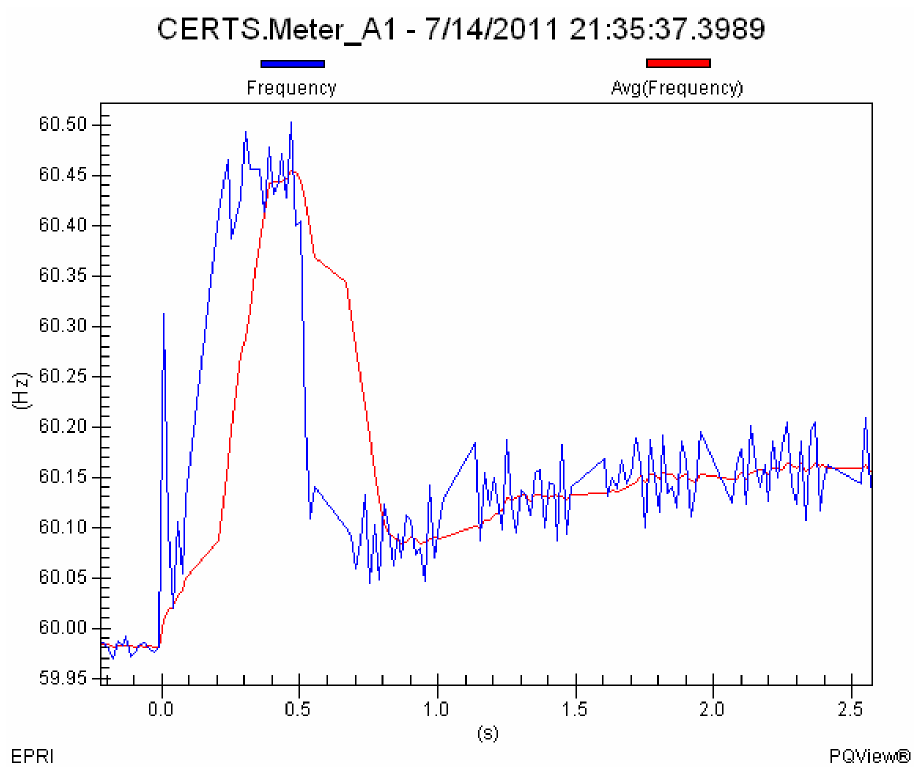

Figure 68 - Genset A1 frequency output before and after the static switch was opened

7.7. Open Static Switch, P =100kW

The procedure for this test sequence was identical to the previous test, with the exception of dispatch points for each genset and the amount of load that was added to the microgrid bus. Table 2 shows the expected output for all equipment before and after the static switch was opened.

Event Open SS				
	Mode	**Start**	**Event**	**End**
$A1_P$	Unit	75kW		100kW
$A2_P$	Unit	5kW		20kW
$B1_P$		Off		Off
Freq		~60Hz		~59.74
L3		70kW		70kW
L4		50kW		50kW
L5		0		0
L6		40kW		40kW
SS	CLOSED	40kW	OPEN	0kW
Grid		80kW		40kW
Let SS re-close				

Table 2 - Expected output of both gensets before and after an islanding event occurred

The total bus load was 160kW, and the total dispatch amount of the gensets was 80kW. Therefore, the utility picked up the remaining 80kW prior to the static switch opening. Due to load bank losses, the actual loading amounts were slightly less than the values shown in Table 2. After the switch opened, the gensets needed to pick up 110kW of protected load. Genset A1 was dispatched high, so it picked up load until it neared its rated capacity of 100kW. Genset A2 picked up remaining 20kW, ignoring its 5kW dispatch point.

Figures 69-73 displays the transition that occurred for both gensets when the static switch was opened.

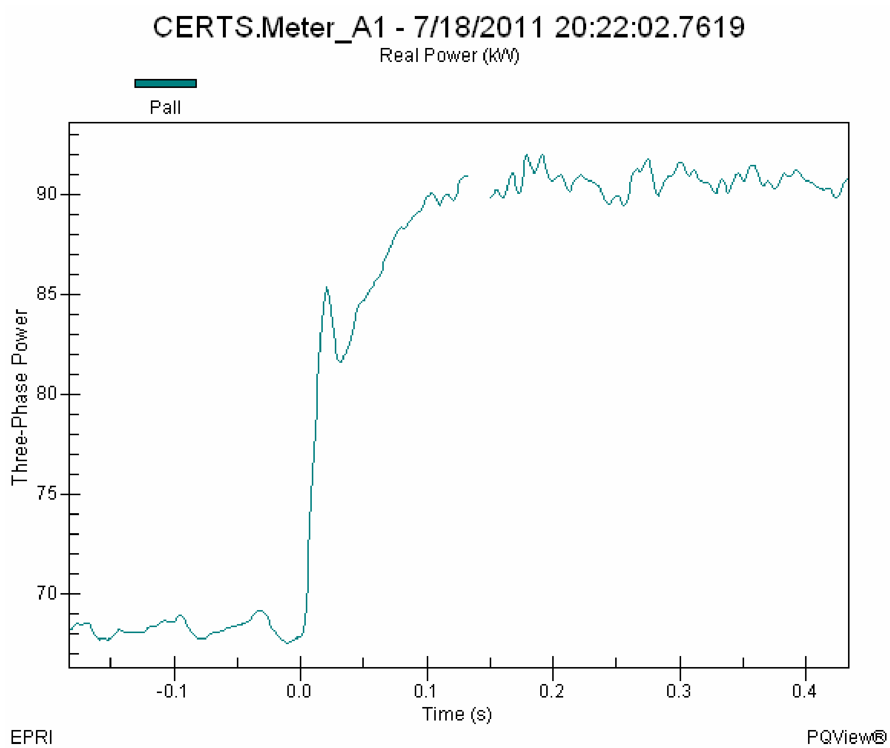

Figure 69 - Genset A1 real power output before and after the static switch opened

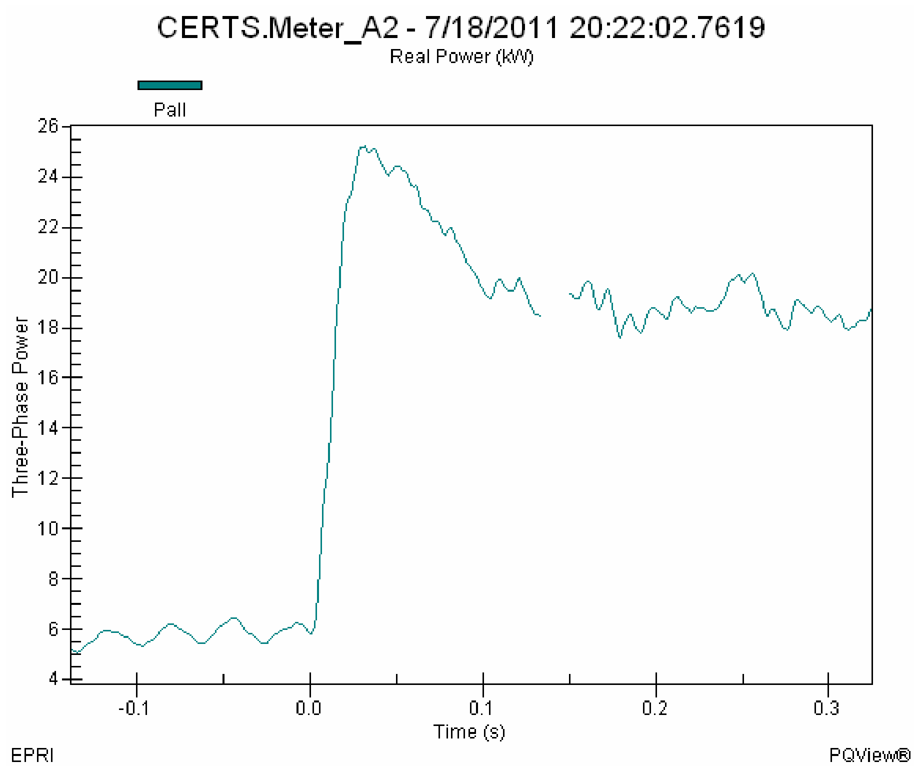

Figure 70 - Genset A2 real power output before and after the static switch opened

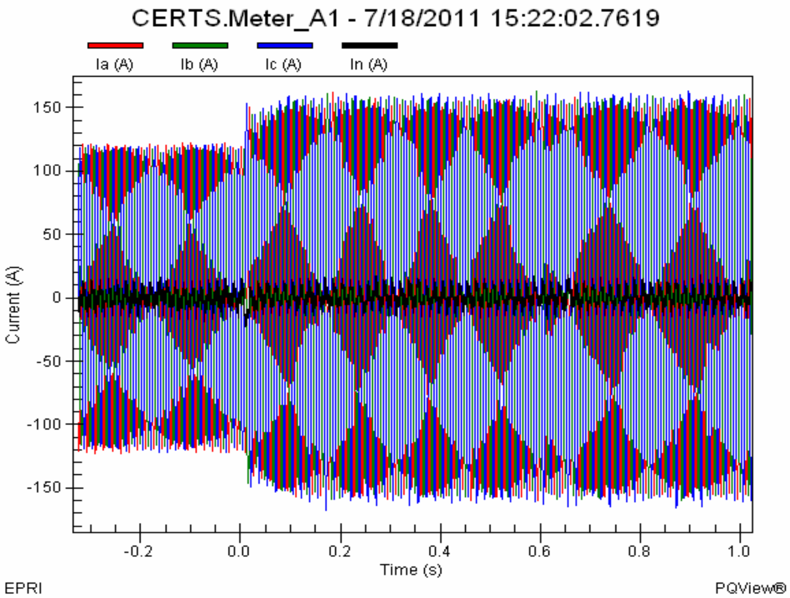

Figure 71 – Genset A1 current waveform as a response to the static switch opening near t=0s

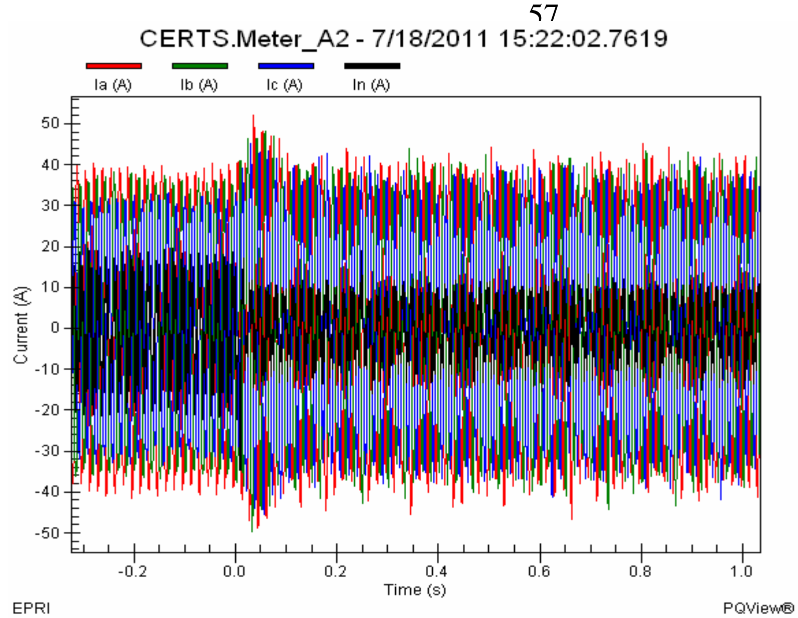

Figure 72 – Genset A2 current waveform as a response to the static switch opening near t=0s

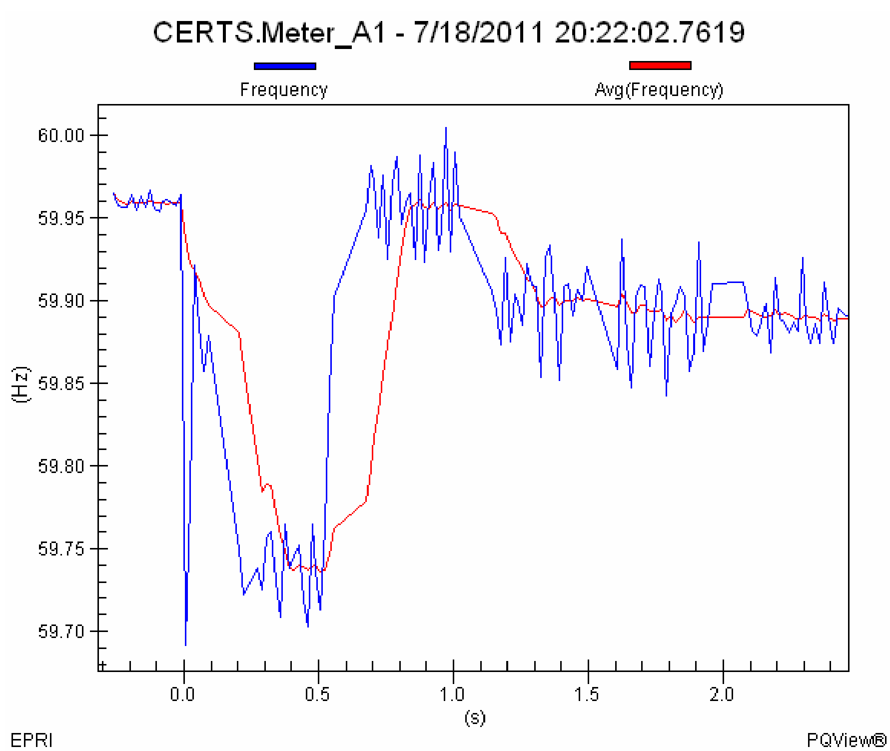

Figure 73 - Genset A1 frequency output before and after the static switch opened

7.8. Unbalanced Load

The previous two test sequences showed the InVerde INV100's ability to operate in tandem with another microsource and transition load in an islanding event. However, the load in those situations was balanced on all three phases. In this next test, gensets A1 & A2 were set to unit control mode and the microgrid was isolated from the utility grid. Initially, the amount of load on the microgrid bus was equal to the amount dispatched between the two gensets. With the system in steady state, phase A of the load bank was reduced to 0kW, creating a load unbalance. The load was distributed between gensets A1 & A2 without any generator or microgrid trips occurring. Table 3 shows the dispatch level and expected loading of all pieces of equipment before and after the load unbalance condition.

Reduce A-Phase Load in Load Bank 3				
	Mode	Start	Event	End
$A1_P$	Unit	70kW		~46.7kW
$A2_P$	Unit	20kW		~13.3kW
$B1_P$		Off		Off
Freq		~60Hz		~60.2
L3		90kW	A-phase = 0kW	60kW
L4		0kW		0kW
L5		0kW		0kW
L6		0kW		0kW
SS	OPEN	0kW		0kW
Grid		0kW		0kW
Should be no current in phase a				

Table 3 - Expected output of both gensets before and after a load unbalance event occurred

Figures 74-75 show genset A1's reaction to the load unbalance condition. A reduction in phase A in the current waveform and real power output can clearly be seen without a protection event occurring.

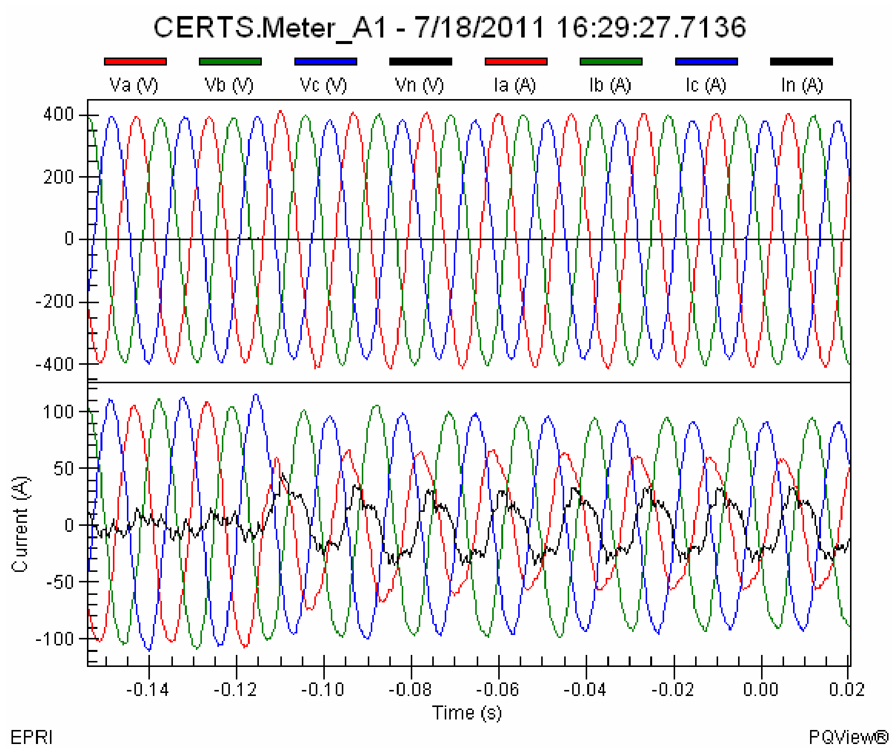

Figure 74 - Genset A1 voltage and current waveforms after a load unbalance event

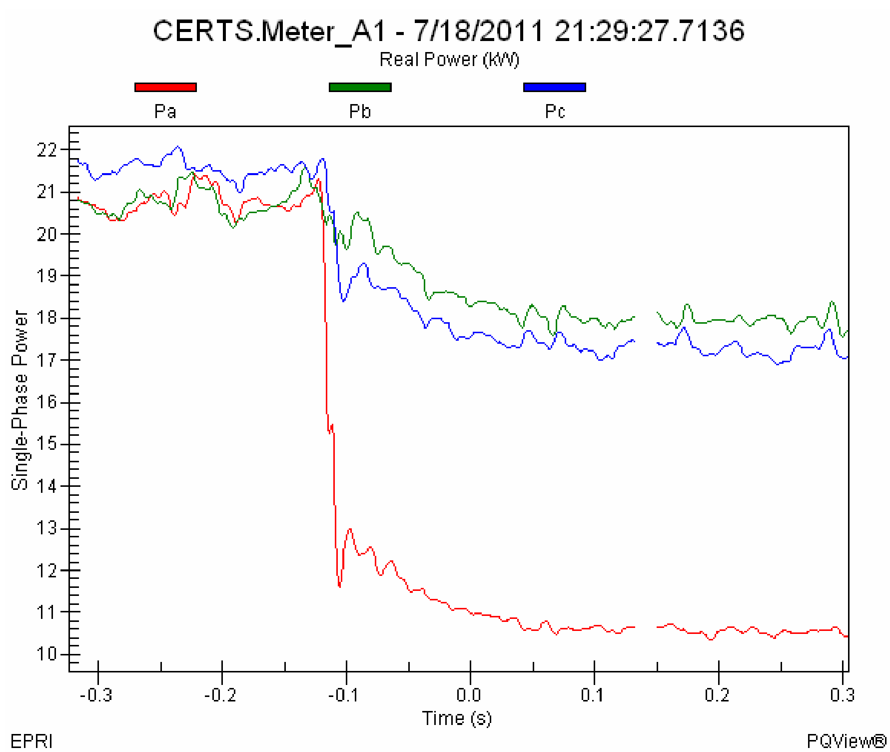

Figure 75 - Genset A1 real power output after a load unbalance event

7.9. Black Start Procedure

This test was performed to check the manual procedure for black-starting the microgrid test bed. This is a contingency in the event of a lengthy utility outage with the microsources offline, and should not cause any generator trips.

To utilize the full generating capacity of the test bed, genset B1 was used in addition to genset A1 & A2. Initially, all three gensets were offline and the test bed safety breaker CB1 was opened to simulate a utility outage. Also, a manual "open" command was issued to the static switch. With no load on the microgrid bus and no utility grid connection, the gensets were then brought online individually. Next, 30kW and 10kVAR was added in three different load banks (LB3, LB4, and LB5). Due to load bank losses the actual load on the microgrid was less than 90kW, and the manually islanded microgrid was now supporting 75kVA of load. This proves the InVerde INV100's black start procedure is functioning and confirms its ability to operate in tandem with other microsources.

To simulate a restoral of the utility grid, safety breaker CB1 was closed and the manual 'open' command was removed from the static switch. This allowed a synchronized close to occur and the load transitioned from the microgrid to the utility grid. Table 4 displays the load on all equipment before and after the static switch closed. The majority of real power was picked up by the utility, and all reactive load remained sourced by the microgrid.

A data trigger was set to capture upon closing of the static switch. Figures 76-78 display genset A1's characteristics as load transferred from the microgrid to the utility grid, as well as real power measured on the utility grid.

Re-connect to the utility grid after black start					
	Start kW	Start kVAR	Event	End kW	End kVAR
$A1_P$	26kW	8kVAR		3kW	7kVAR
$A2_P$	22kW	19.5kVAR		8kW	19.5kVAR
$B1_P$	21kW	6.5kVAR		7kW	7.5kVAR
L3	22.5kW	10kVAR		22.5kW	10kVAR
L4	22.5kW	10kVAR		22.5kW	10kVAR
L5	22.5kW	10kVAR		22.5kW	10kVAR
L6	0kW	0kVAR		0kW	0kVAR
SS	OPEN	OPEN	'open' command removed	CLOSED	CLOSED
Grid	0kW	0kW		52kW	0kVAR

Table 4 - Expected output of all equipment before and after re-connecting to utility grid

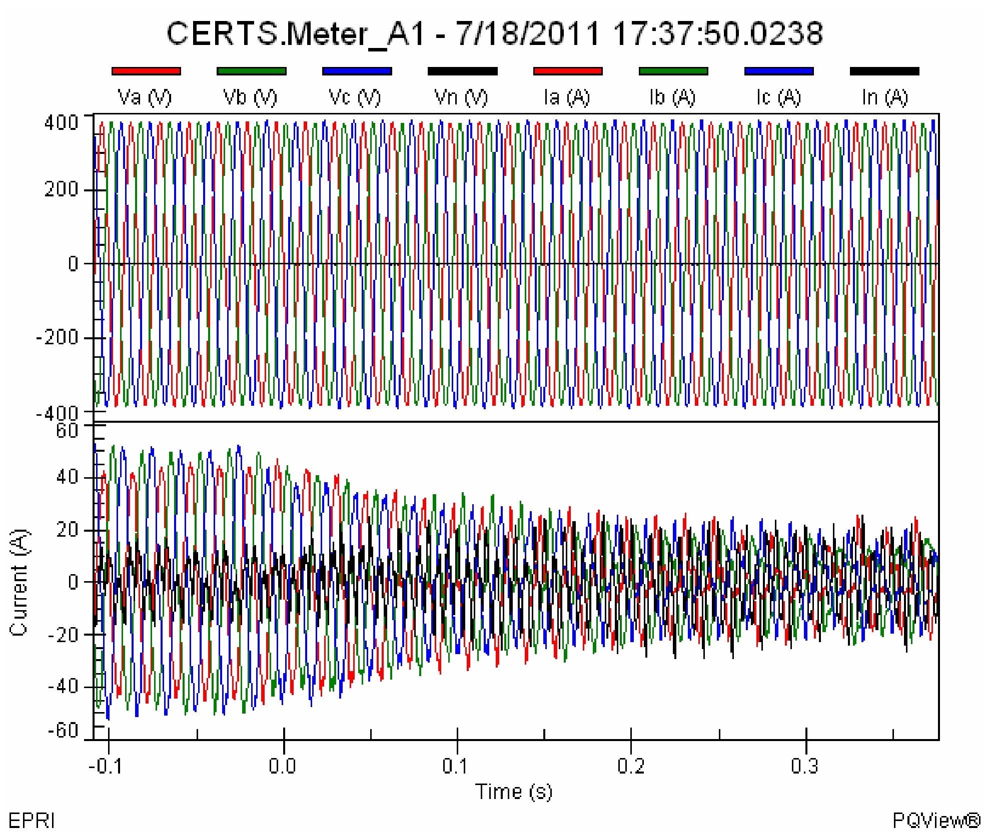

Figure 76 - Genset A1 current and voltage waveform during a load transition from the microgrid to the utility grid

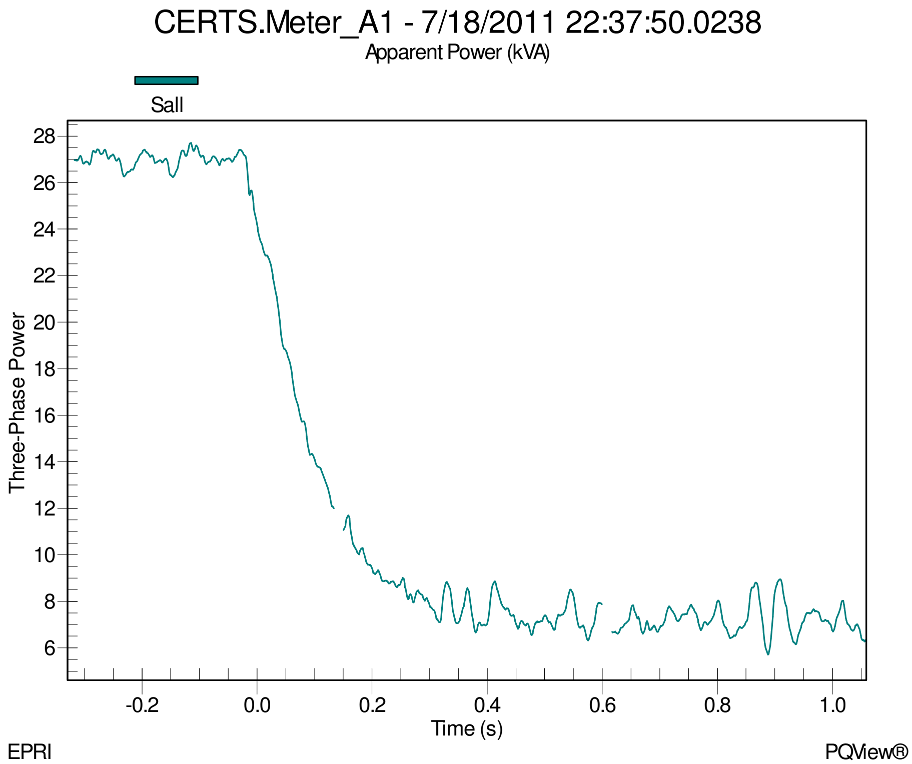

Figure 77 - Genset A1 apparent power output during a load transition from the microgrid to the utility grid

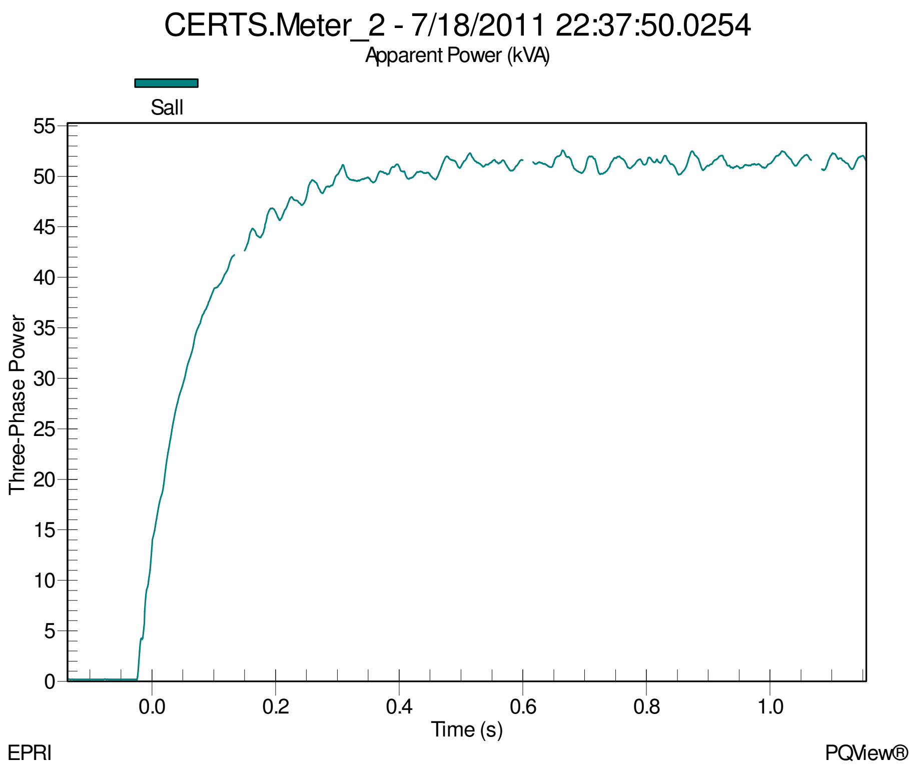

Figure 78 - Utility grid apparent power output during a load transition from the microgrid to the utility grid

7.10. Black Start Capacity

This next sequence was performed to test the InVerde INV100's ability to black start with existing load on the microgrid bus. The microgrid remained isolated from the utility grid, and no other gensets were utilized. Using LB3, 30kW and 10kVAR of load was added to the microgrid bus. Next, genset A1 was started and immediately shut down after attempting to connect to the bus. Without further modifications to the inverter, the InVerde INV100 is incapable of performing a black start with existing real and reactive load on the bus.

7.11. Pmax controller

In order to test the implementation of the pmax controller, load was added to the microgrid bus with two gensets running simultaneously. To begin, the genset A1 was dispatched to 50kW and genset A2 was dispatched to 20kW. Additionally, the pmax controller for both gensets was set to 60kW.

Using LB4, a base load of 50kW was added to the microgrid bus, and the gensets shared the load without genset A1 reaching its pmax limit. All data captures throughout this sequence of tests were triggered upon operation of LB3. Next, LB3 was used to add an additional 50kW of load (100kW total load) to push genset A1 to its 60kW pmax limit. This forced genset A2 to pick up the remaining load. After data was recorded, the same 50kW load was then removed from the bus. This displayed the behavior of the InVerde INV100 both when the determined pmax threshold was reached, and then the transition to loading below the pmax limit. For a baseline measurement, the gain setting in the InVerde INV100 was first set to 0.1. Then, the gain was adjusted to values of 0.06, 0.08, 0.12, and 0.14 and the test procedure was repeated. Once all tests were complete another test was run at a gain setting of 0.1 to ensure the InVerde INV100 was properly returned to its original state.

An initial analysis of the frequency response at each gain setting shows that the InVerde INV100 remained largely unchanged as the gain was adjusted. The transient frequency was expected to be more volatile as the gain was adjusted up and down from its initial set point. Inconclusive results were obtained, potentially due to poor frequency measurement within the test bed or improper implementation of the pmax gain in the inverter.

Figure 79 displays real power output as well as current and voltage waveforms for genset A1. The addition of real load that pushed genset A1 to its pmax limit is shown at t=-0.01s in the graphs. As a comparison, figure 80 represents real power output and waveform data for genset A2 during the same event. The output of genset A2 is a result of the pmax limiting that occurred on genset A1, and the subsequent sharing of real load on the microgrid bus. The voltage waveforms indicate stable voltage response to the pmax limiter for both gensets. The gain setting was 0.1 for all the results displayed.

In contrast to loading beyond the pmax limit, figures 81 & 82 display the responses of gensets A1 & A2, respectively, to the reduction of loading below the pmax threshold. As is displayed, the real power output of both gensets returns to the levels seen before

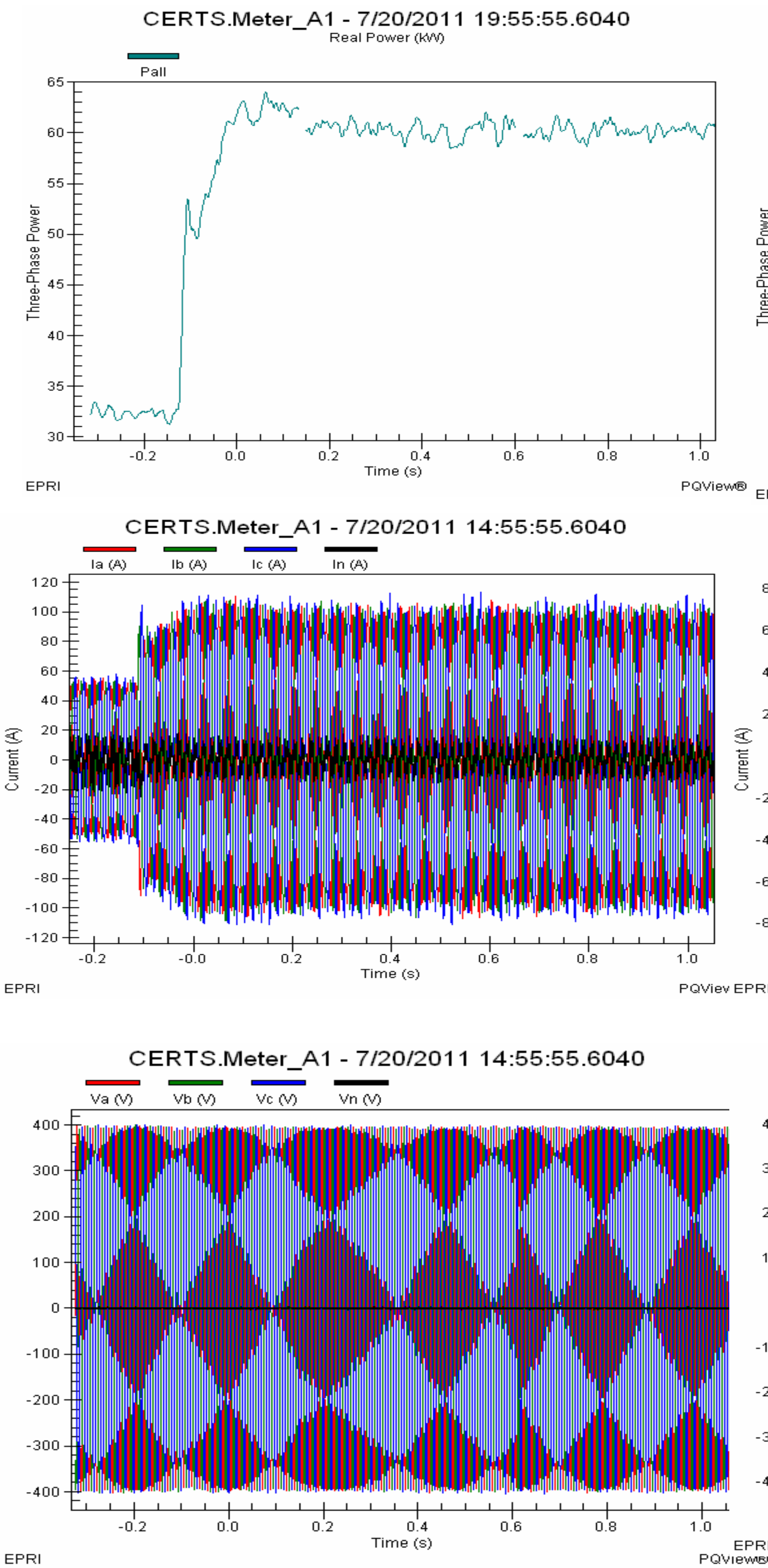

Figure 79 - Genset A1 real power output, voltage waveform, and current waveform as a reaction to loading past the Pmax limit. Gain setting of 0.1

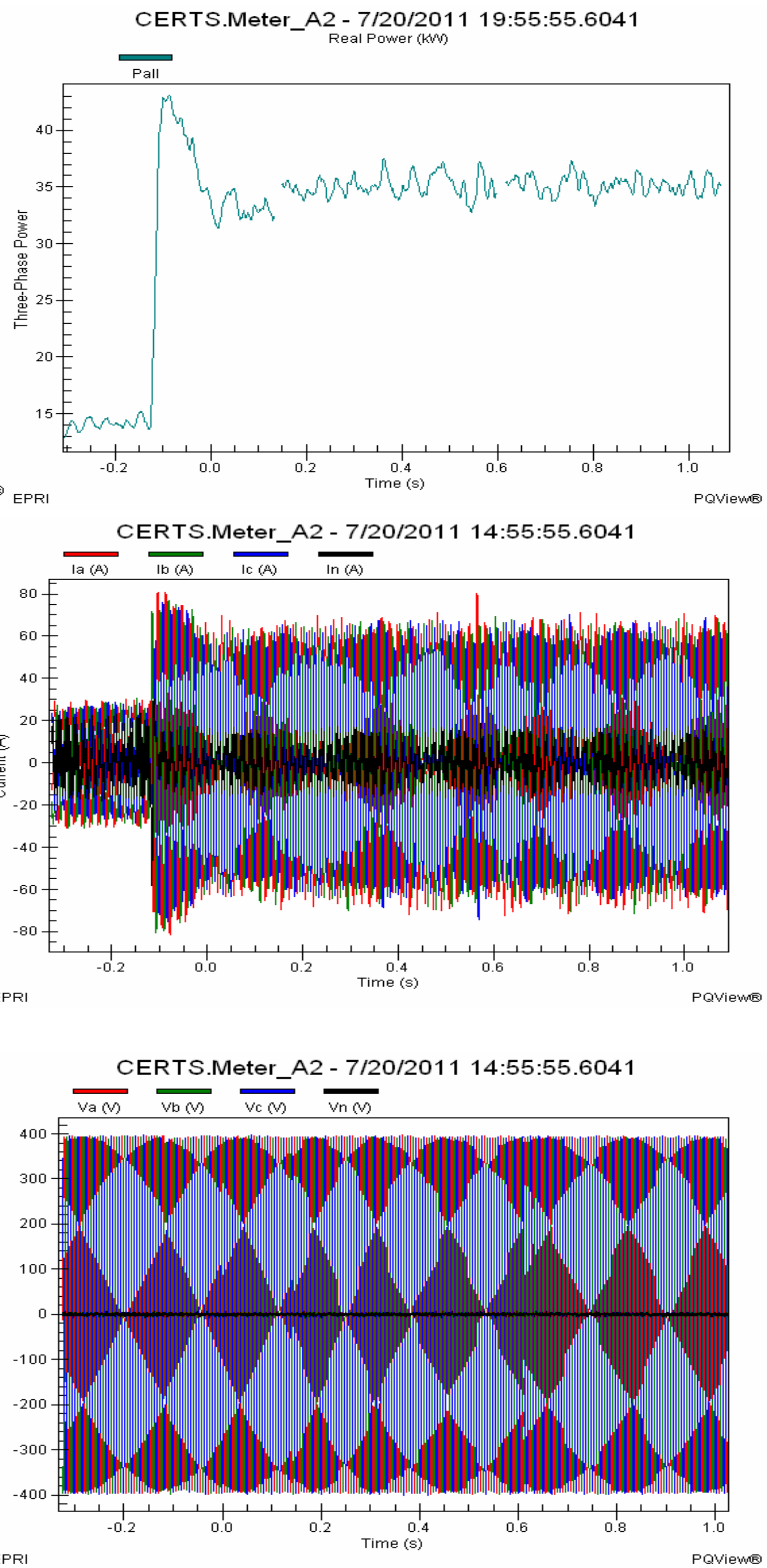

Figure 80 – Genset A2 real power output, voltage waveform, and current waveform as a reaction to loading past the Pmax limit. Gain setting of 0.1

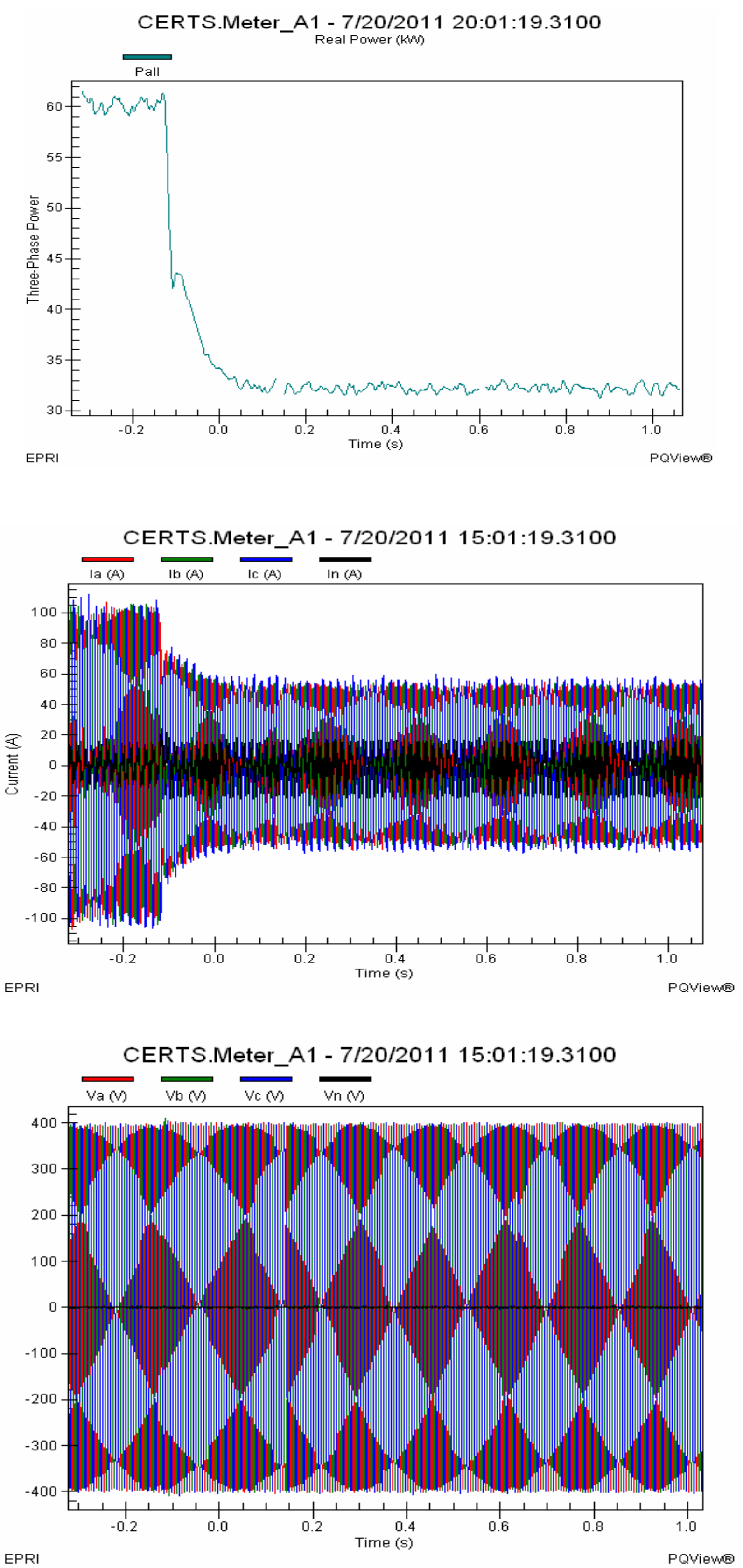

Figure 81 – Genset A1 real power output, voltage waveform, and current waveform as a reaction to reduction of load below the Pmax limit. Gain setting of 0.1

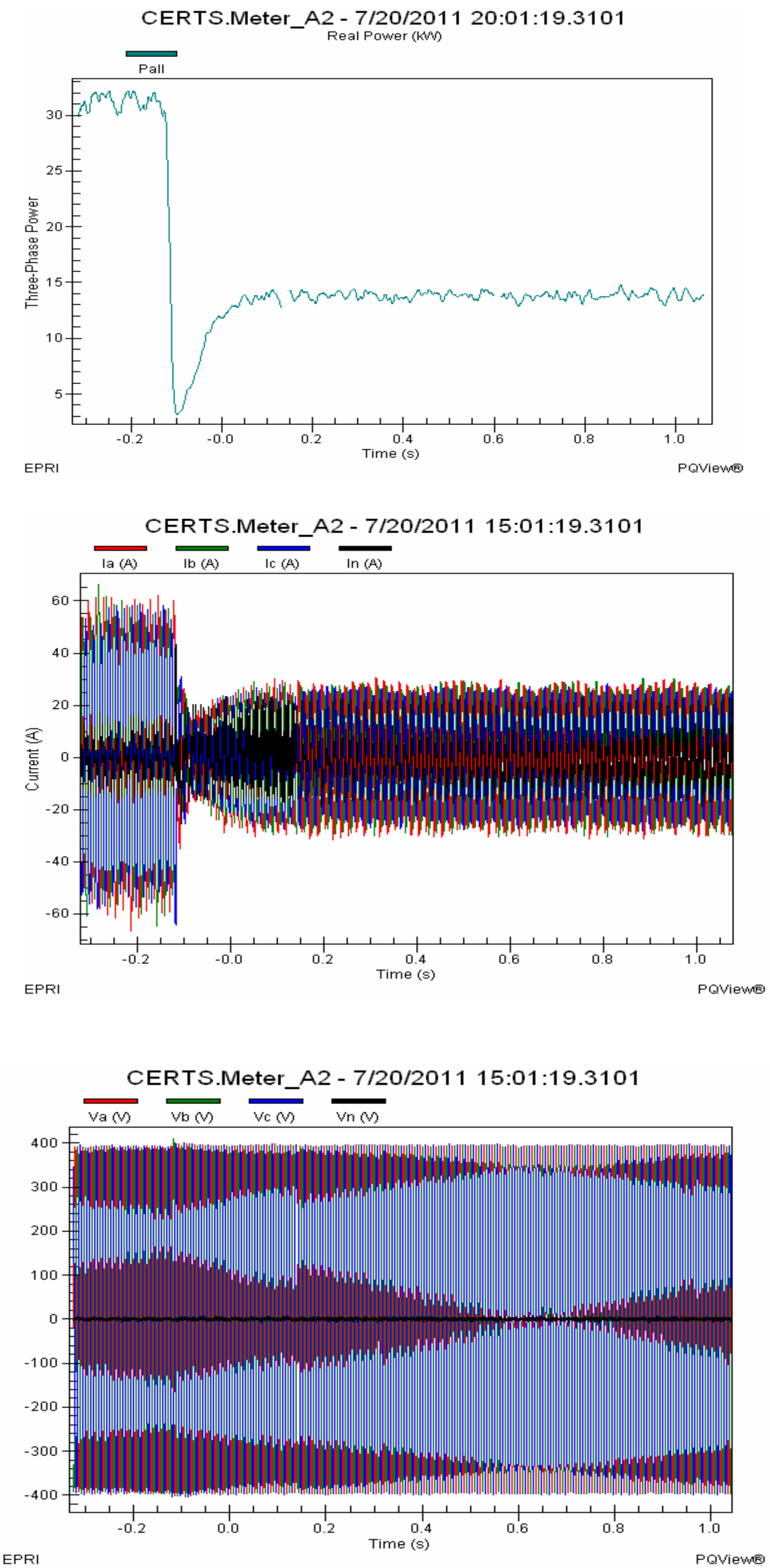

Figure 82 – Genset A2real power output, voltage waveform, and current waveform as a reaction to reduction of load below the Pmax limit. Gain setting of 0.1

8. Summary

The Tecogen InVerde INV 100 commercial unit performed most of its normal operating procedures within the normal limits of the manufacturer's guidelines. However there were a few anomalies recorded during testing that may conclude a need for further corrections in the inverter and also corrections on droop settings adjustments to allow better control over these abnormalities.

It was noticed during the initial testing of the InVerde INV100 that while it was connected to a transformer for impedance between genset A1 and the microgrid bus its voltage was unstable. This was observed considerably as the unit was load step tested and the unit went into droop control. The voltage from the genset inverter would continue to rise as real load was added to the microgrid bus. After talking with the genset manufacturer Tecogen and the CERTS team it was decided to replace the transformer with a reactance panel as a source of impedance. With the reactance panel installed in the Tecogen InVerde INV100 cabinet the same test was repeated. The voltage instability issue did not reappear during this test and the genset voltage remained stable throughout the remainder of the testing procedures conducted on the InVerde INV 100.

Another abnormality that was recorded during testing was sub harmonic oscillations in voltage and current. This was observed during testing when the Tecogen InVerde INV100 was grid tied and dispatched below 10 kW, and that the instability would cause the generator voltage and current to oscillate and within one to two minutes of start up would cause genset A1 to shutdown on DC overvoltage. As long as the Tecogen InVerde INV 100 was dispatched with a minimum of 10 kW of load the genset would operate as expected or if we started genset A1 non grid tied and islanded the oscillations were less prevalent. This may point to an issue within the inverter controls that needs further investigation into the root cause.

Testing of the InVerde INV100 also showed a potential for a single phase unbalance or phase loss without a protective trip sequence occurring. In some instances this may be desirable and help with reliability to continue supplying voltage to the remaining phases and reduce customer outage. However, for other customers with three phase motor loads or other equipment this could become detrimental and cause extensive equipment failure or damage to systems connected to the genset. However, due to proper filtering the system remained stable during the unbalance event. This was recorded during the Unbalance Load test shown in Fig 73 of this report.

During analysis of test results it was observed that an abnormal small reduction in A-phase voltage was occurring. The magnitude of the difference between phases was 3 to 5 volts and was observed only when the Tecogen InVerde Inv 100 was isolated from the utility bus. This can clearly be seen in the RMS voltage test data captures shown in this report. These results were compared to the prior testing results captured from the InVerde INV100 before the reactance panel was installed, and also results from the Tecogen prototype units during phase II testing and the anomaly was not present. This was displayed in meter data from all points on the microgrid, eliminating the possibility of a single meter malfunction. All of these factors suggest this could be an inverter design issue or it could be caused by the addition of the reactance panel. Either way, the voltage was less than 2% of the total voltage and it was deemed to be within normal operating conditions to continue testing.

Some work remains to correct known issues with the InVerde INV100's voltage stability and its ability to operate on a bus without any load. However, the testing performed on this genset display real and reactive load sharing in response to the droop controls. These are indicators of the proper implementation of CERTS controls in the InVerde INV100.