CERTS Microgrid Test Bed

Battery Energy Storage System Report: Phase 1

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1.0 Introduction

This document is a report on testing conducted with a Battery Energy Storage System (ESS) connected to the CERTS Microgrid Test Bed, located at American Electric Power's Walnut Test Site in Groveport, OH. The testing is designed to demonstrate the ESS's conformity to the CERTS control methodology and to properly interact with the existing CERTS compatible distributed energy resources.

A CERTS microgrid utilizes a set of control algorithms common to distributed energy resources which allows for system wide stability within rated conditions without a requirement for direct communications between devices. This type of network, peer-to-peer and plug and play, creates no dependencies as in master-slave control architectures allowing for high system flexibility and reliability.

Specifically, the CERTS algorithm implements four functions on each DER to allow harmonization of the DERs in the microgrid. These are:

1. Frequency Stability - achieved via a frequency vs. real power droop controller.
2. Voltage Stability - achieved via a voltage vs. reactive power droop controller. Each source operates in the grid-forming mode.
3. Pmax – drives a unit's frequency down when its real power maximum output is exceeded thereby recruiting other DERs to increase their real power output.
4. Pmin – drives a unit's frequency higher when its real power output is at or below its minimum setting thereby recruiting other DERs to reduce their real power output.

2.0 Definitions

CERTS Microgrid: A CERTS Microgrid builds on the definition of a Microgrid below. A CERTS microgrid utilizes a set of control algorithms common to distributed energy resources which allows for system wide stability within rated conditions without a requirement for direct communications between devices. A low bandwidth, low reliability, communications network can then be overlaid to optimize the operation of devices for various priorities such as fuel consumption, load demands, operating costs, etc. This type of network, peer-to-peer and plug and play creates no dependencies as in master-slave control architectures allowing for high system flexibility and reliability.

Critical Load: Critical load is load considered crucial for continued plant operations, and therefore is not shedable. These loads can take the form of life safety systems, necessary communication systems, vital operational equipment, emergency lighting, etc. In reality there also exists a class of loads which would not be economical to add intelligence to and would therefore remain fixed under overload conditions. These loads would also be grouped with Critical loads as they would not be made available for load shedding.

Difficult Loads: There are a number special loads utilized to stress the microgrid DER equipment. These loads include a 10 HP motor dynamometer exclusively in Load Bank 3, a harmonic current load which can be connected to any of the Load Banks 3 – 6, and large 'team' loads which have capacities requiring multiple DER to be successfully energized.

Distributed Energy Resource: Stand-alone equipment capable of sourcing or sinking electrical power into an electrical bus. Examples include: diesel/electric generators, battery storage systems, photovoltaic panels (solar panels), wind turbines, etc. ***Also referred to as: DER.***

Energy Management System (EMS): A control program written in LabView to issue commands to the microgrid and read the current state of devices and metered values.

Energy Storage System (ESS): A battery energy storage system assembled by Princeton Power Systems utilizing a GTIB 480-100 grid-tied inverter with 72 Marathon M12V155FT sealed lead acid batteries arranged in two strings of 36 batteries each. The system is rated for 100 kW discharge and 50 kW charge.

Generator "A1": An 'InVerde 100', inverter based combined heat and power generator set assembled by Tecogen Inc. of Waltham, Massachusetts. The unit is fueled by natural gas and is rated to support 100 kW of electrical load and 700 kBtu/hr of thermal load. The inverter on this unit allows it increased flexibility, as if frees the engine to operate over a wide range of rotational speeds (RPM), as opposed to a fixed speed.

Generator "A2": An original prototype inverter based generator set assembled by Tecogen. The unit is fueled by natural gas and is rated to support 60 kW of electrical load. This unit is a prototype used as an intermediate step in the development of the CERTS Controls Algorithms.

Generator "B1": A Synchronous generator set assembled by MTU Onsite Energy and controlled with a Woodward easYgen controller. The unit is fueled by natural gas, and is rated at 93 kW.

Grid Connected: Mode when the microgrid is connected to the electrical grid through the grid interface switch enabling the exchange of real and reactive power with the local utility. ***Also referred to as: "Grid Tied".***

Grid Connection Type: The CERTS Microgrid Test Bed contains a series inductance in the grid connection which can be bypassed as needed. When inserted it provides a weakly coupled grid connection simulating a distant, high impedance feeder connection. When bypassed it provides a strongly coupled grid connection simulating a close to substation, low impedance feeder connection. This adjustment is facilitated using series inductance "L11".

Grid Disconnected: Mode when the microgrid is disconnected from the electrical grid at the utility interface switch. The microgrid is operating independently from the grid and is internally responsible for the power quality delivered to the load. ***Also referred to as: "Islanded".***

Grid Interface Switch: The grid paralleling and protection switch used to connect and disconnect from the utility grid as necessary or desired. Within the CERTS Microgrid both a semiconductor and a mechanical version of this switch are available. Where the differences are important it is noted which switch is used, otherwise the response is similar with either. The semiconductor switch was assembled by S&C. This consists of a Silicon Controlled Rectifier (SCR) based switch with input, output, and bypass breakers, paired with a custom DSP controller. The mechanical switch consists of an industrial power breaker with a Schweitzer Engineering Laboratories relay. In addition to isolating the microgrid during protection events specified in IEEE 1547, the grid interface switch also performs synchronized reconnection when the proper conditions are met. ***Also referred to as: "GIS"***

Load Banks: There are 4 load banks located within the CERTS Microgrid Test Bed: Load Bank 3, Load Bank 4, Load Bank 5, and Load Bank 6. Each is capable of consuming a maximum 95 kW of real load and 60 kVAr of reactive (inductive) load. It should be noted that each load bank is constructed of wire

wrapped resistors which vary in resistance as they heat up, causing the load bank to consume slightly less than dispatched real power, approximately 15%. Load Bank 3 is located in Zone 3, which also contains Generator A1. Load Bank 4 is located in Zone 4 which also contains Generator A2. Load bank 4 was specially modified to incorporate Smart Load functions, including the shedding of non-critical load when deemed necessary thru observation of the electrical bus connected to it. Load Bank 5 is located in Zone 5 which also contains Generator B1. Finally Load Bank 6 is located outside of the protected zones of the microgrid, in Zone 6, and remains connected to the utility under all conditions. Load Bank 6 is used as a benchmark, against which the protected zone power quality is gauged. ***Also referred to as: LB3, LB4, LB5 and LB6.***

Microgrid: A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and islanded modes of operation.

National Instruments Compact RIO: NI cRio is a re-configurable embedded control and acquisition system manufactured by National Instruments. The cRIO system's rugged hardware architecture includes I/O modules, a reconfigurable FPGA chassis, and an embedded real time controller. This replaced the existing PLC equipment in Load Bank 4 and is utilized to implement the Smart Loads functionality in the load bank.

National Instruments LabVIEW: Labview is a graphical programming tool, developed by National Instruments, used in embedded control and monitoring applications. The Smart Load functions within the cRIO system have been programmed with LabVIEW.

Non-Critical Load: Non-Critical load is load considered available and capable of adjusting consumption based on a system desire or need. These loads take the form of environmental thermal systems, energy storage, process flows which can be throttled, etc. Generally these loads can be adjusted, at least briefly, with little consequence to their primary function. As a requirement these loads must have some minimum self-controllability either derived from internal processes or from some form of communication.

Smart Load: A load which has capabilities beyond the simple consumption of energy. Load Bank 4 is a Smart Load with load-shedding functions which operate under overload conditions. These loads allow the removal of non-critical loads when necessary to maintain the integrity of the microgrid electrical bus. This load acts as a peer within the CERTS microgrid, operating on predefined set points and locally collected information only.

3.0 The CERTS Microgrid Test Bed

The Walnut Test Facility is an extension of the American Electric Power Dolan Technology Center and is designed for the purpose of testing distributed energy resource components and concepts. The facility houses four separate test beds each with its own 13,200/480V transformer and utility metering. The microgrid test bed occupies test bed #1.

The microgrid test bed features several key pieces of equipment which enable testing to be performed on the microgrid safely and with repeatability. Key components include; varying types of Distributed Energy Resources (DER), controllable loads including Smart Loads, and an extensive data collection

network. The test facility also supplies a low impedance electric utility connection with protective equipment, a high pressure natural gas supply, a cooling water supply and a security network for physical equipment protection.

Prior CERTS Microgrid Testing has examined a CERTS compatible directly coupled synchronous generator, homogenous inverter based generators, various methods of microgrid protection, difficult and unsupportable load operation, power quality assessments, semiconductor and mechanical grid interface switch functionality, and smart load capabilities.

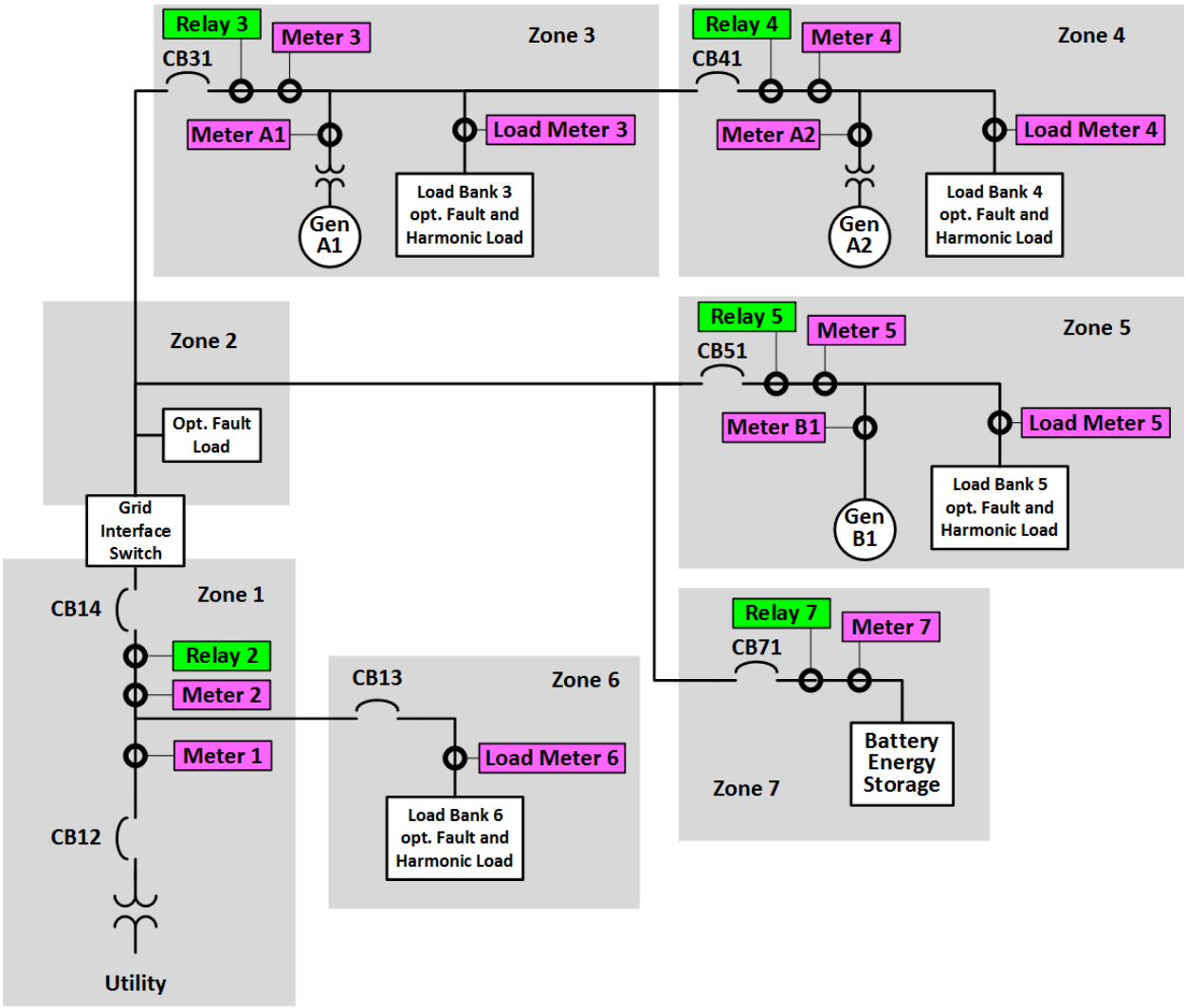

Figure 1: CERTS Microgrid One-line Diagram

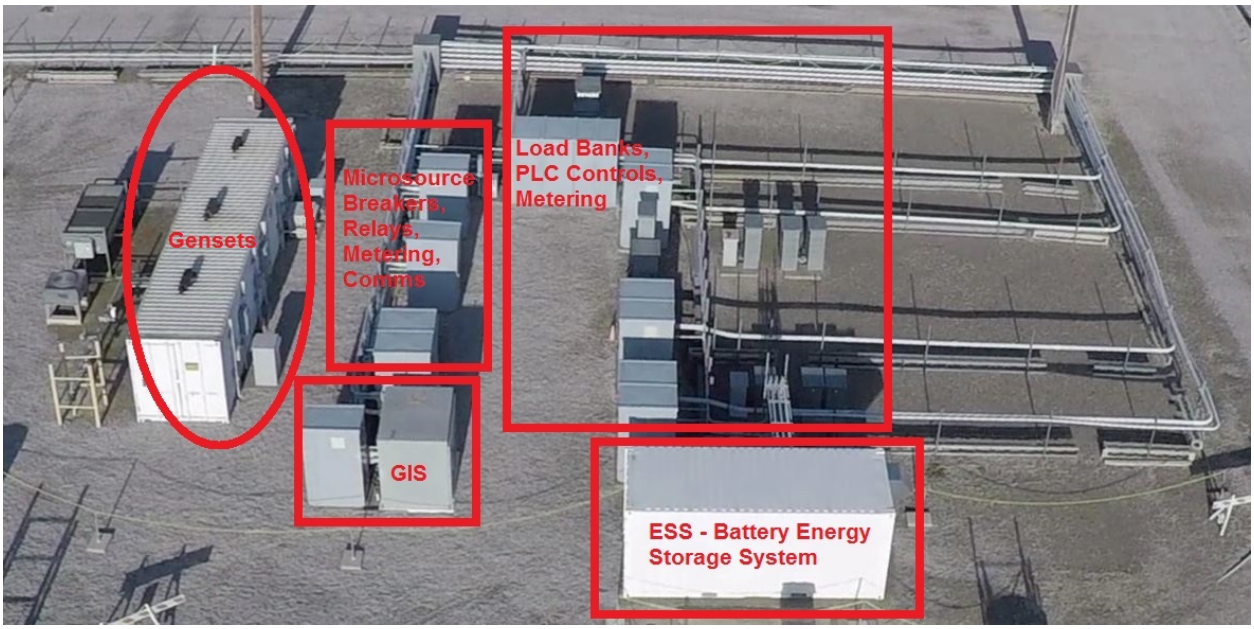

Figure 2: CERTS Microgrid Aerial Photo

4.0 Executive Summary

The integration of different types of Distributed Energy Resources (DERs) into a microgrid can present a challenge to the steady-state behavior and transient stability under different operating conditions.

This report examines the behavior of a CERTS control based battery energy storage system (ESS) both in standalone use and in conjunction with other CERTS control based DERs while in either the islanded or grid-connected state. The microgrid contains both inverter-connected and synchronous gen-sets with natural gas engine prime movers.

A CERTS microgrid utilizes a set of control algorithms common to distributed energy resources which allows for system wide stability within rated conditions without a requirement for direct communications between devices. This type of network, peer-to-peer and plug and play, creates no dependencies as in master-slave control architectures allowing for high system flexibility and reliability.

Specifically, the CERTS algorithm implements four functions on each DER to allow harmonization of the DERs in the microgrid. These are:

1. Frequency Stability - achieved via a frequency vs. real power droop controller.
2. Voltage Stability - achieved via a voltage vs. reactive power droop controller. Each source operates in the grid-forming mode.
3. Pmax – drives a unit's frequency down when its real power maximum output is exceeded thereby recruiting other DERs to increase their real power output.
4. Pmin – drives a unit's frequency higher when its real power output is at or below its minimum setting thereby recruiting other DERs to reduce their real power output.

For the standalone case the following capabilities of the ESS are examined: 1) load step response; 2) voltage regulation; 3) frequency vs. real power droop control; 4) voltage vs. reactive power droop control; 5) unbalanced loads; 6) P_{max} control; 7) P_{min} control; and 8) transition between charging and discharging. The results of the standalone tests are summarized in Table 1 below. It is shown that the ESS performs all CERTS functionality as expected. There are a couple of issues where the ESS does not behave as anticipated but these are due to operating limits of the inverter and not related to the CERTS algorithm. First, the ESS is not able to handle load rejections larger than 85 kW even though it is rated for 100 kW. Second, the ESS does not recover from a steady state overload above 105 kW to some value less than 100 kW.

Standalone Test Name	**Objective**	**# of Tests**	**CERTS and Equipment Pass/Fail**	**Comments**
Load Step Response	Determine the ability to handle load increases and rejections across its operating range.	34	No CERTS criteria involved. Equipment: **31 Pass**; **3 Fail**.	The ESS (rated at 100 kW) is not able to handle load rejections larger than 85 kW. In these cases the inverter trips off. Also, the inverter trips when a load rejection is attempted from an overloaded condition above 105 kW.
Voltage Regulation	Verify that the ESS is capable of holding the correct output voltage throughout its operating range.	12	**All Pass**	The ESS maintains proper voltage at various voltage set points across its real power operating range.
Frequency vs. Real Power Droop Control	Verify proper frequency response to real power loads.	18	**All Pass**	The ESS exhibits the proper frequency response to all real power outputs. Voltage is properly decoupled from real power output.
Voltage vs. Reactive Power Droop Control	Verify proper voltage response to reactive power loads.	15	**All Pass**	The ESS exhibits the proper voltage response to all reactive power outputs. Frequency is properly decoupled from reactive power output.
Unbalanced Loads	Verify ESS response to unbalanced load conditions. Confirm proper frequency droop response. Quantify the harmonic content on the voltage waveform.	8	**All Pass**	The ESS handles all unbalanced load conditions with the proper frequency droop response to the total real power load. The THD of the voltage waveform on the microgrid bus remains below 4%.

Standalone Test Name	Objective	# of Tests	CERTS and Equipment Pass/Fail	Comments
P_{max} Control	Verify proper frequency response to real power overload conditions.	7	**All Pass**	The P_{max} functionality is properly activated in all real power overload conditions. The P_{max} functionality is properly decoupled from reactive power.
P_{min} Control	Verify proper frequency response to real power underload conditions.	8	CERTS: **All Pass**; Equipment: **7 Pass**; **1 Fail**.	The P_{min} functionality is properly activated in all real power underload conditions. The P_{min} functionality is properly decoupled from reactive power. The equipment failure is due to an attempt to reject 90 kW of load which was previously identified as an issue.
Charging/ Discharging Transition	Ensure stable voltage and frequency operation when transitioning between charging and discharging modes.	18	**All Pass**	The ESS is able to transition between charging and discharging modes over its entire operating range while maintaining expected voltage and frequency operating characteristics.

Table 1: ESS Standalone Test Results Summary

For cases where the ESS is used with other DERs the following scenarios are examined: 1) load sharing; 2) P_{max} control activated on one DER, islanded; and 3) P_{min} control activated on one DER, islanded. The ESS performed well with regards to sharing load with both types of DERs in the microgrid. It also performed well in the P_{max} and P_{min} control tests with the inverter-connected gen-set. However, there are issues with the P_{max} and P_{min} control tests when the ESS is paired with the synchronous generator. In those cases the ESS responded to the load transition much more quickly than the synchronous generator. During the P_{max} control tests, under certain conditions, the ESS would exceed its capability and trip off. During the P_{min} control tests, the ESS rejects the entire load during transition from grid-connected to islanded mode thus preventing the synchronous generator from activating its P_{min} functionality. However, in this case the microgrid does survive and achieve the expected steady-state conditions. These results are summarized in Table 2 below.

Multiple DER Units Test Name	Objective	# of Tests	CERTS and Equipment Pass/Fail	Comments
Load Sharing	Determine how two sources share load during transitions within their normal operating droop range, i.e. without activating P_{max} or P_{min}.	32	**All Pass**	The ESS in combination either A1 or B1 successfully passes all multiple unit load sharing test cases related to real power load sharing and frequency expectations when transitioning between grid-tied and islanded modes of operation.
P_{max} Control Activated on One DER in Islanded mode.	Verify proper frequency response to real power overload conditions of one DER when a pair of DERs are islanded.	13	CERTS: **10 Pass**; **3 Fail**.	The ESS in combination with A1 (an inverter-tied unit) successfully passes all P_{max} Control islanding tests conducted. Both units respond quickly to the additional load. The overloaded unit's P_{max} functionality is activated and the supporting unit relieves the overloaded unit. The ESS in combination with B1 (a synchronous gen-set) fails 3 of the P_{max} Control islanding tests conducted. The ESS responds to the real power load increase much more quickly than B1 and as a result picks up the majority of real power load. In these cases, the ESS's current capability is exceeded resulting in the unit tripping and the collapse of the microgrid.
P_{min} Control Activated on One DER in Islanded mode.	Verify proper frequency response to real power underload conditions of one DER when a pair of DERs are islanded.	12	CERTS: **11 Pass**; **1 Fail**.	The ESS in combination with A1 (an inverter-tied unit) successfully passes all P_{min} Control islanding tests conducted. Both units respond quickly to the load reduction. The minimally loaded unit's P_{min} functionality is activated and the supporting unit relieves the minimally loaded unit. The ESS in combination with B1 (a synchronous gen-set) fails 1 of the P_{min} Control islanding tests conducted. The ESS responds to the real power load decrease much more quickly than B1 and as a result rejects the majority of real power load. In the failed case B1's Pmin functionality should have been activated but wasn't since the ESS rejected the entire load. In this case the microgrid survived and steady-state was achieved based on the normal droop curve settings.

Table 2: Multiple Unit Test Results Summary

Overall, the ESS performs well in both the standalone and multiple DER configurations. The conditions identified where survivability might be jeopardized could likely be avoided by proper engineering, design, and operational considerations of the microgrid implementation. In addition, these conditions could also likely be avoided by adjustments to the inverter design and control implementation.

5.0 Test Results

5.1 Emergency Shutdown Test – Stand Alone

Performance Goal

Verify proper operation of emergency shutdown command issued from the EMS. The ESS should completely shut down quickly at the remote issuance of an emergency shutdown command.

Description of Procedure

The ESS is dispatched to 50 kW, 480V_{LL}, 1% Frequency Droop, 5% Voltage Droop and operated islanded from the utility. The generator is started and connected to the islanded microgrid electrical bus. LB3 is set to a balanced load of 50 kW. Once the system reaches steady state an event is captured when the "Emergency Shutdown" command is issued from the remote control panel.

Test Settings

The ESS is set as follows:
$P_{dispatch}$ = 50 kW
$E_{dispatch}$ = 480 V_{LL}
Frequency Droop = 1.0%
Voltage Droop = 5%

Test Results

Table 3 below summarizes the system voltage behavior for the emergency shutdown test.

Event	GIS	Bus Voltage (V)		Result
		Pre-Event	Post-Event	
Emergency Stop	Open	274.5 V	1.8 V	Pass

Table 3: Emergency Shutdown Tabular Results

Analysis

At the issuance of the Emergency Shutdown command the ESS shutdown and all zone breakers opened as expected. Figure 3 shows the RMS voltage and current of the ESS as it responded to the shutdown command. The system behaved as anticipated.

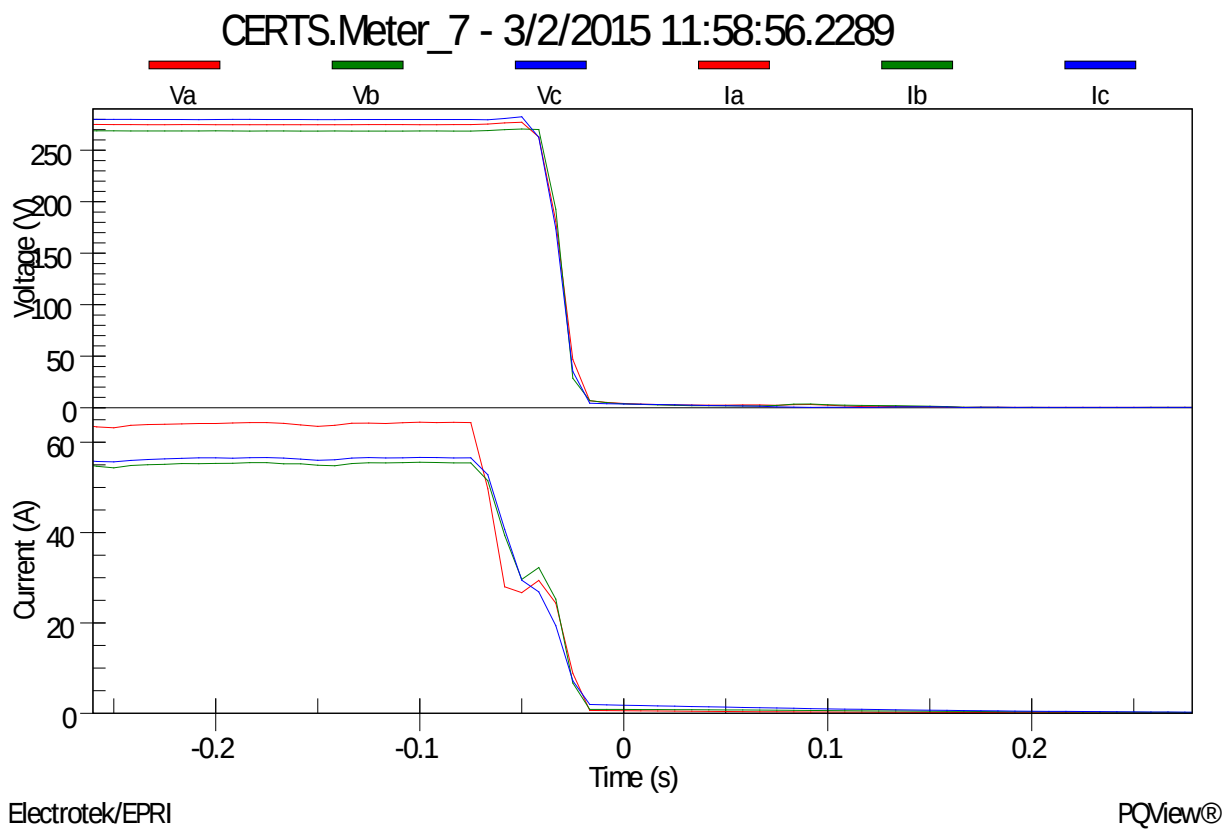

Figure 3: Emergency Shutdown RMS Voltage and Current

5.2 ESS State of Charge

Performance Goal

The ESS does not have an inherent method for determining the state of charge (SoC) of the battery stack. This test is designed to provide an estimate of the SoC under a loaded condition and during rest. These two conditions are examined since the SoC versus voltage profile will be different under the loaded and unloaded conditions.

Description of Procedure

For the test under load the ESS is placed in Grid Following Mode and set to discharge at a constant power of 34 kW. Reactive Power Droop is disabled. Load Bank 3 is set to 50 kW. The microgrid is utility connected. The ESS is connected to the microgrid. Battery stack terminal voltage and energy consumed are recorded at 5 minute intervals until the battery is depleted as determined by Minimum Discharge Voltage setting of 400 V.

For the test in the unloaded condition the ESS is placed in Grid Following Mode and set to discharge at a constant power of 30 kW. Reactive Power Droop is disabled. Load Bank 3 is set to 50 kW. The microgrid is utility connected. The ESS is connected to the microgrid and discharged for 3 minutes and then disconnected from the microgrid. This allows approximately 1.5 kWh of energy to be depleted from

the battery system. The batteries are rested for 2 minutes to allow the terminal voltage time to recover from the loaded condition. Two minutes provides adequate recovery to the terminal voltage. The battery stack terminal voltage and energy consumed are recorded. The ESS is reconnected to the microgrid and the cycle repeated until the battery is depleted as determined by Minimum Discharge Voltage setting of 400 V.

Test Settings

The ESS is set as follows:
Mode: Grid Following
$P_{setpoint}$ = Varies (34 kW or 30 kW)
Voltage Dispatch = 480 V_{LL}
Frequency Droop = Disabled
Voltage Droop = Disabled

Test Results

Table 4 below summarizes the results for test during a constant discharge of 34 kW.

Battery SoC Under 34 kW Load			
Time (hh:mm)	Battery Terminal Voltage (V)	Cumulative Battery Energy Depleted (kWh)	State of Charge
12:05	449.0	0.0	100%
12:10	436.9	2.8	93%
12:15	437.5	5.6	85%
12:20	437.4	8.4	78%
12:25	437.0	11.3	71%
12:30	436.5	14.1	63%
12:35	435.7	16.9	56%
12:40	435.0	19.7	49%
12:45	434.0	22.5	41%
12:50	432.6	25.3	34%
12:55	430.5	28.2	26%
13:00	427.5	31.0	19%
13:05	422.0	33.8	12%
13:10	409.5	36.6	4%
13:13	400.0	38.3	0%

Table 4: Battery State of Charge Under 34 kW Load

Table 5 below summarizes the results for the test where an intermittent load of 30 kW is applies for 3 minutes followed by a 2 minute rest period at which point the battery voltage is measured.

Battery SoC with 2 Minute Rest			
Time (hh:mm)	Battery Terminal Voltage (V)	Cumulative Battery Energy Depleted (kWh)	State of Charge
15:04	470.1	0	100 %
15:09	460.5	2	94%
15:14	460.0	3	90%
15:19	459.5	4	87%
15:24	459.1	6	81%
15:29	458.8	7	77%
15:34	458.3	9	71%
15:39	457.9	10	68%
15:44	457.2	11	65%
15:49	456.7	13	58%
15:54	455.9	14	55%
15:59	455.2	16	48%
16:04	454.7	17	45%
16:09	454.0	19	39%
16:14	453.4	20	35%
16:19	452.5	21	32%
16:24	452	23	26%
16:29	450.1	24	23%
16:34	449.4	26	16%
16:39	449.1	27	13%
16:44	448.2	29	6%
16:49	445.9	30	3%
16:54	446	31	0%

Table 5: Battery State of Charge - Intermittent 30 kW Load with 2 Minute Rest

Analysis

Figure 4 and Table 4 show the battery state of charge as a function of DC bus terminal voltage during a continuous discharge event at a rate of 34 kW. Battery stack terminal voltage and energy consumed are recorded at 5 minute intervals until the battery is depleted as determined by Minimum Discharge Voltage setting of 400 V. The relationship is non-linear and has an exponential shape. The battery SoC is somewhat difficult to estimate during discharge while the SoC is greater than approximately 35%. The terminal voltage only ranges from 433 V to 437 V when the SoC is in the range of 35% to 93%. Once the SoC falls below 30% at approximately 431 V a better estimate of the SoC can be determined from the terminal voltage.

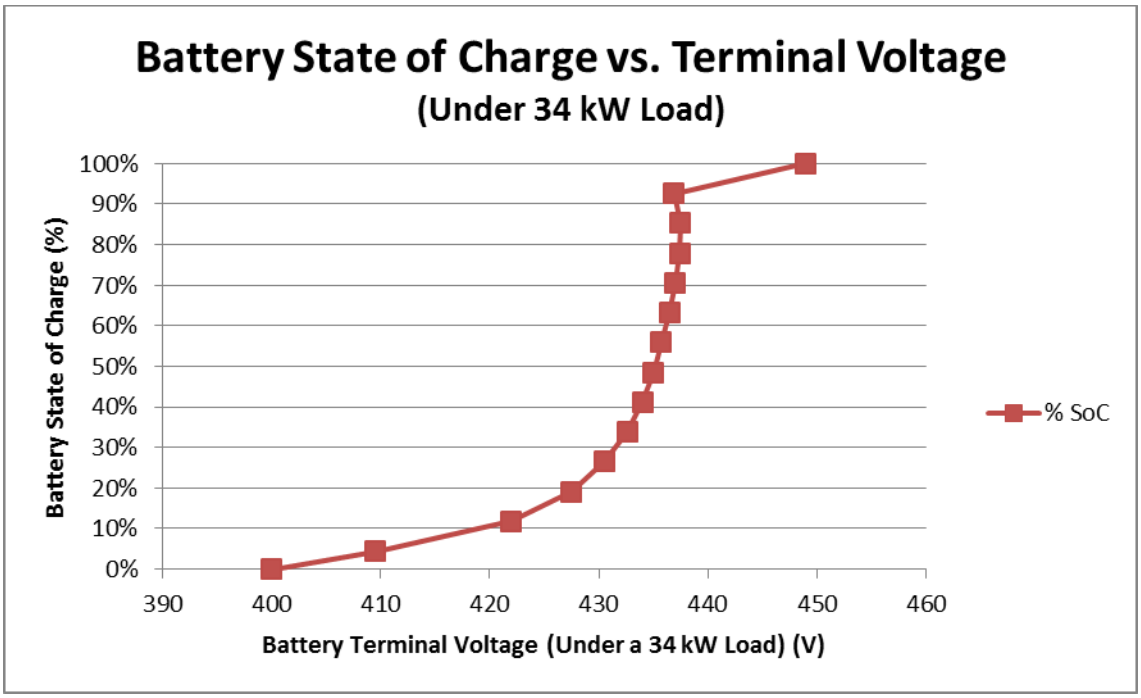

Figure 4: Battery State of Charge as a function of Terminal Voltage While loaded at 34 kW

Figure 5 and Table 5 show the battery state of charge as a function of DC bus terminal voltage after a 2 minute rest period. The battery is discharged at a constant rate of 30 kW in grid following mode for 3 minute intervals (1.5 kWh per interval). The discharging is stopped and the battery voltage is allowed to recover for 2 minutes at which time the battery voltage and energy consumed are recorded.

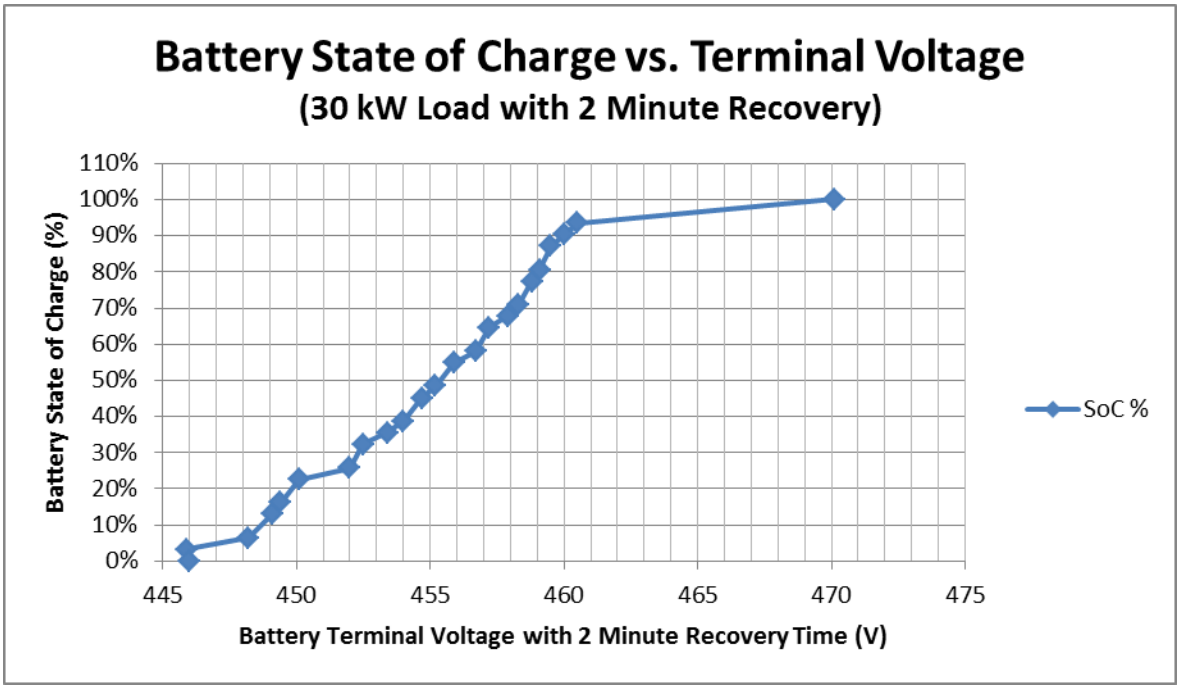

Figure 5: Battery State of Charge as a function of Terminal Voltage - Intermittent 30 kW Load with 2 Minute Recovery

The SoC versus voltage profile is different between the loaded and unloaded cases as expected and demonstrated in Table 4, Table 5, Figure 4, and Figure 5. The battery stack voltage will be higher in the unloaded case. When the battery is under load there will be a voltage drop that reduces the terminal voltage due to several factors such as: battery internal resistance; resistance of connectors and cables between individual batteries, leads to the inverter, DC disconnect switch and fuses; internal corrosion of the battery cells; and the chemistry of the electrolyte.

5.3 Load Step Response - Stand Alone

Performance Goal

Verify the ESS's ability to respond to loads and load step changes of increasing magnitude. This test is designed to quantify the ESS's load step capability throughout its operating range by stressing the ESS at various operating points. The ESS is tested with varying load steps under varying initial load conditions. A successful "Pass" criterion is the transition from one load point to another demonstrating stability in voltage and frequency. The ESS should continue to carry the load in steady state unless prolonged overload occurs. Under overload conditions the ESS should perform a protection trip and safely shutdown.

Description of Procedure

The ESS is dispatched to 50 kW, 480 V_{LL}, 1% Frequency Droop, 5% Voltage Droop and operated islanded from the utility. The ESS is started and connected to the islanded microgrid electrical bus. Various initial loads are placed on the ESS. Various load steps are placed on the ESS and each event is recorded. Each load step is then removed and that event is also recorded.

Test Settings

ESS parameters are set as follows:
Pdispatch = 50 kW
Frequency Droop = -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)
AC Power Limit = 105 kW
Voltage Droop = -0.24 V/kVAr
Voltage Dispatch = 480 V [Inverter Voltage Reference = 102.5 per PPS*]
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V.

Table 6 below lists the test cases that are executed. Initial loads are shown as fixed numbers (e.g. 20 kW), and the load step is shown with a transition increasing (e.g. 0→20 kW) or decreasing (e.g. 20→0 kW).

Test Event	ESS Dispatch	GIS	Load Bank 4	Load Bank 5	Load Bank 3	Total Load Transition
A	50 kW	Open	0 kW	0 kW	0→20 kW	0→20 kW Load Step
B	50 kW	Open	0 kW	0 kW	20→0 kW	20→0 kW Load Step

Test Event	ESS Dispatch	GIS	Load Bank 4	Load Bank 5	Load Bank 3	Total Load Transition
C	50 kW	Open	20 kW	0 kW	0→20 kW	20→40 kW Load Step
D	50 kW	Open	20 kW	0 kW	20→0 kW	40→20 kW Load Step
E	50 kW	Open	40 kW	0 kW	0→20 kW	40→60 kW Load Step
F	50 kW	Open	40 kW	0 kW	20→0 kW	60→40 kW Load Step
G	50 kW	Open	60 kW	0 kW	0→20 kW	60→80 kW Load Step
H	50 kW	Open	60 kW	0 kW	20→0 kW	80→60 kW Load Step
I	50 kW	Open	80 kW	0 kW	0→20 kW	80→100 kW Load Step
J	50 kW	Open	80 kW	0 kW	20→0 kW	100→80 kW Load Step
K	50 kW	Open	80 kW	0 kW	20→40 kW	100→120 kW Load Step This load step is anticipated to cause a protection trip of the ESS
L	50 kW	Open	80 kW	0 kW	40→20 kW	120→100 kW Load Step This load step may require bypass if ESS is incapable of operation at initial conditions
M	50 kW	Open	0 kW	0 kW	0→40 kW	0→40 kW Load Step
N	50 kW	Open	0 kW	0 kW	40→0 kW	40→0 kW Load Step
O	50 kW	Open	20 kW	0 kW	0→40 kW	20→60 kW Load Step
P	50 kW	Open	20 kW	0 kW	40→0 kW	60→20 kW Load Step
Q	50 kW	Open	40 kW	0 kW	0→40 kW	40→80 kW Load Step
R	50 kW	Open	40 kW	0 kW	40→0 kW	80→40 kW Load Step
S	50 kW	Open	60 kW	0 kW	0→40 kW	60→100 kW Load Step
T	50 kW	Open	60 kW	0 kW	40→0 kW	100→60 kW Load Step
U	50 kW	Open	0 kW	0 kW	0→60 kW	0→60 kW Load Step
V	50 kW	Open	0 kW	0 kW	60→0 kW	60→0 kW Load Step
W	50 kW	Open	20 kW	0 kW	0→60 kW	20→80 kW Load Step
X	50 kW	Open	20 kW	0 kW	60→0 kW	80→20 kW Load Step
Y	50 kW	Open	40 kW	0 kW	0→60 kW	40→100 kW Load Step
Z	50 kW	Open	40 kW	0 kW	60→0 kW	100→40 kW Load Step
AA	50 kW	Open	0 kW	0 kW	0→80 kW	0→80 kW Load Step
AB	50 kW	Open	0 kW	0 kW	80→0 kW	80→0 kW Load Step
AC	50 kW	Open	20 kW	0 kW	0→80 kW	20→100 kW Load Step
AD	50 kW	Open	20 kW	0 kW	80→0 kW	100→20 kW Load Step
AE	50 kW	Open	0 kW	0 kW	0→95 kW	0→95 kW Load Step
AF	50 kW	Open	0 kW	0 kW	95→0 kW	95→0 kW Load Step
AG	50 kW	Open	0 kW	0 kW	90→0 kW	90→0 kW Load Step
AH	50 kW	Open	0 kW	0 kW	85→0 kW	85→0 kW Load Step

Table 6: Load Step Response Test Cases

Test Results

Table 7 below summarizes the results of the load step response tests including real power, voltage, and frequency for both pre-event and post-event periods.

Load Step Response Test Results									
Test Event	Total Load Step (kW)	Energy Storage System						Pass / Fail	Notes
		Real Power (Pre-Event)	Real Power (Post-Event)	Voltage Avg (Pre-Event)	Voltage Avg (Post-Event)	Frequency (Pre-Event)	Frequency (Post-Event)		
A	0→20	0.0	19.8	278.4	278.0	60.1	60.1	Pass	
B	20→0	18.4	0.2	278.0	278.4	60.1	60.2	Pass	
C	20→40	20.5	40.4	278.1	277.6	60.1	60.0	Pass	
D	40→20	38.7	20.4	277.6	278.0	60.0	60.1	Pass	
E	40→60	39.3	58.8	277.6	277.1	60.0	60.0	Pass	
F	60→40	57.1	38.9	277.1	277.6	60.0	60.0	Pass	
G	60→80	57.4	76.7	277.1	276.7	60.0	59.9	Pass	
H	80→60	75.0	57.0	276.7	277.1	59.9	60.0	Pass	
I	80→100	74.4	94.1	276.6	276.1	59.9	59.8	Pass	
J	100→80	92.5	74.7	276.1	276.6	59.8	59.9	Pass	
K	100→120	92.6	111.6	276.1	275.5	59.8	59.0	Pass	Frequency declining past the 5s window
L1	120→100	103.3	91.5	278.8	276.0	50.0	59.8	Pass	
L2	120→100	113.0	0.0	278.6	0.5	-	-	Fail[1]	Inverter Tripped: IGBT Bridge Error
L3	120→100	113.0	0.0	278.4	0.4	-	-	Fail[1]	Inverter Tripped: IGBT Bridge Error
L4	120→100	112.7	0.0	277.8	0.3	-	-	Fail[1]	Inverter Tripped: IGBT Bridge Error
M	0→40	0.7	39.7	278.2	277.4	60.2	60.0	Pass	
N	40→0	36.5	0.7	277.5	278.2	60.1	60.2	Pass	
O	20→60	20.8	59.6	277.8	276.9	60.1	60.0	Pass	
P	60→20	56.4	20.7	276.9	277.8	60.0	60.1	Pass	
Q	40→80	39.1	77.7	277.3	276.5	60.0	59.9	Pass	
R	80→40	74.1	38.6	276.5	277.3	59.9	60.0	Pass	
S	60→100	59.9	59.8	276.9	276.0	56.3	94.9	Pass	
T	100→60	91.3	56.2	276.0	276.9	59.8	60.0	Pass	
U	0→60	0.7	59.6	278.2	277.0	60.0	60.0	Pass	
V	60→0	54.6	0.7	277.1	278.2	60.0	60.2	Pass	
W	20→80	21.0	79.2	277.8	276.5	60.1	59.9	Pass	
X	80→20	74.4	20.9	276.6	277.8	59.9	60.1	Pass	
Y	40→100	38.8	96.7	277.4	276.1	60.0	59.8	Pass	
Z	100→40	92.1	39.1	276.1	277.3	59.8	60.0	Pass	
AA	0→80	0.7	78.5	278.2	276.5	60.2	59.9	Pass	
AB	80→0	72.4	0.7	276.6	278.2	59.9	60.2	Pass	
AC	20→100	20.9	98.0	277.8	276.0	60.1	59.8	Pass	
AD	100→20	91.8	20.8	276.0	277.8	59.8	60.1	Pass	
AE	0→95	0.7	94.0	282.5	276.1	60.2	59.8	Pass	
AF	95→0	89.4	0.0	276.2	0.3	-	-	Fail[1]	Inverter Tripped: IGBT Bridge Error
AG	90→0	85.8	0.0	276.6	0.3	-	-	Fail[1]	Inverter Tripped: IGBT Bridge Error
AH	85→0	81.4	0.7	276.5	278.3	59.9	60.2	Pass	
1. These failures are not related to the CERTS algorithm but rather represent a limit of the operating capability of the inverter.									

Table 7: Load Step Response Test Results

Analysis

The ESS successfully passes all load step increases which range from 20 kW to 95 kW in magnitude.

The ESS is not able to handle step load decreases when the initial load is greater than 105 kW (Events L2 through L4) or when the step load decrease exceeds 85 kW (Events AF and AG). In all five cases the inverter experiences an IGBT Bridge Error. It is possible that this is a result of an overvoltage condition on the DC bus especially in the large load rejection cases. No additional information on the cause of the fault is available from the inverter.

Test Event K is for a step from 100 kW to 120 kW (actual load from 92.59 kW to 111.6 kW). This also passes and the frequency is in decline as P_{max} has been exceeded.

Test Event L is for a step from 120 kW to 100 kW. This test is run four times, L1 to L4. The first time it passes as the load decreases from 103 kW to 92 kW and the frequency increases from 50 Hz to 59.82 Hz. The next three times the test is executed it fails as the inverter trips when the load rejection is attempted. In these three cases the pre-event load is about 113 kW which is in excess of the AC Power Limit of 105 kW. These failures are not related to the CERTS algorithm but rather represent a limit of the operating capability of the inverter.

Test Events M through AD are for the step load events that include 40 kW, 60 kW, and 80 kW steps. The ESS is able to handle these events and performs as expected.

Test Event AE performs a step load from 0 kW to 95 kW which is successful. This is the largest step load that can be performed at the test bed using only one load bank.

Test Event AF attempts to perform a step load from 95 kW to 0 kW but the ESS trips during these attempts. A step load from 90 kW to 0 kW is also attempted (Test Event AG) but results in the ESS tripping as well. A step load from 85 kW to 0 kW (Test Event AH) is successful. The failure of the ESS to perform a load rejection greater than 85 kW is not related to the CERTS algorithm but rather represent a limit of the operating capability of the inverter.

Figure 6 through Figure 10 show the results of Test Event A, a step load from 0 kW to 20 kW, which is successful and unremarkable.

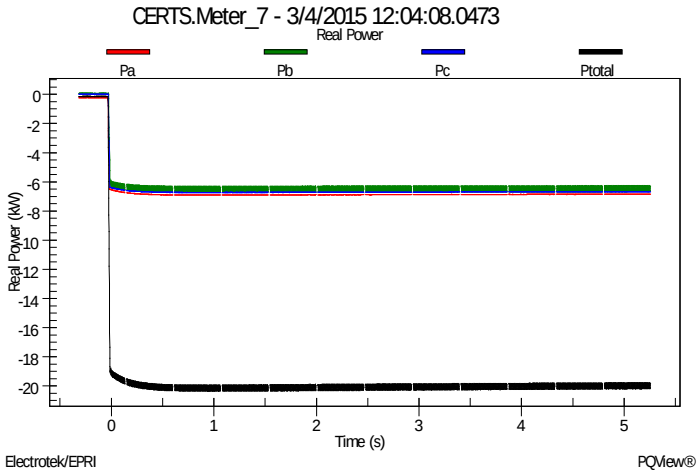

Figure 6: Test Event A: Step Load 0 kW to 20 kW, Real Power

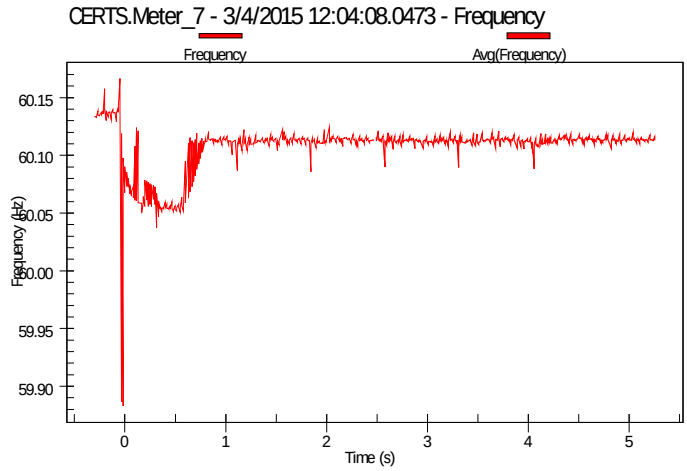

Figure 7: Test Event A: Step Load 0 kW to 20 kW, Frequency

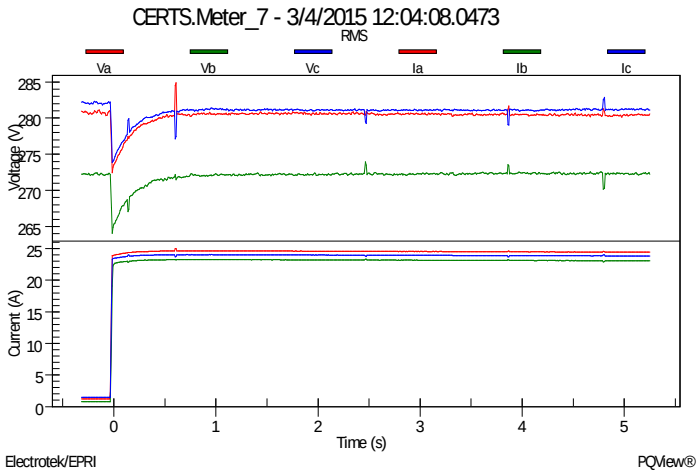

Figure 8: Test Event A: Step Load 0 kW to 20 kW, RMS Voltage & Current

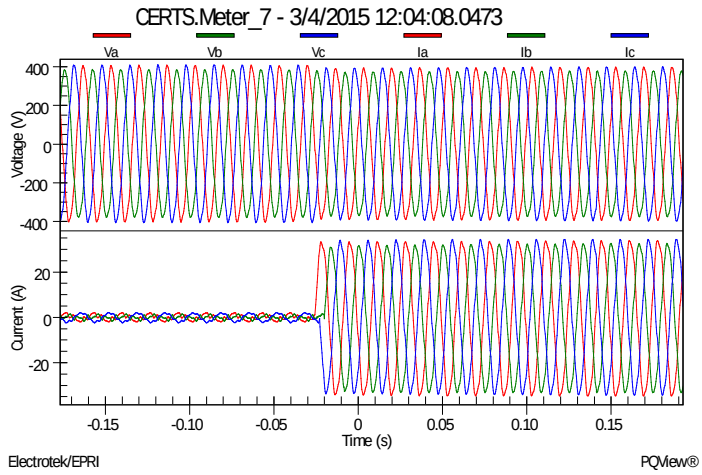

Figure 9: Test Event A: Step Load 0 kW to 20 kW, Waveform Voltage & Current (Zoomed)

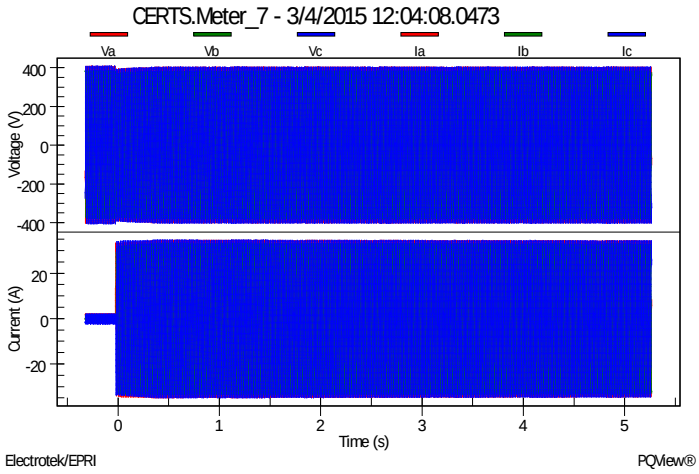

Figure 10: Test Event A: Step Load 0 kW to 20 kW, Waveform Voltage & Current

Figure 11 through Figure 12 show the results of Test Event B, a step load from 20 kW to 0 kW, which is successful and unremarkable.

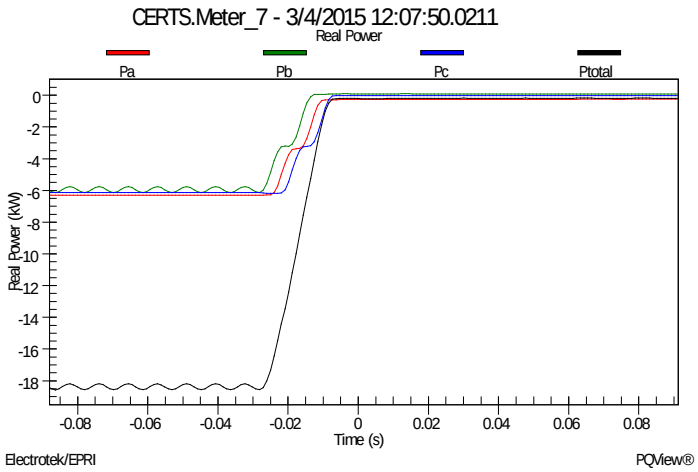

Figure 11: Test Event B, Step Load 20 kW to 0 kW, Real Power

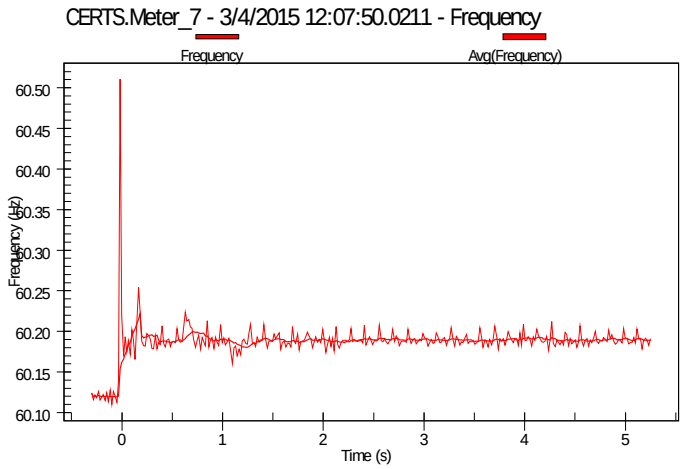

Figure 12: Test Event B, Step Load 20 kW to 0 kW, Frequency

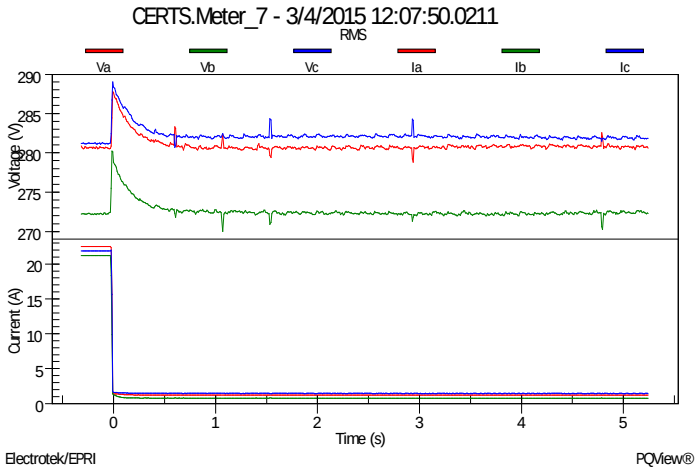

Figure 13: Test Event B, Step Load 20 kW to 0 kW, RMS Voltage and Current

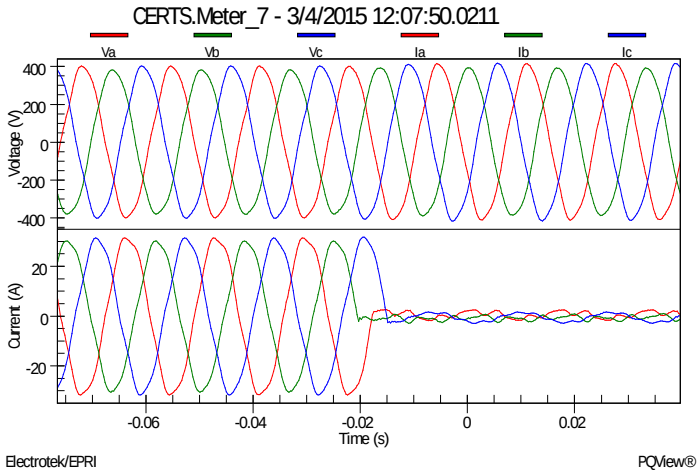

Figure 14: Test Event B, Step Load 20 kW to 0 kW, Waveform Voltage and Current (Zoomed)

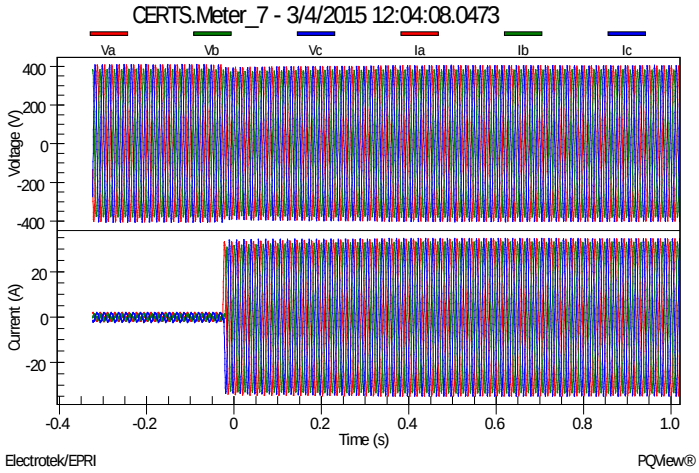

Figure 15: Test Event B, Step Load 20 kW to 0 kW, Waveform Voltage and Current

Figure 16 through Figure 20 show results for Test Event L1, a designed step load from 120 kW to 100 kW, actual load step is from 103 kW to 92 kW, which does pass. The initial load of 103 kW exceeded P_{max} which results in an initial frequency of 50 Hz. The ESS will operate at this frequency since 50 Hz is the minimum frequency setting and no under frequency tripping is enabled. When the load is reduced to 92 kW the frequency returns to 59.82 Hz in accordance with its frequency droop setting. The RMS voltages are seen in Figure 18 to swing significantly with the voltage varying from approximately 255 Vrms to 310 Vrms. In this case the initial frequency is 50 Hz and the P_{max} functionality is active. This phenomenon will be revisited in the section on P_{max} but appears to be an artifact of either the metering hardware or the data processing performed in software. It is not likely that the RMS voltage is varying as indicated in the graph.

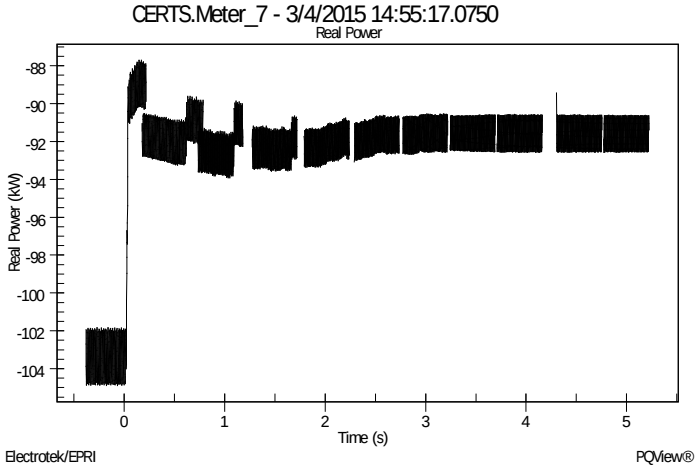

Figure 16 Test Event L1: Real Power, Step Load 120 kW to 100 kW

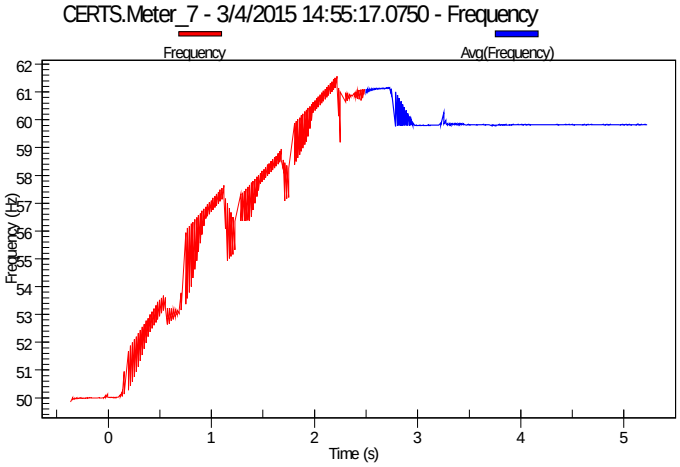

Figure 17 Test Event L1: Frequency, Step Load 120 kW to 100 kW

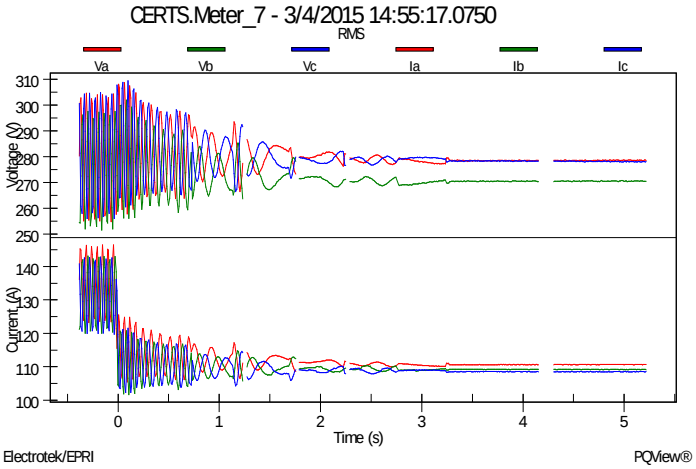

Figure 18 Test Event L1: RMS Voltage and Current, Step Load 120 kW to 100 kW

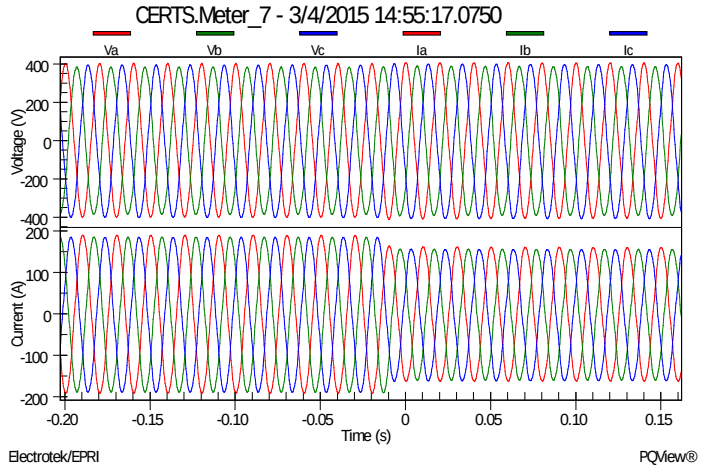

Figure 19 Test Event L1: Voltage and Current Waveform, Step Load 120 kW to 100 kW

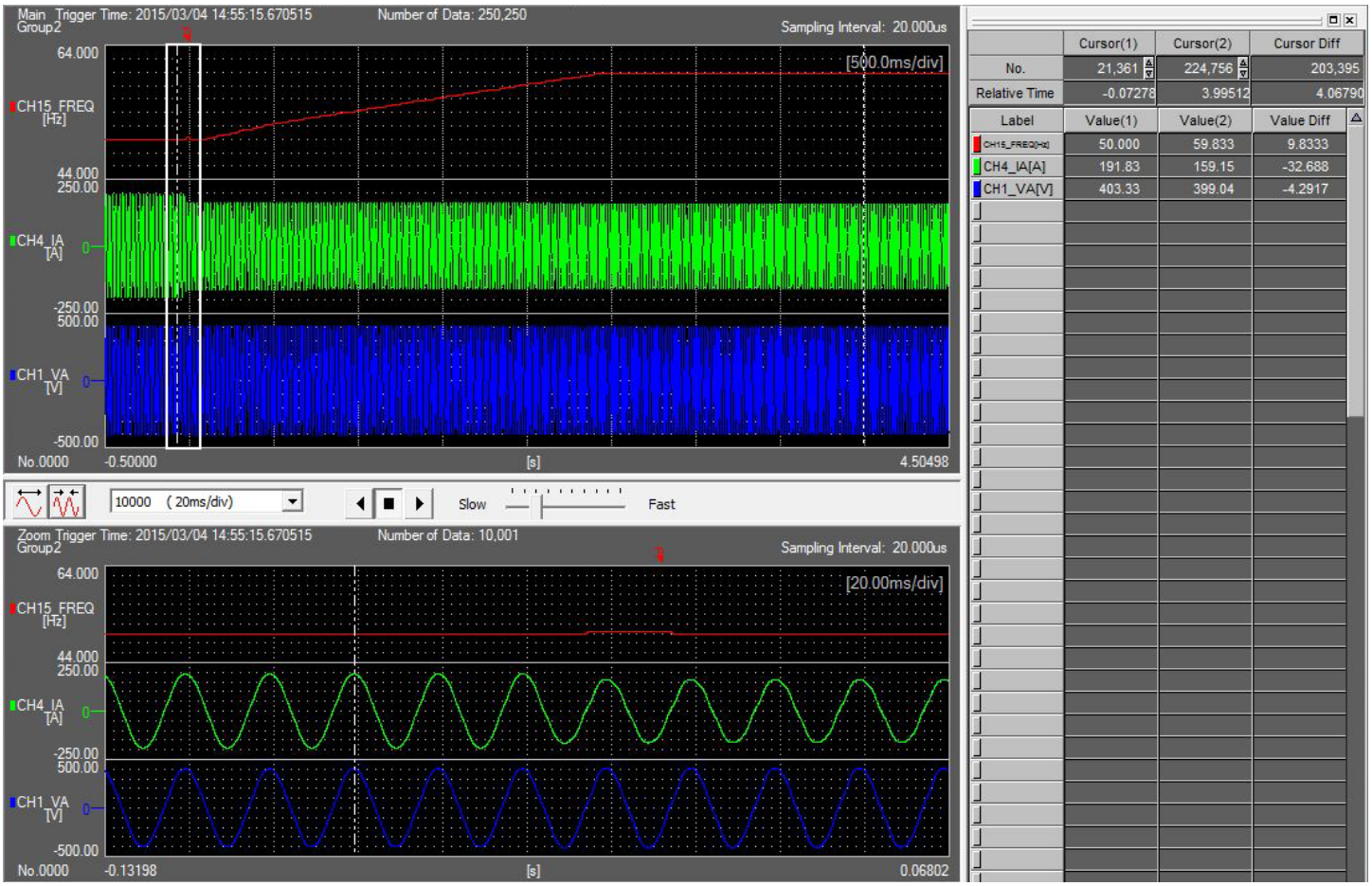

Figure 20 Test Event L1: Frequency, Current, and Voltage from Yokogawa, Step Load 120 kW to 100 kW

Figure 21 through Figure 25 show results for Test Event L2, a designed step load from 120 kW to 100 kW, however in this case the initial real power load is 113 kW as compared to 103 kW in Test Event L1.

In this case the test does not pass and results in the inverter tripping off due to an IGBT Bridge Error. In this case the pre-event load is 113 kW which is in excess of the AC Power Limit of 105 kW. This failure is not related to the CERTS algorithm but rather represents a limit of the operating capability of the inverter. In Figure 22, PQView incorrectly shows the pre-event frequency to be 60 Hz while in Figure 25 the Yokogawa correctly shows it to be 50 Hz.

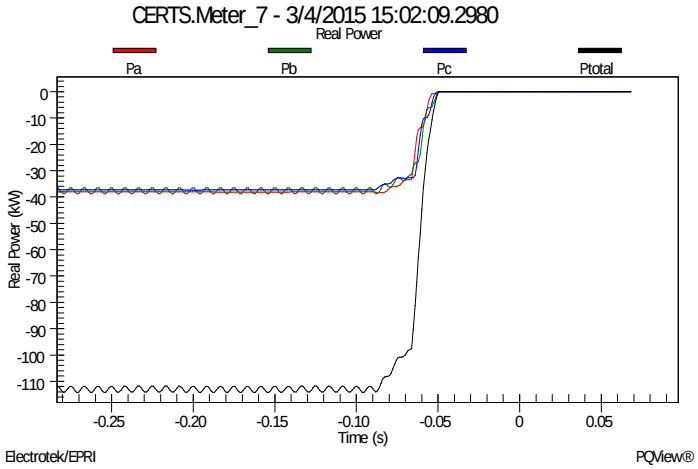

Figure 21 Test Event L2: Real Power, Step Load 120 kW to 100 kW

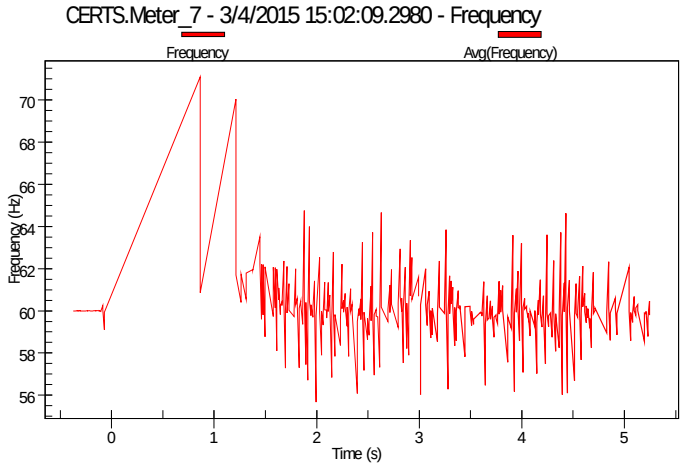

Figure 22 Test Event L2: Frequency, Step Load 120 kW to 100 kW

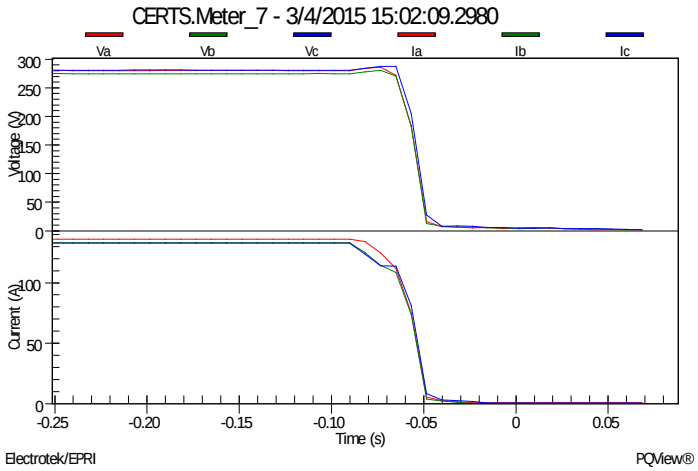

Figure 23 Test Event L2: RMS Voltage and Current, Step Load 120 kW to 100 kW

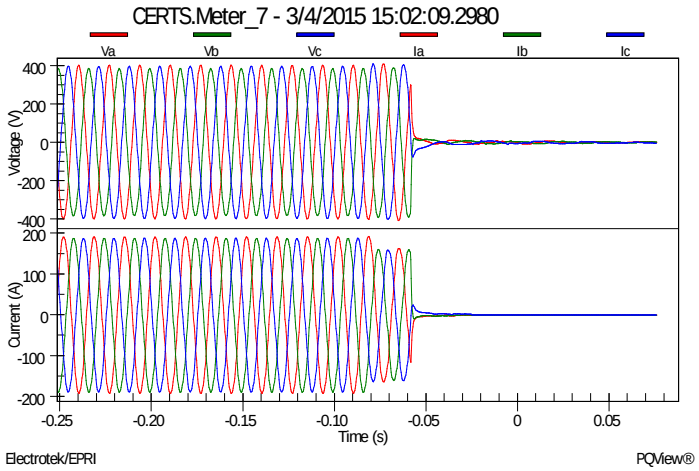

Figure 24 Test Event L2: Voltage and Current Waveform, Step Load 120 kW to 100 kW

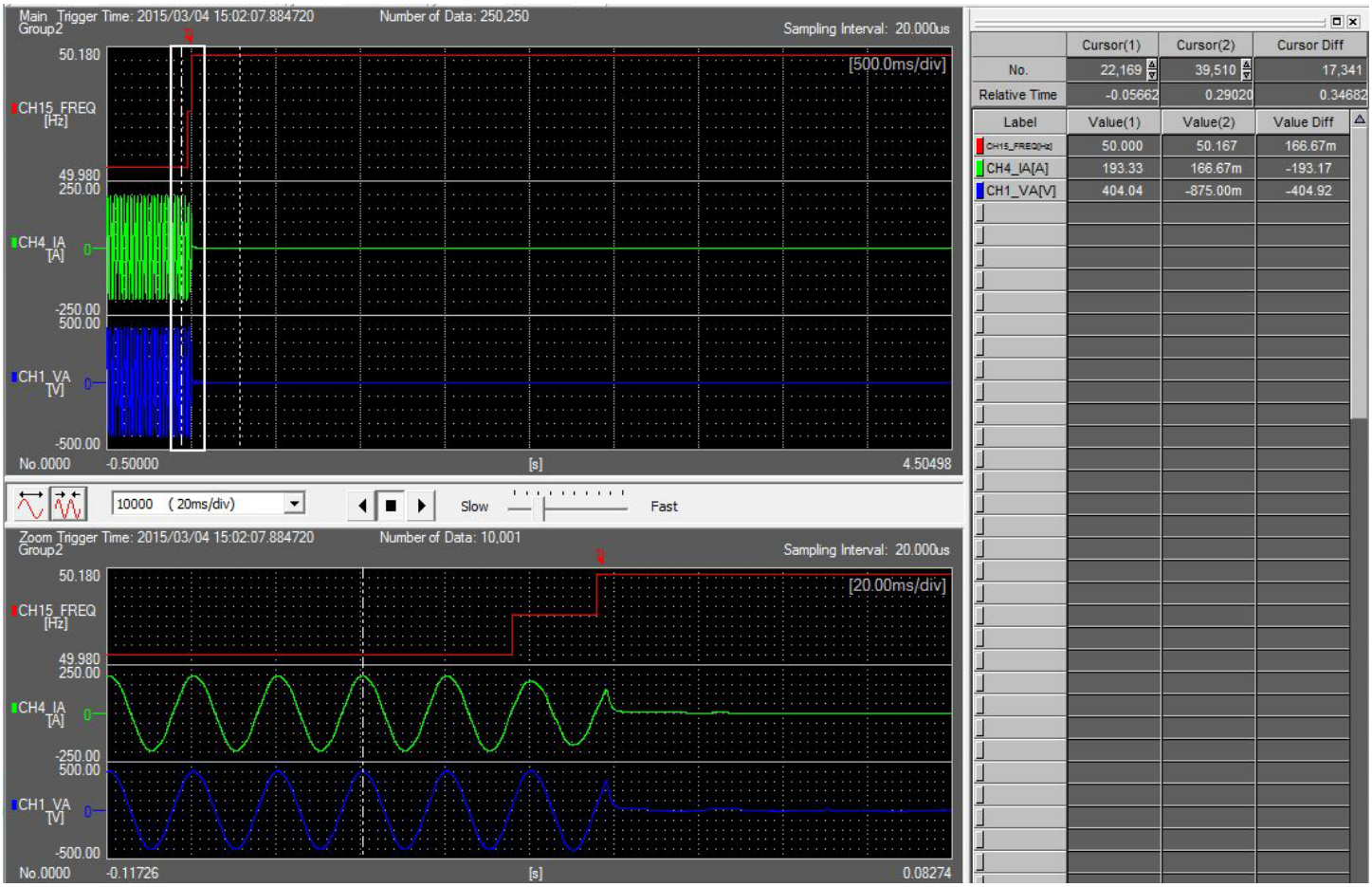

Figure 25 Test Event L2: Frequency, Current, and Voltage from Yokogawa, Step Load 120 kW to 100 kW

Figure 26 through Figure 30 show results for Test Event AF, a designed load rejection from 95 kW to 0 kW (89 kW to 0 kW actual), which does not pass and results in the inverter tripping off due to an IGBT Bridge Error. It is possible that the error is a result of high voltage on the inverter's DC bus. The failure of the ESS to perform a load rejection greater than 85 kW is not related to the CERTS algorithm but rather represent a limit of the operating capability of the inverter.

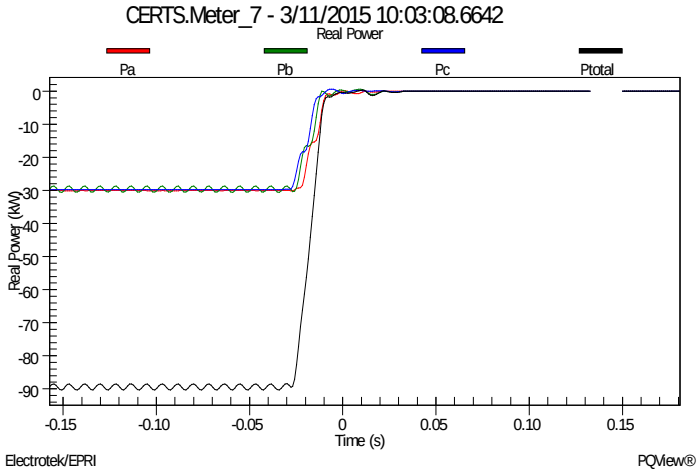

Figure 26 Test Event AF: Real Power, Step Load 95 kW to 0 kW

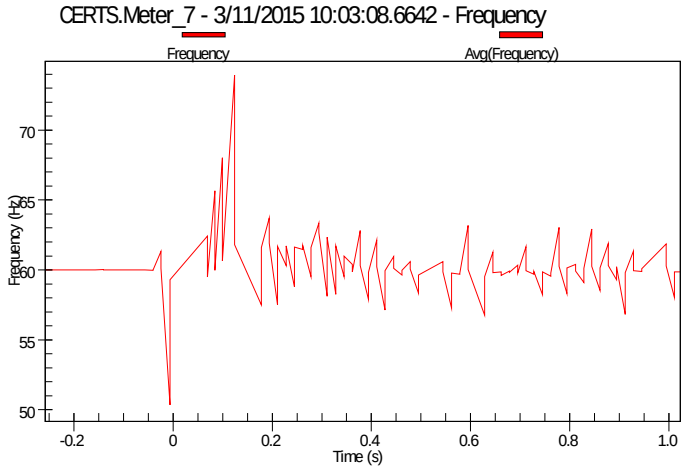

Figure 27 Test Event AF: Frequency, Step Load 95 kW to 0 kW

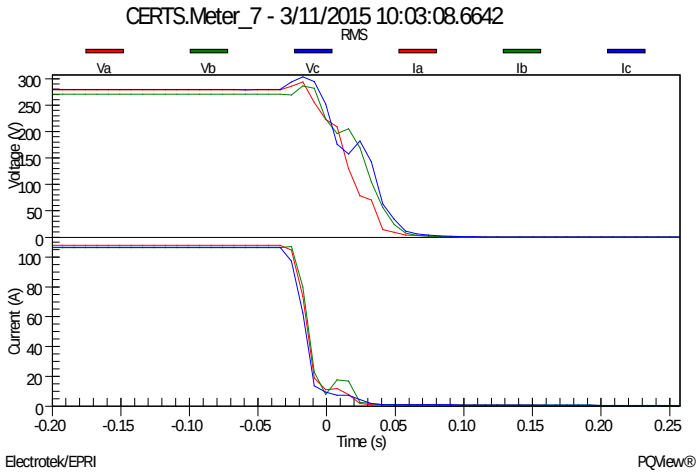

Figure 28 Test Event AF: RMS Voltage and Current, Step Load 95 kW to 0 kW

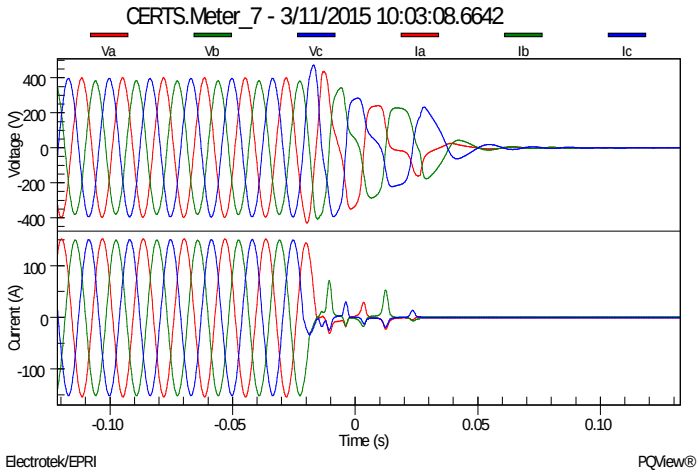

Figure 29 Test Event AF: Voltage and Current Waveform, Step Load 95 kW to 0 kW

Figure 30 Test Event AF: Frequency, Voltage, and Current from Yokogawa, Step Load 95 kW to 0 kW

Figure 31 through Figure 35 show results for Test Event AH, a designed load rejection from 85 kW to 0 kW (81 kW to 0 kW actual), which does pass. This is the largest load rejection that is successful.

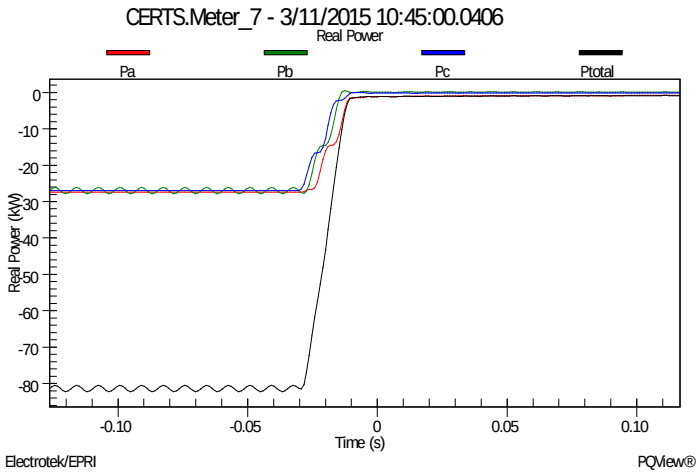

Figure 31 Test Event AH: Real Power, Step Load 85 kW to 0 kW

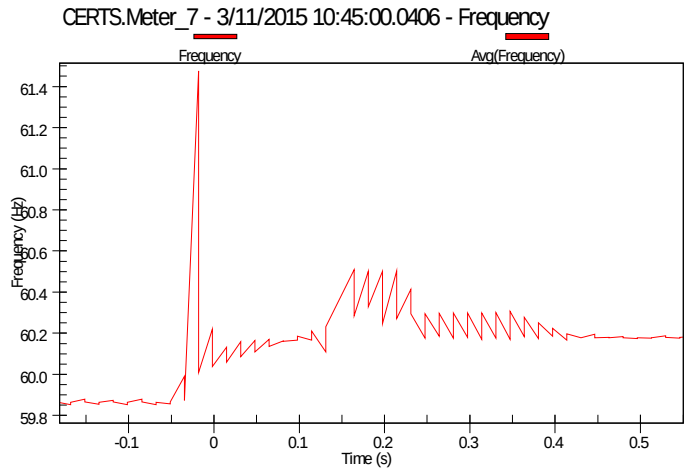

Figure 32 Test Event AH: Frequency, Step Load 85 kW to 0 kW

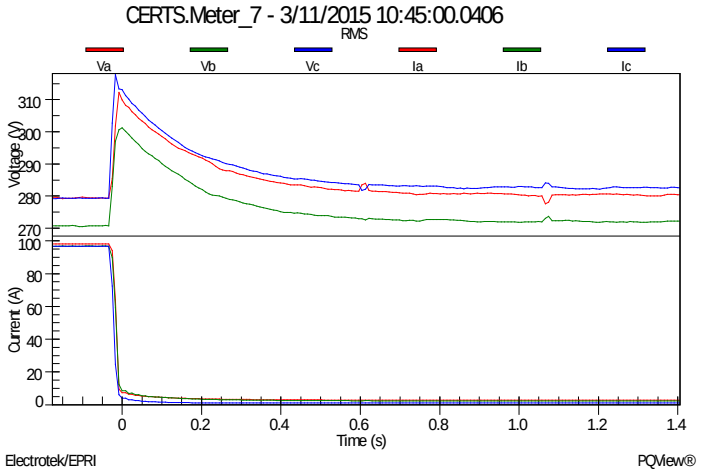

Figure 33 Test Event AH: RMS Voltage and Current, Step Load 85 kW to 0 kW

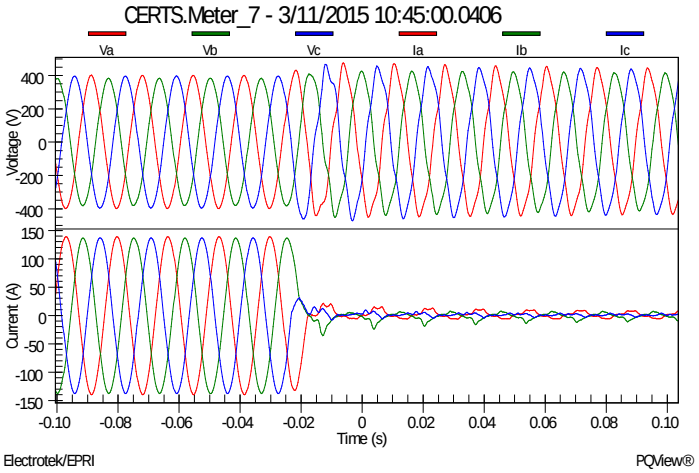

Figure 34 Test Event AH: Voltage and Current Waveform, Step Load 85 kW to 0 kW

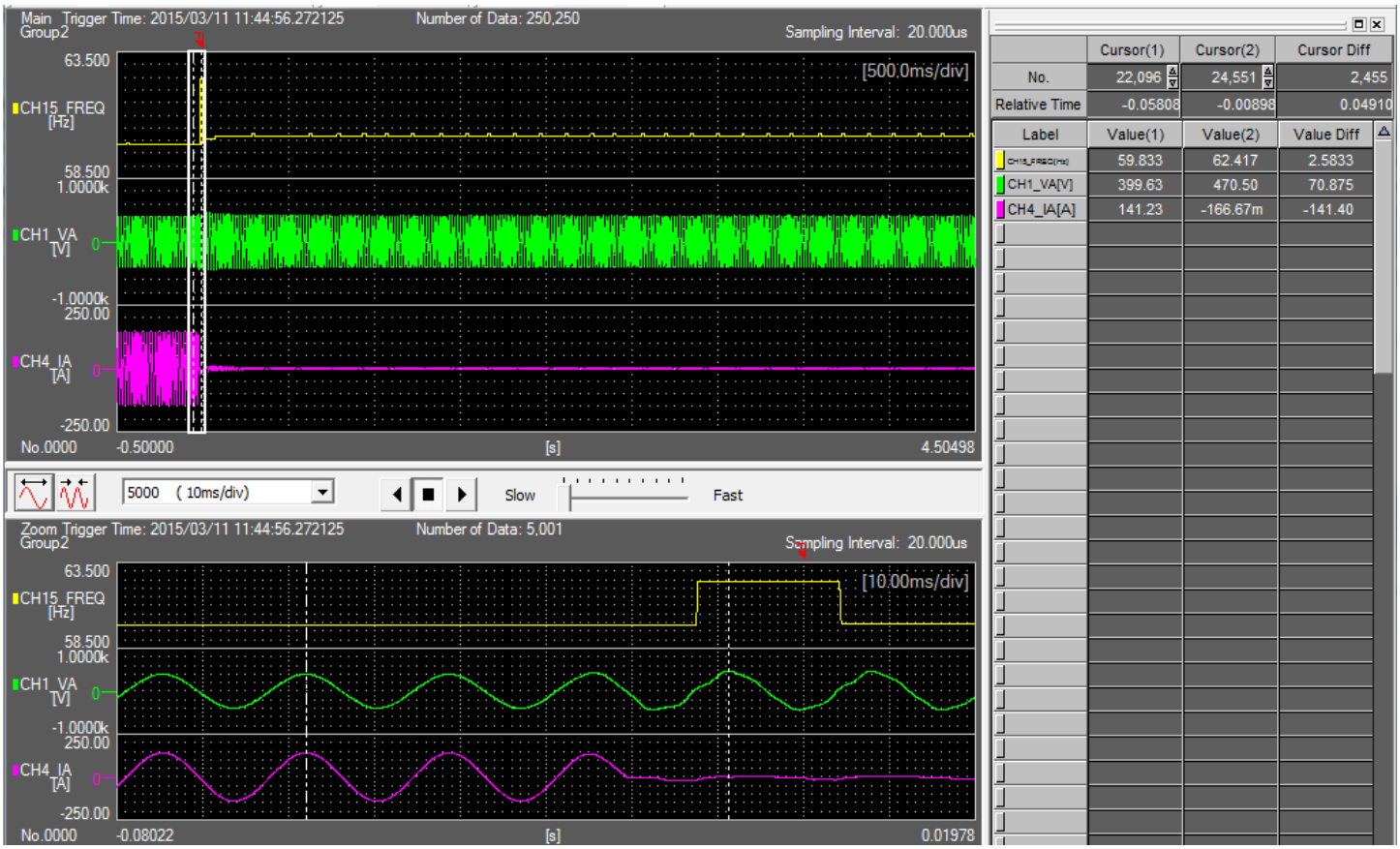

Figure 35 Test Event AH: Frequency, Voltage, and Current from Yokogawa, Step Load 85 kW to 0 kW

Figure 36 through Figure 40 show results for Test Event O, a step load from 20 kW to 60 kW, which is successful and unremarkable.

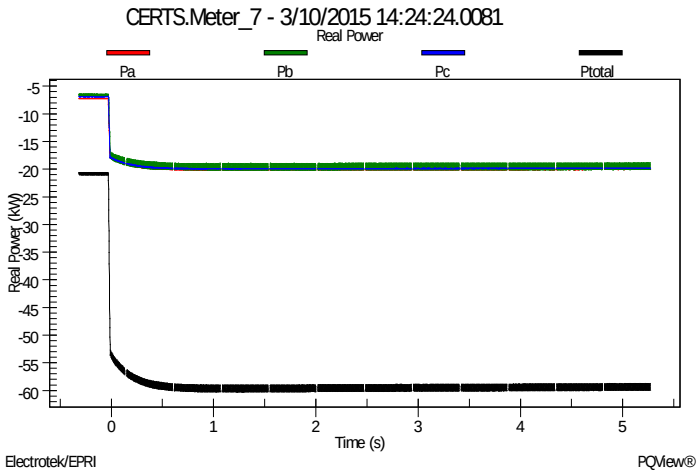

Figure 36: Test Event O: Step Load 20 kW to 60 kW, Real Power

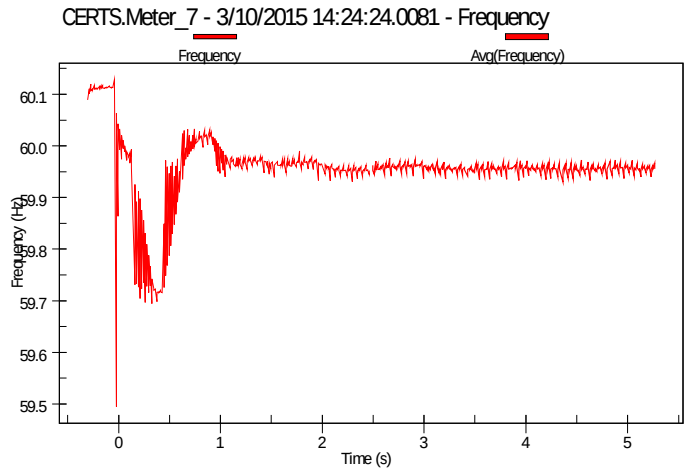

Figure 37: Test Event O: Step Load 20 kW to 60 kW, Frequency

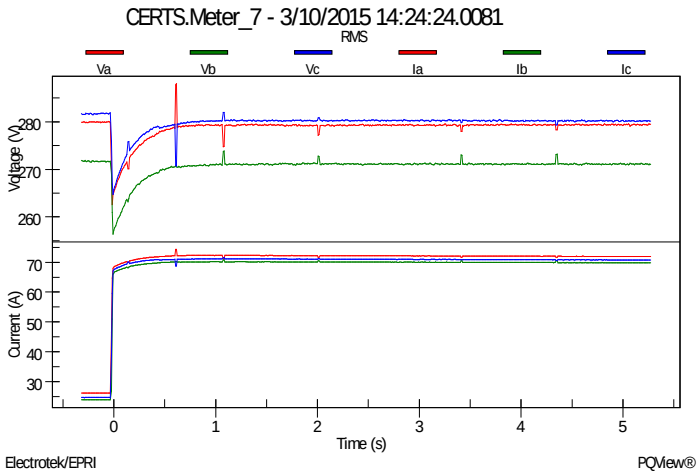

Figure 38: Test Event O: Step Load 20 kW to 60 kW, RMS Voltage & Current

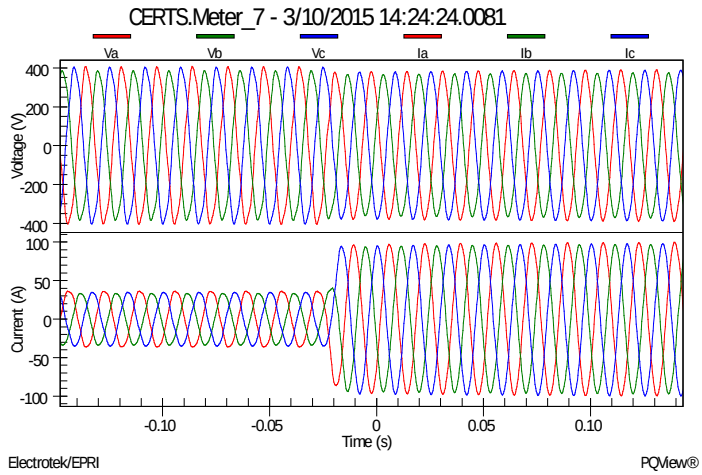

Figure 39: Test Event O: Step Load 20 kW to 60 kW, Waveform Voltage & Current (Zoomed)

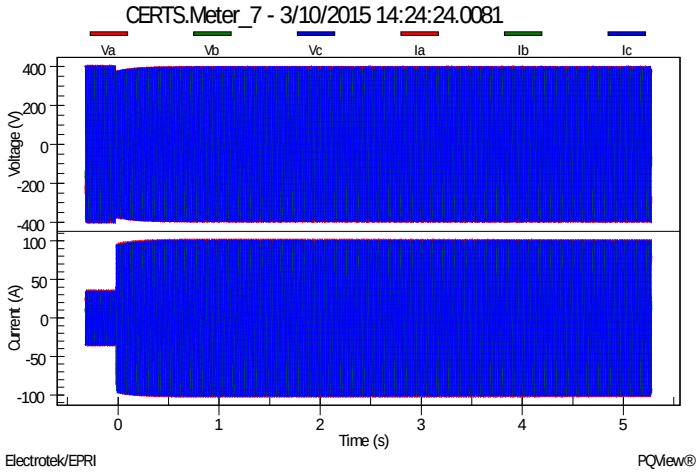

Figure 40: Test Event O: Step Load 20 kW to 60 kW, Waveform Voltage & Current

Figure 41 through Figure 45 show results for Test Event P, a step load from 60 kW to 20 kW, which is successful and unremarkable.

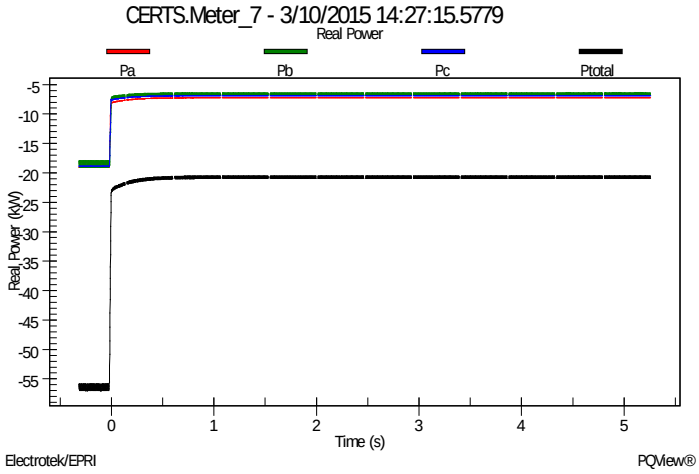

Figure 41: Test Event P: Step Load 60 kW to 20 kW, Real Power

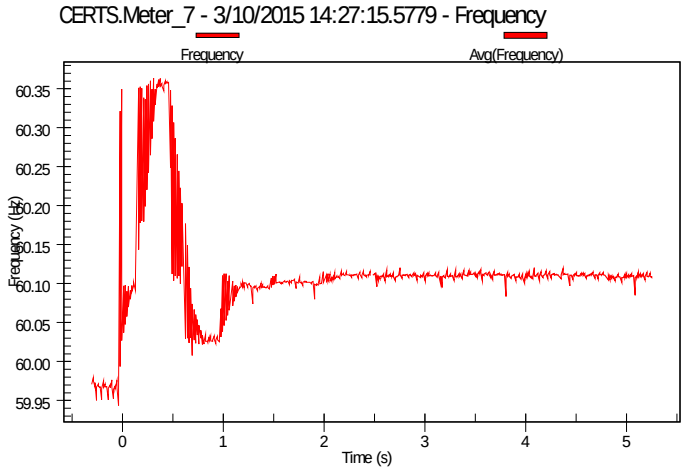

Figure 42: Test Event P: Step Load 60 kW to 20 kW, Frequency

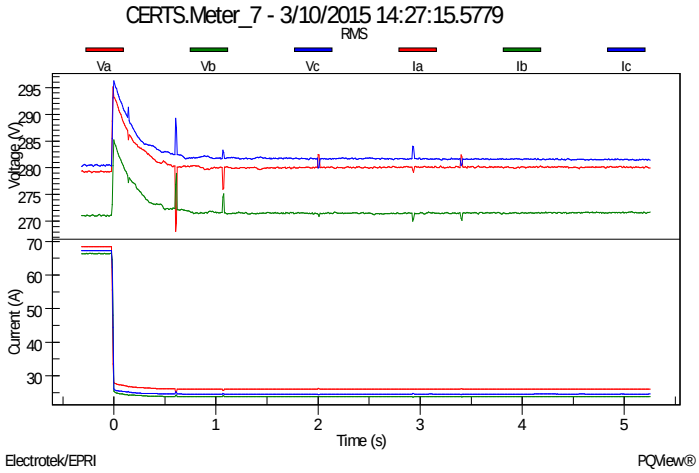

Figure 43: Test Event P: Step Load 60 kW to 20 kW, RMS Voltage & Current

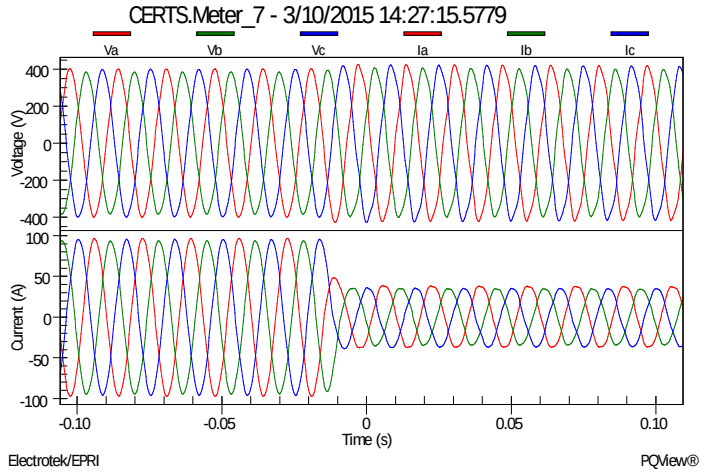

Figure 44: Test Event P: Step Load 60 kW to 20 kW, Waveform Voltage & Current (Zoomed)

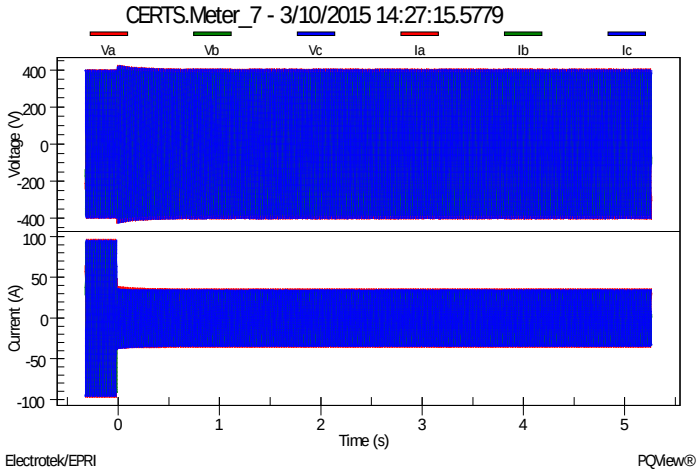

Figure 45: Test Event P: Step Load 60 kW to 20 kW, Waveform Voltage & Current

Figure 46 through Figure 50 show results for Test Event W, a step load from 20 kW to 80 kW, which is successful and unremarkable.

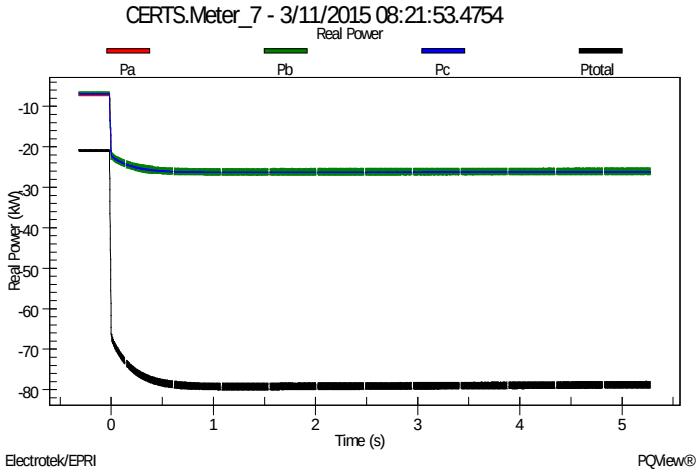

Figure 46: Test Event W: Step Load 20 kW to 80 kW, Real Power

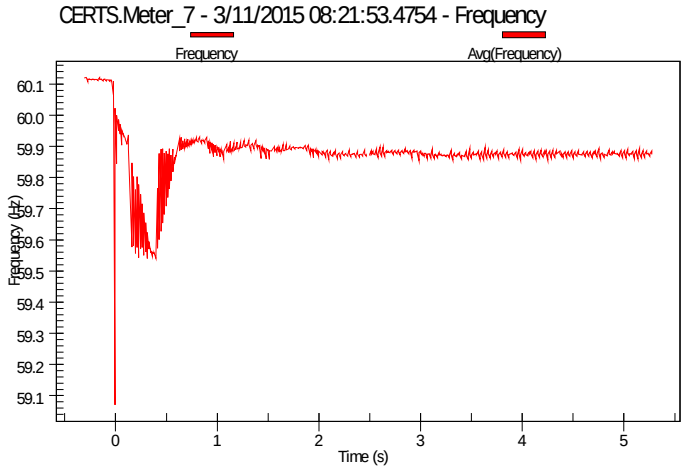

Figure 47: Test Event W: Step Load 20 kW to 80 kW, Frequency

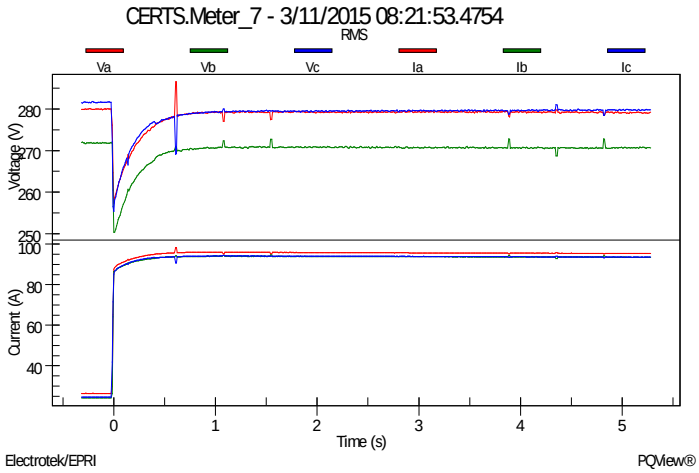

Figure 48: Test Event W: Step Load 20 kW to 80 kW, RMS Voltage & Current

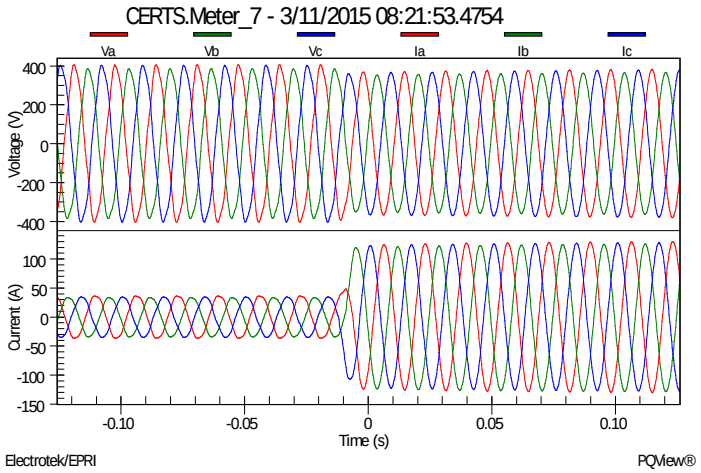

Figure 49: Test Event W: Step Load 20 kW to 80 kW, Waveform Voltage & Current (Zoomed)

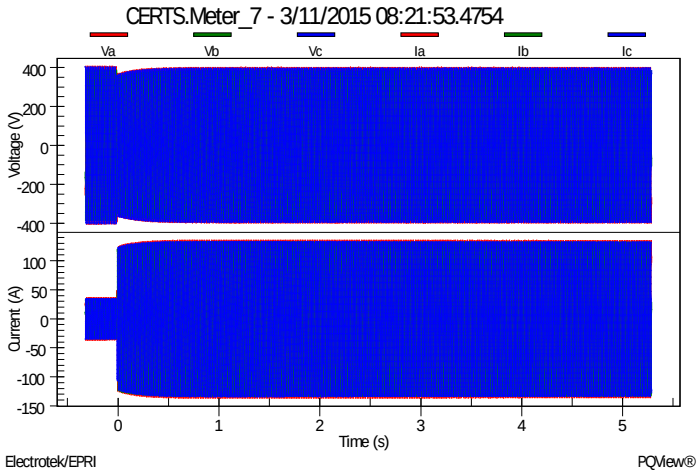

Figure 50: Test Event W: Step Load 20 kW to 80 kW, Waveform Voltage & Current

Figure 51 through Figure 55 show results for Test Event X, a step load from 80 kW to 20 kW, which is successful and unremarkable.

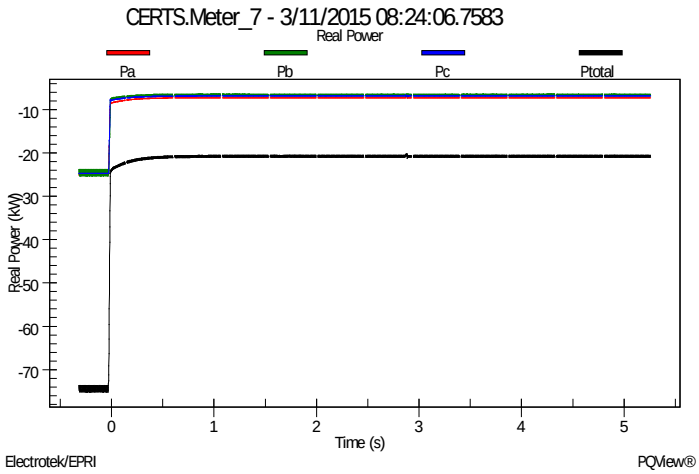

Figure 51: Test Event X: Step Load 80 kW to 20 kW, Real Power

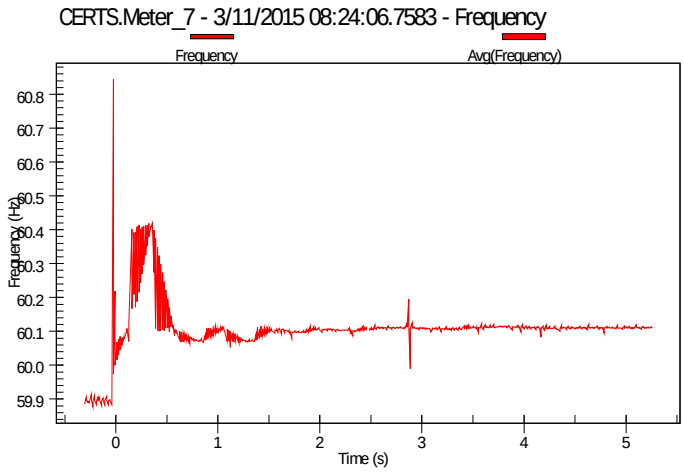

Figure 52: Test Event X: Step Load 80 kW to 20 kW, Frequency

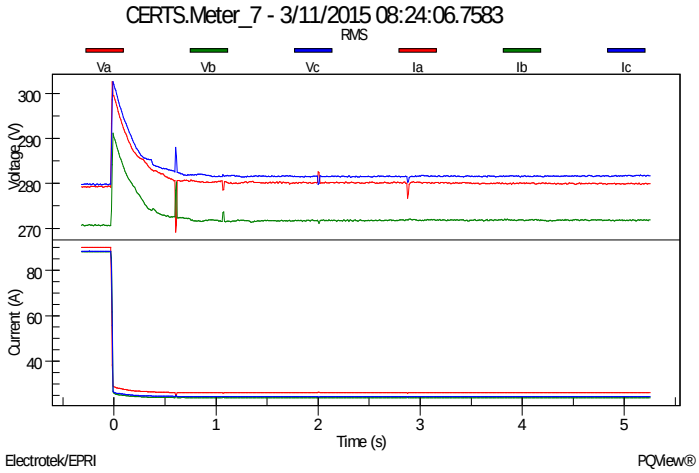

Figure 53: Test Event X: Step Load 80 kW to 20 kW, RMS Voltage & Current

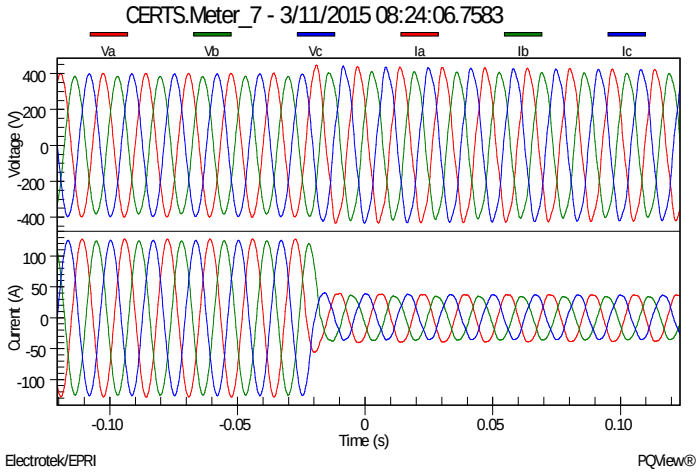

Figure 54: Test Event X: Step Load 80 kW to 20 kW, Waveform Voltage & Current (Zoomed)

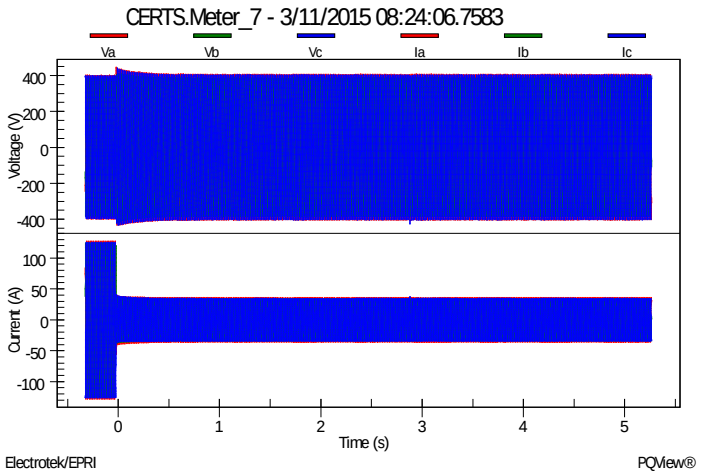

Figure 55: Test Event X: Step Load 80 kW to 20 kW, Waveform Voltage & Current

Figure 56 through Figure 60 show results for Test Event S, a step load from 60 kW to 100 kW, which is successful and unremarkable.

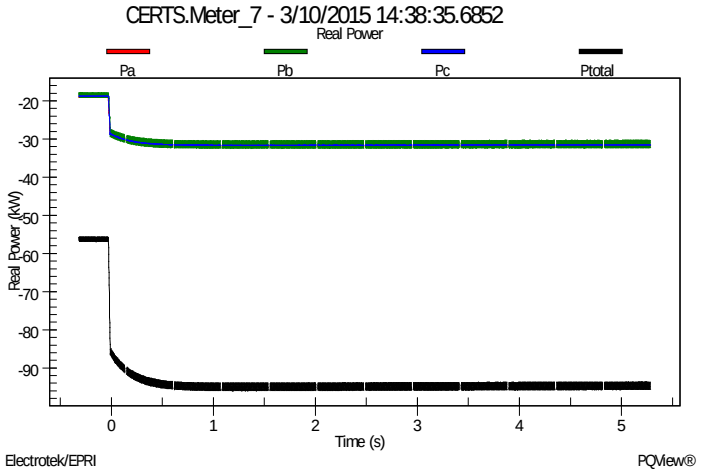

Figure 56: Test Event S: Step Load 60 kW to 100 kW, Real Power

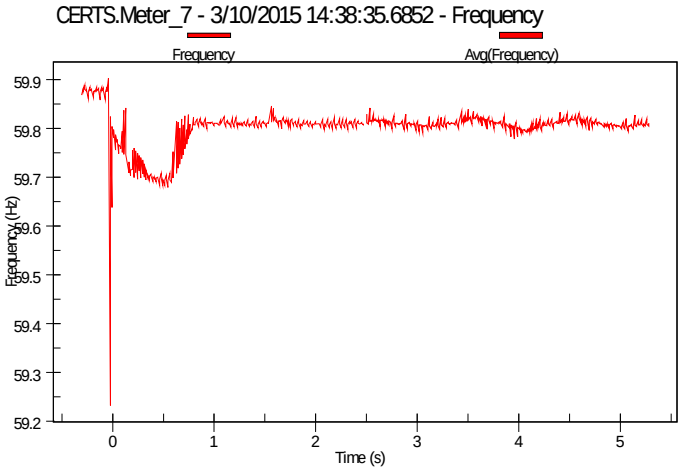

Figure 57: Test Event S: Step Load 60 kW to 100 kW, Frequency

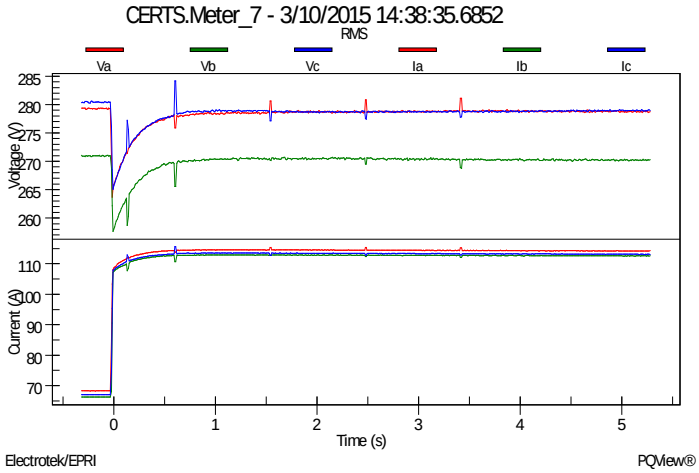

Figure 58: Test Event S: Step Load 60 kW to 100 kW, RMS Voltage & Current

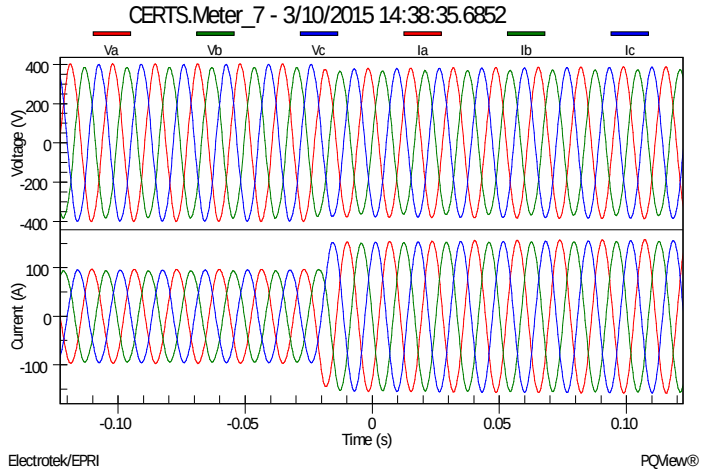

Figure 59: Test Event S: Step Load 60 kW to 100 kW, Waveform Voltage & Current (Zoomed)

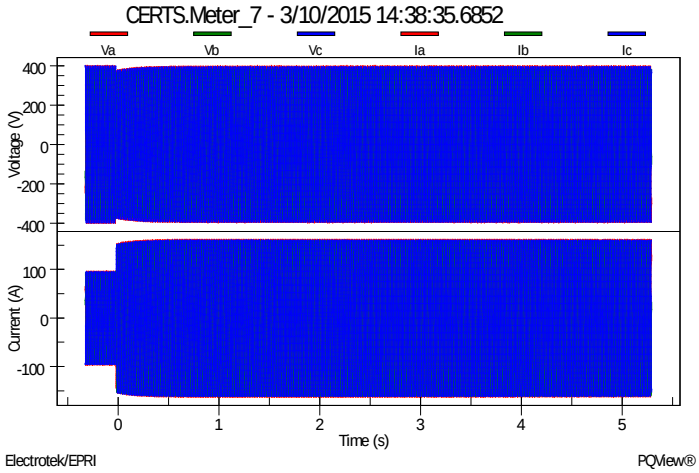

Figure 60: Test Event S: Step Load 60 kW to 100 kW, Waveform Voltage & Current

Figure 61 through Figure 65 show results for Test Event T, a step load from 100 kW to 60 kW, which is successful and unremarkable.

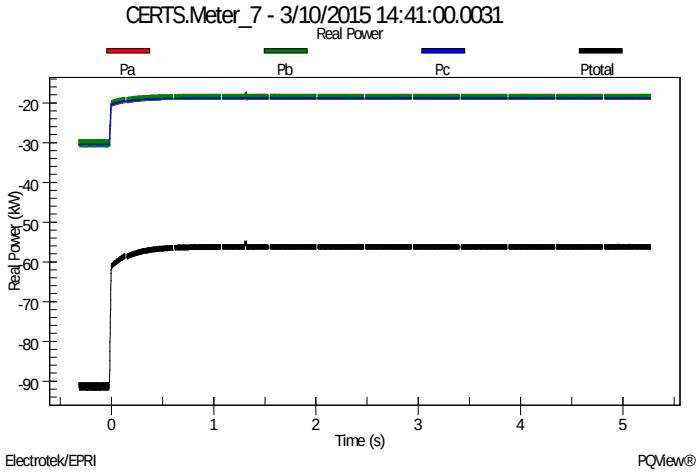

Figure 61: Test Event T: Step Load 100 kW to 60 kW, Real Power

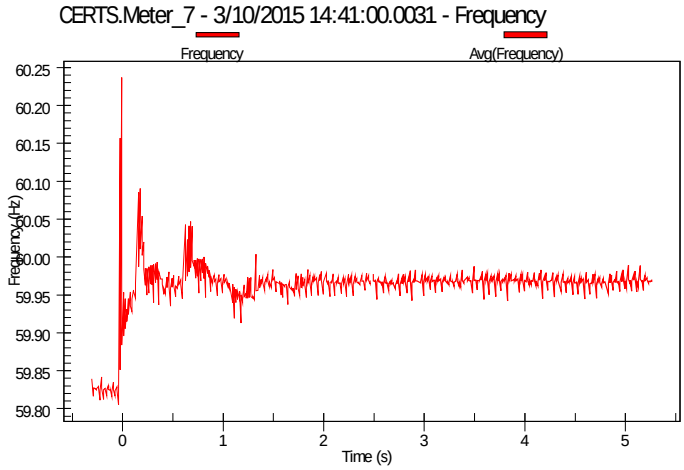

Figure 62: Test Event T: Step Load 100 kW to 60 kW, Frequency

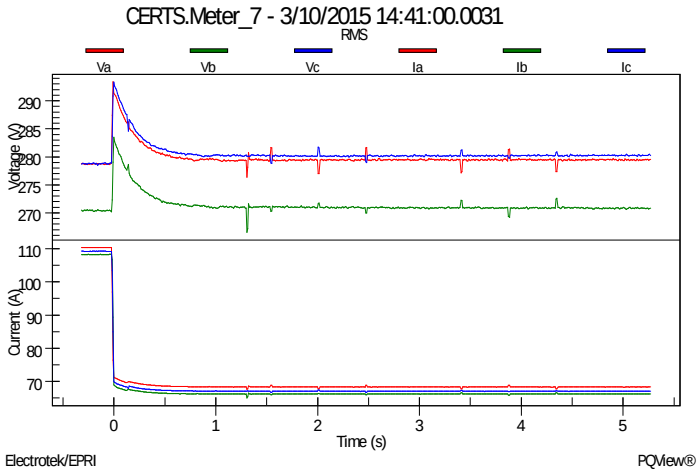

Figure 63: Test Event T: Step Load 100 kW to 60 kW, RMS Voltage & Current

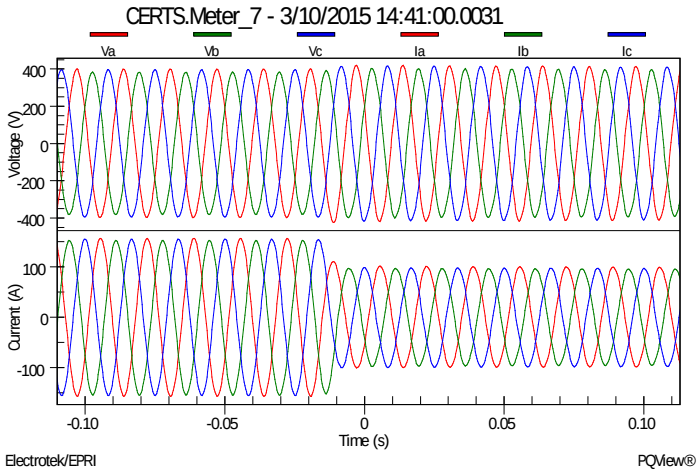

Figure 64: Test Event T: Step Load 100 kW to 60 kW, Waveform Voltage & Current (Zoomed)

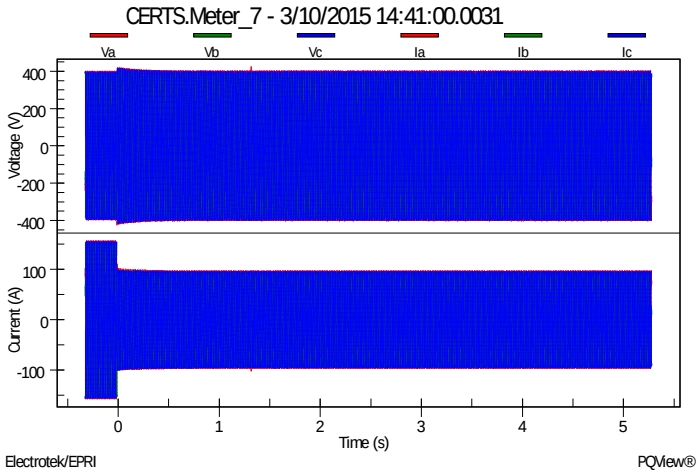

Figure 65: Test Event T: Step Load 100 kW to 60 kW, Waveform Voltage & Current

5.4 Initial Voltage Regulation Test – Stand Alone

Performance Goal

Verify that the ESS is capable of holding the correct output voltage throughout its operating range. Voltage set points in the ESS are varied from 95% to 105% of nominal voltage (480V_{LL}). Actual voltage levels will be compared to expected values.

Description of Procedure

The ESS is dispatched to 50 kW, 1% Frequency Droop, a voltage range from 95% to 105% of 480 V_{LL} nominal, 5% Voltage Droop and operated islanded from the utility. The ESS is started and connected to the islanded microgrid electrical bus. For a given dispatch voltage, voltage measurements are taken at different loading values ranging from no load to approximately 100 kW.

Test Settings

ESS parameters are set as follows:
Pdispatch = 50 kW
Frequency Droop = -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)
AC Power Limit = 105 kW
Voltage Droop = -0.24 V/kVAr
Voltage Dispatch = Varies from 95% to 105% of nominal [Inverter Voltage Reference = 102.5 per PPS*]
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V_{LL}.

Table 8 below lists the test cases. Load bank and total load transitions are indicated with an arrow (→).

Test Event	ESS (Dispatch = 50 kW)	GIS	Load Bank 3 (kW)	Load Bank 5 (kW)	Total (kW)
A	480 V	Open	0	0	0
B	480 V	Open	0	0→30	0→30
C	480 V	Open	0	30→65	30→65
D	480 V	Open	0→35	65	65→100
E	504 V	Open	0	0	0
F	504 V	Open	0	0→30	0→30
G	504 V	Open	0	30→65	30→65
H	504 V	Open	0→35	65	65→100
I	456 V	Open	0	0	0
J	456 V	Open	0	0→30	0→30
K	456 V	Open	0	30→65	30→65
L	456 V	Open	0→35	65	65→100

Table 8: Initial Voltage Regulation Test Cases

Test Results

Table 9 below summarizes the results of initial voltage regulation tests including real and reactive power, voltage, and steady state voltage error for all events.

Test Event	ESS Real Power Observed	ESS Reactive Power Observed	ESS Voltage		Steady State Error (%)	Pass/Fail
			Target	Actual		
A	0.72	1	276.86	277.79	0.34%	PASS
B	31.13	1.2	276.83	277.15	0.11%	PASS
C	66.16	2.06	276.71	276.2	-0.19%	PASS
D	97.74	2.87	276.60	275.3	-0.47%	PASS
E	0.84	1.93	290.73	291.67	0.32%	PASS
F	34.27	2.24	290.69	290.88	0.07%	PASS
G	72.83	3.2	290.56	289.83	-0.25%	PASS
H	107.17	4.08	290.43	288.84	-0.55%	PASS
I	0.59	0.42	262.94	263.94	0.38%	PASS
J	27.77	0.57	262.92	263.27	0.13%	PASS
K	59.97	1.33	262.82	262.3	-0.20%	PASS
L	88.08	2.07	262.71	261.44	-0.48%	PASS

Table 9: Initial Voltage Regulation Test

Analysis

The ESS successfully passes the voltage regulation tests over its voltage and real power operating range.

The observed voltage at the ESS's meter deviated from its expected value by no more than 0.55% in all cases and ranges from -0.55% to 0.38%. The voltage is consistently slightly high at lighter loads and slightly low at heavier loads. This slight voltage droop is likely due to the impedance between the ESS and its meter. Figure 66 displays the measured and expected voltage response as a function of the real power provided from the ESS. The measured voltage response is seen to cross the target voltage response for each dispatch voltage at approximately the midpoint of each pair of graphs.

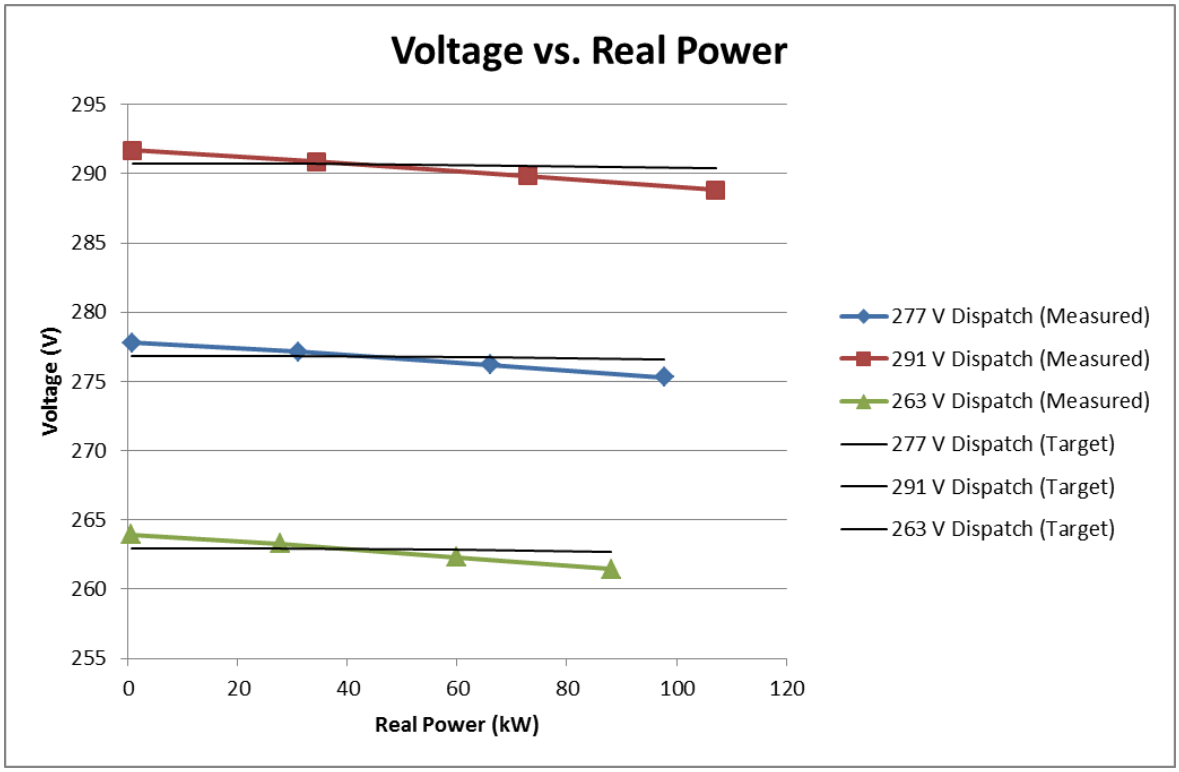

Figure 66 Voltage Regulation Test – Voltage as a function of Real Power

5.5 Frequency vs. Real Power Droop Control – Stand Alone

Performance Goal

Verify the Frequency vs. Real Power Droop is properly implemented in the ESS. Determine whether the Frequency vs. Real Power and the Voltage vs. Reactive Power Controllers are properly decoupled by evaluating the voltage as function of real power.

Description of Procedure

The ESS is dispatched to three different values over these tests (25 kW, 100 kW and -50 kW), 480 V_{LL}, 1% Frequency Droop, 5% Voltage Droop and operated islanded from the utility. The ESS is started and connected to the islanded microgrid electrical bus. At the various real power dispatch values, a series of 20 kW step loads are applied. At each load value the real power, frequency, and voltage will be measured.

Test Settings

ESS parameters are set as follows:
Pdispatch = Varies (25 kW, 100 kW, and -50 kW)
Frequency Droop = 1% or -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)

AC Power Limit = 105 kW
Voltage Droop = 5% or -0.24 V/kVAr
Voltage Dispatch = 480 V [Inverter Voltage Reference = 102.5 per PPS*]
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V.

Table 10 below lists the test cases. Load bank and total load transitions are indicated with an arrow (→).

Test Event	ESS $P_{dispatch}$ (kW)	GIS	Load Bank 3 (kW)	Load Bank 4 (kW)	Total (kW)
A	25	Open	0	0	0
B	25	Open	0→20	0	0→20
C	25	Open	20→40	0	20→40
D	25	Open	40→60	0	40→60
E	25	Open	60→80	0	60→80
F	25	Open	80	0→20	80→100
G	100	Open	0	0	0
H	100	Open	0→20	0	0→20
I	100	Open	20→40	0	20→40
J	100	Open	40→60	0	40→60
K	100	Open	60→80	0	60→80
L	100	Open	80	0→20	80→100
M	-50	Open	0	0	0
N	-50	Open	0→20	0	0→20
O	-50	Open	20→40	0	20→40
P	-50	Open	40→60	0	40→60
Q	-50	Open	60→80	0	60→80
R	-50	Open	80	0→20	80→100

Table 10: ESS Frequency vs Real Power Droop Control Test Cases

Test Results

Table 11 below summarizes the results of frequency versus real power droop control tests including real power, frequency, and voltage for all events.

Test Event	ESS Real Power Observed (kW)	Energy Storage System Frequency (Hz)		Frequency Error	Voltage (V)	Pass/Fail
		Target	Measured			
A	0.73	60.10	60.11	0.02%	277.1	Pass
B	20.37	60.02	60.01	-0.01%	277.3	Pass
C	38.05	59.95	59.94	-0.01%	277.6	Pass
D	55.56	59.88	59.87	-0.01%	277.7	Pass
E	72.79	59.81	59.80	-0.01%	277.9	Pass
F	91.93	59.73	59.72	-0.02%	278.0	Pass
G	0.73	60.40	60.41	0.02%	277.0	Pass
H	20.14	60.32	60.31	-0.02%	277.2	Pass
I	37.86	60.25	60.24	-0.01%	277.6	Pass
J	55.49	60.18	60.17	-0.01%	277.7	Pass
K	72.78	60.11	60.09	-0.03%	277.8	Pass
L	93.63	60.03	60.01	-0.03%	278.0	Pass
M	0.74	59.80	59.83	0.06%	277.2	Pass
N	20.2	59.72	59.71	-0.02%	277.3	Pass
O	37.92	59.65	59.65	0.00%	277.7	Pass
P	55.41	59.58	59.57	-0.01%	277.7	Pass
Q	72.75	59.51	59.50	-0.02%	277.9	Pass
R	93.93	59.42	59.42	-0.01%	278.2	Pass

Table 11: Frequency vs. Real Power Droop Control Test Results

Analysis

The Frequency vs. Real Power Controller performs within acceptable limits. The frequency error ranges from -0.03% to 0.06%. The target droop slope is -0.004 Hz/kW and the measured droop slope is -0.0043 Hz/kW.

Figure 67 compares the measured frequency and real power results with the target values at three different dispatch points. The equations for the trend lines of the measured values are displayed. The Frequency vs. Real Power Droop controller is shown to be well behaved.

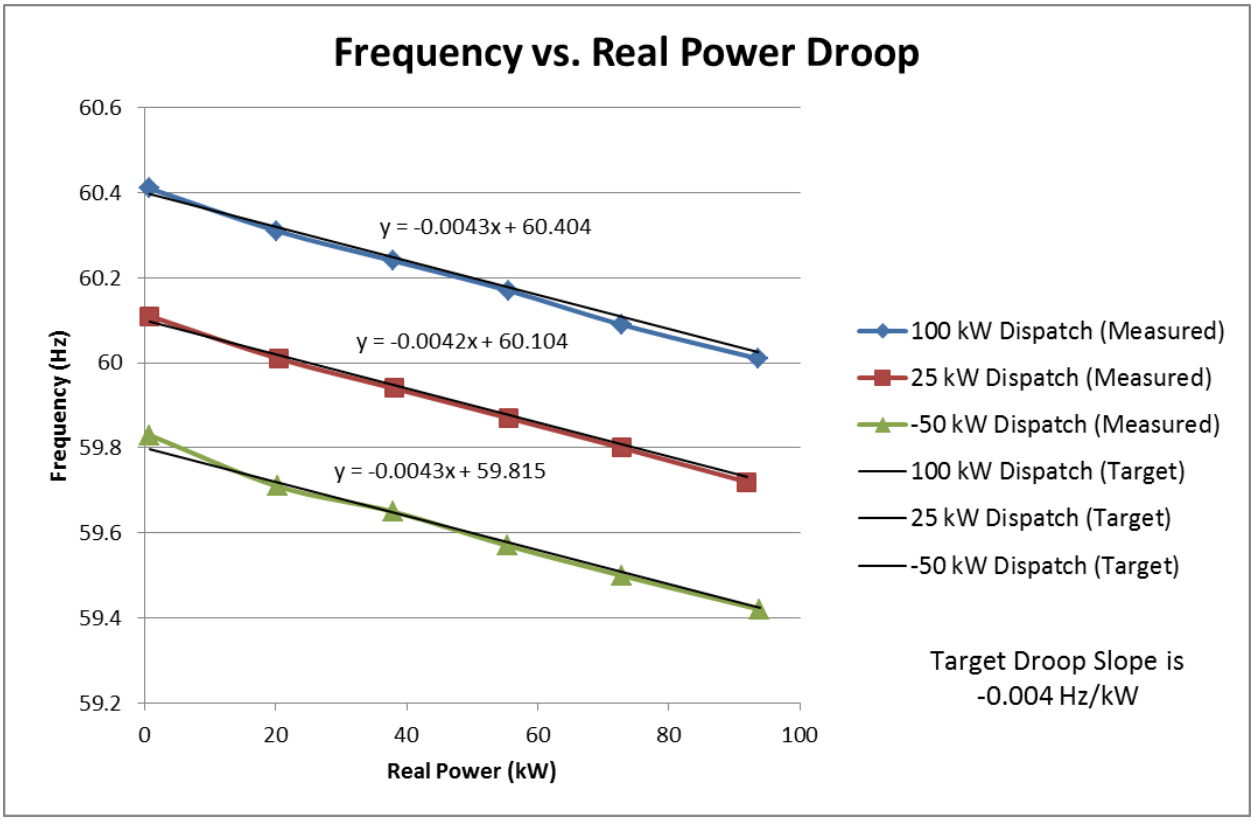

Figure 67: Frequency vs. Real Power Droop Control

Figure 68 compares the measured voltage and real power results at three different dispatch points. The equations for the trend lines of the measured values are displayed. The voltage control is shown to be properly decoupled from the real power. At all three real power dispatch points there is a slight increase in voltage as the load increases. This is most likely due to the value for the transformer impedance that is modelled in the ESS's inverter which appears to be slightly too high. A smaller value should produce a more flat voltage response.

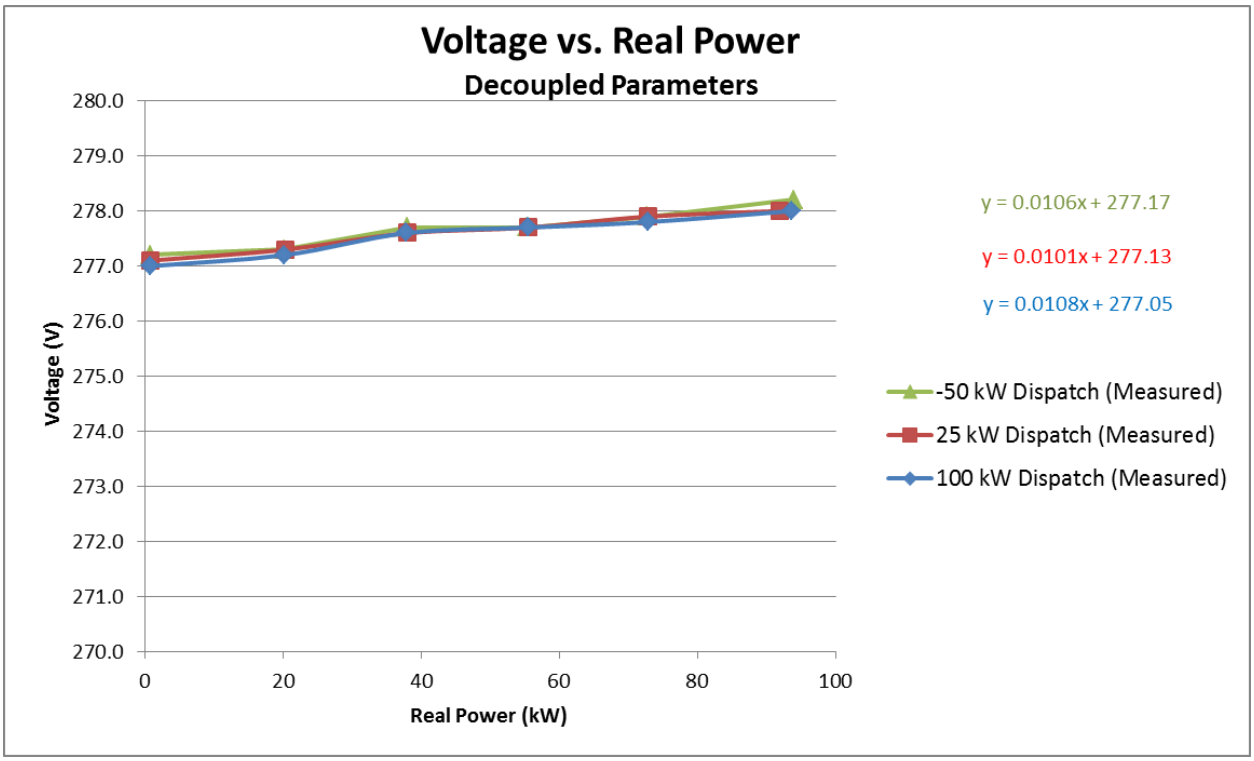

Figure 68: Voltage vs. Real Power - Decoupled Parameters

5.6 Voltage vs. Reactive Power Droop Control – Stand Alone

Performance Goal

Verify the Voltage vs. Reactive Power Droop is properly implemented in the ESS. Determine whether the Frequency vs. Real Power and the Voltage vs. Reactive Power Controllers are properly decoupled by evaluating the frequency as function of reactive power.

Description of Procedure

The ESS is dispatched to 0 kW, 1% Frequency Droop, three different voltage values over these tests ranging from 95% to 105% of nominal (456 V_{LL}, 480 V_{LL}, and 504 V_{LL}), 5% Voltage Droop and operated islanded from the utility. The ESS is started and connected to the islanded microgrid electrical bus. At the various voltage dispatch values, a series of 20 kVAr step loads are applied. At each load value the reactive power, voltage, and frequency is measured.

Test Settings

ESS parameters are set as follows:
Pdispatch = 0 kW
Frequency Droop = 1% or -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)

AC Power Limit = 105 kW
Voltage Droop = 5% or -0.24 V_{LL}/kVAr
Voltage Dispatch = Varies: 456 V_{LL}, 480 V_{LL}, and 504 V_{LL} equivalent to 263 V_{LN}, 277 V_{LN}, and 291 V_{LN}. *
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V.

Table 12 below lists the test cases. Load bank and total load transitions are indicated with an arrow (→).

Test Event	Generator B1	GIS	Load Bank 3 (kVAr)	Load Bank 4 (kVAr)	Total Load (kVAr)
A	Dispatch = 0 kW Voltage = 480 V_{LL}	Open	0	0	0
B	Dispatch = 0 kW Voltage = 480 V_{LL}	Open	0→20	0	0→20
C	Dispatch = 0 kW Voltage = 480 V_{LL}	Open	20→40	0	20→40
D	Dispatch = 0 kW Voltage = 480 V_{LL}	Open	40→60	0	40→60
E	Dispatch = 0 kW Voltage = 480 V_{LL}	Open	60	0→20	60→80
F	Dispatch = 0 kW Voltage = 480 V_{LL}	Open	60	20→40	80→100
G	Dispatch = 0 kW Voltage = 504 V_{LL}	Open	0	0	0
H	Dispatch = 0 kW Voltage = 504 V_{LL}	Open	0→20	0	0→20
I	Dispatch = 0 kW Voltage = 504 V_{LL}	Open	20→40	0	20→40
J	Dispatch = 0 kW Voltage = 504 V_{LL}	Open	40→60	0	40→60
K	Dispatch = 0 kW Voltage = 504 V_{LL}	Open	60	0→20	60→80
L	Dispatch = 0 kW Voltage = 504 V_{LL}	Open	60	20→40	80→100
M	Dispatch = 0 kW Voltage = 456 V_{LL}	Open	0	0	0
N	Dispatch = 0 kW Voltage = 456 V_{LL}	Open	0→20	0	0→20
O	Dispatch = 0 kW Voltage = 456 V_{LL}	Open	20→40	0	20→40
P	Dispatch = 0 kW Voltage = 456 V_{LL}	Open	40→60	0	40→60
Q	Dispatch = 0 kW Voltage = 456 V_{LL}	Open	60	0→20	60→80
R	Dispatch = 0 kW Voltage = 456 V_{LL}	Open	60	20→40	80→100

Table 12: Voltage vs. Reactive Power Droop Control Test Cases

Test Results

Table 13 below summarizes the results of voltage versus reactive power droop control tests including reactive power, voltage, and frequency for all events. Note that Events F, L, and R are not able to be executed. Each of these required Load Bank 4 to perform a load step from 20 kVAr to 40 kVAr. At the time of these tests Load Bank 4 was not able to perform this load step. Those events were intended to transition the total load on the ESS from 80 kVAr to 100 kVAr.

Test Event	ESS Reactive Power Observed (kVAr)	Energy Storage System Voltage (V)		Voltage Error	Frequency (Hz)	Pass/Fail
		Target	Measured			
A	1.37	276.94	277.4	0.17%	59.99	Pass
B	20.29	274.32	274.5	0.07%	59.99	Pass
C	40.14	271.57	271.6	0.01%	59.99	Pass
D	57.40	269.17	269.2	-0.01%	59.98	Pass
E	76.17	266.57	266.7	0.05%	59.97	Pass
F						
G	2.47	290.64	290.1	0.09%	59.99	Pass
H	23.28	287.76	287.6	-0.06%	59.99	Pass
I	45.05	284.74	284.6	-0.05%	59.98	Pass
J	63.91	282.13	282.0	-0.05%	59.97	Pass
K	81.98	279.63	279.2	-0.15%	59.97	Pass
L						
M	0.57	263.19	263.6	0.15%	59.99	Pass
N	17.83	260.80	261.3	0.19%	59.99	Pass
O	35.77	258.32	258.6	0.11%	59.99	Pass
P	51.48	256.14	256.3	0.06%	59.98	Pass
Q	66.75	254.02	254.1	0.03%	59.98	Pass
R						

Table 13: Voltage vs. Reactive Power Droop Control

Analysis

The Voltage vs. Reactive Power Controller performs within acceptable limits. The voltage error ranges from -0.15% to 0.19%. The target droop slope is -0.1386 V_{LN}/kVAr (equivalent to -0.24 V_{LL}/kVAr) and the average measured droop slope is -0.1443 V_{LN}/kVAr which is a difference of 4.1%.

Figure 69 compares the measured voltage and reactive power results with the target values at three different dispatch points. The equations for the trend lines of the measured values are displayed. The Voltage vs. Reactive Power Droop controller is shown to be well behaved.

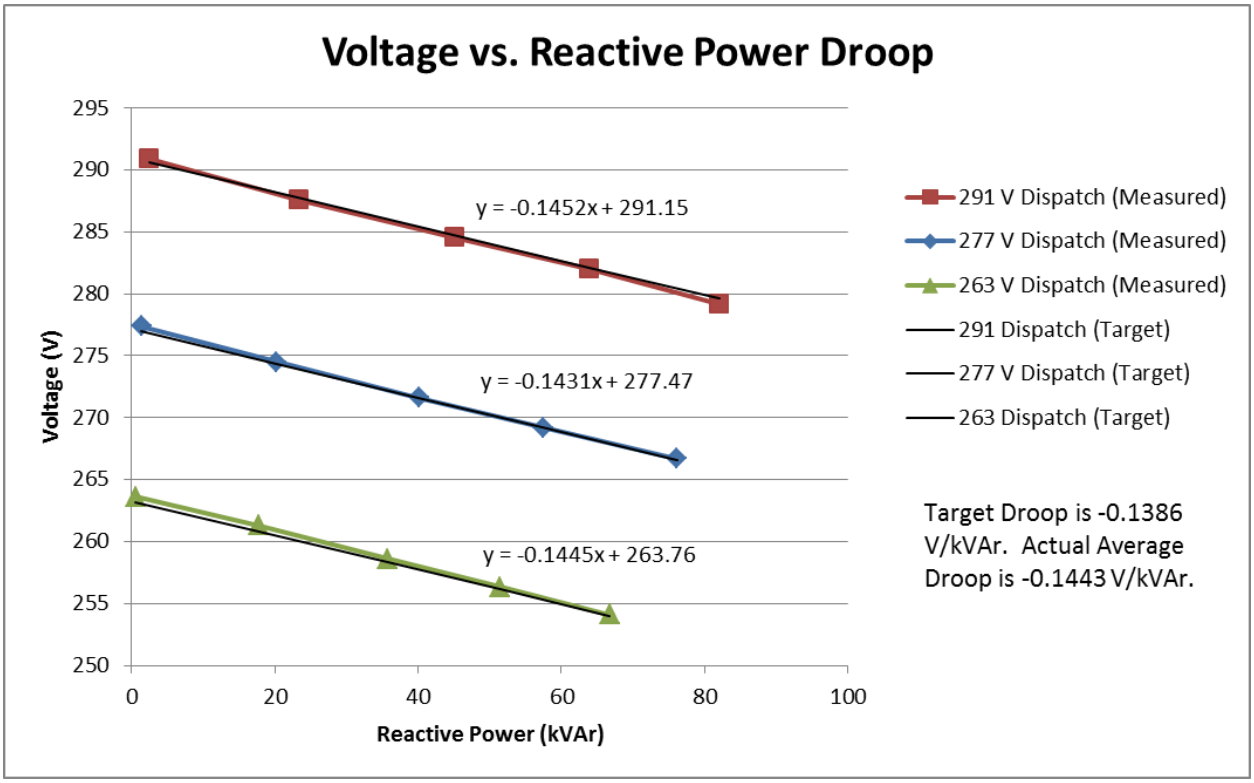

Figure 69: Voltage vs. Reactive Power Droop Control

Figure 70 compares the measured frequency and reactive power results at three different dispatch points. The equations for the trend lines of the measured values are displayed. The frequency control is shown to be properly decoupled from the reactive power. At all three voltage dispatch points there is a slight decrease in frequency as the reactive load increases. This is most likely due to the real power losses in the system as they would be slightly increasing as the reactive load and thus current are increasing (i.e. I^2R losses in the conductors are increasing with reactive load increases).

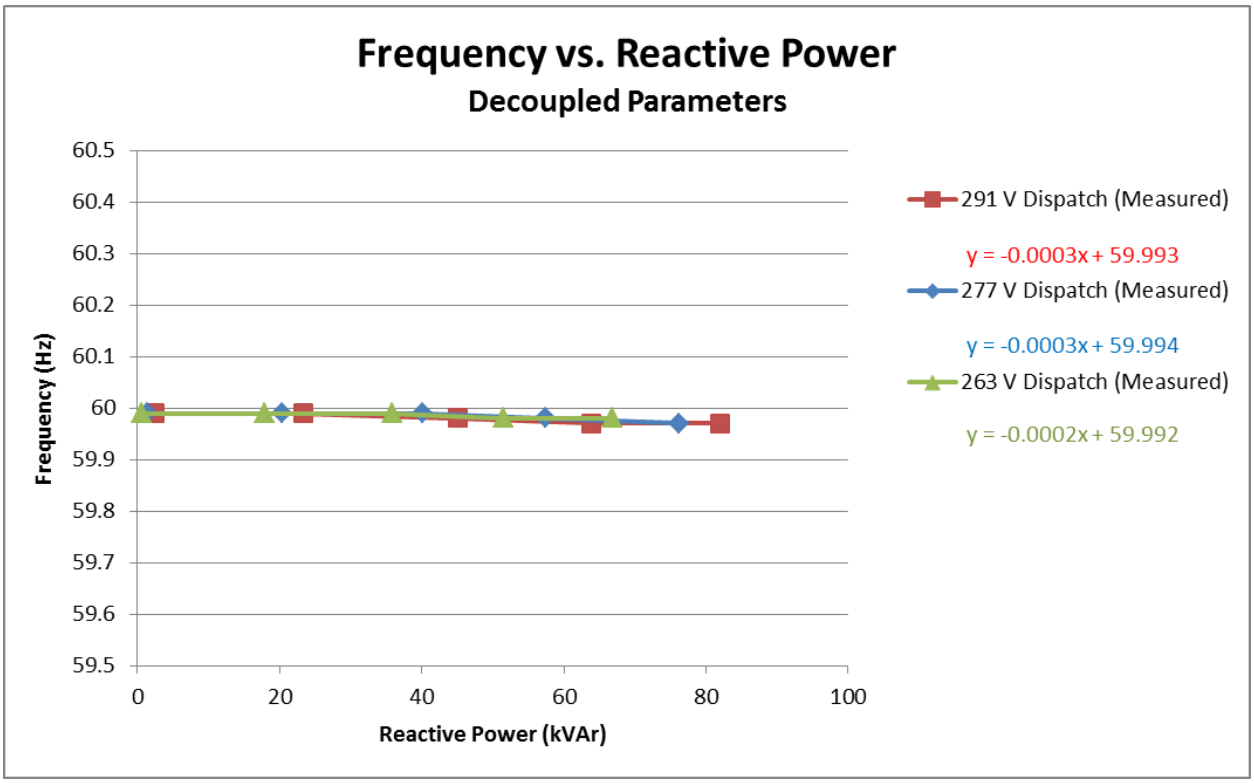

Figure 70: Frequency vs. Reactive Power - Decoupled Parameters

5.7 Unbalanced Load - Stand Alone

Performance Goal

Verify smooth operation of the ESS response to an unbalanced load condition. Confirm proper power calculation for the frequency vs. real power droop controller. Quantify the harmonic content on the voltage waveform.

Description of Procedure

The ESS is dispatched to 0 kW, 1% Frequency Droop, three different voltage values over these tests ranging from 95% to 105% of nominal (456 V_{LL}, 480 V_{LL}, and 504 V_{LL}), 5% Voltage Droop and operated islanded from the utility. The ESS is started and connected to the islanded microgrid electrical bus. At the various voltage dispatch values, a series of 20 kVAr step loads are applied. At each load value the reactive power, voltage, and frequency is measured.

Test Settings

ESS parameters are set as follows:
$P_{dispatch}$ = Varies (0 kW or 90 kW to match initial load conditions)
Frequency Droop = 1% or -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)
AC Power Limit = 105 kW

Voltage Droop = 5% or -0.24 V/kVAr
Voltage Dispatch = 480 V_{LL} [Inverter Voltage Reference = 102.5 per PPS*]
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V.

Table 14 below lists the test cases. Load bank and total load transitions are indicated with an arrow (→).

Test Event	$P_{dispatch}$ (kW)	Load Bank 5 (kW)	Total (kW)
A	0	ΦA: 0 ΦB: 0 ΦC: 0	0
B	90	ΦA: 30 ΦB: 30 ΦC: 30	90
C	90	ΦA: 30 → 0 ΦB: 30 ΦC: 30	90 → 60
D	90	ΦA: 30 ΦB: 30 → 0 ΦC: 30	90 → 60
E	90	ΦA: 30 ΦB: 30 ΦC: 30 → 0	90 → 60
F	90	ΦA: 30 → 0 ΦB: 30 → 0 ΦC: 30	90 → 30
G	90	ΦA: 30 ΦB: 30 → 0 ΦC: 30 → 0	90 → 30
H	90	ΦA: 30 → 0 ΦB: 30 ΦC: 30 → 0	90 → 30

Table 14: Unbalanced Load Test Cases

Test Results

Table 15 below summarizes the results of unbalanced load tests including real power, frequency, and voltage THD for all events.

Test Event	$P_{dispatch}$ (kW)	Phase	Initial Load (kW)		Final Load (kW)		Frequency (Hz)			Voltage THD (%)[2]		Pass/Fail
			Per Phase	Total	Per Phase	Total	Initial[1]	Final[1] (Measured)	Final (Expected)	Initial	Final	
A	0	A	-0.22	-0.14	-0.22	-0.14	60.00	60.00	60.00	3.17	3.19	Pass
		B	0.08		0.08					2.7	2.67	
		C	0.00		0.00					3.06	3.06	
B	90	A	-28.51	-85.66	-28.43	-85.48	60.00	60.00	60.02	0.83	0.85	Pass
		B	-28.75		-28.70					1.06	1.08	
		C	-28.40		-28.34					0.88	0.87	
C	90	A	-27.96	-83.76	-0.33	-52.81	60.00	60.16	60.15	0.87	2.8	Pass
		B	-28.13		-28.52					1.13	1.45	
		C	-27.66		-23.96					0.89	1.35	
D	90	A	-28.49	-85.29	-24.37	-52.93	60.00	60.16	60.15	0.89	1.42	Pass
		B	-28.69		0.03					1.08	2.83	
		C	-28.12		-28.59					0.83	1.78	
E	90	A	-28.46	-85.34	-28.75	-53.22	60.00	60.17	60.15	0.89	1.86	Pass
		B	-28.80		-24.45					1.09	1.78	
		C	-28.08		-0.02					0.84	2.72	
F	90	A	-27.92	-83.81	-0.28	-24.62	60.00	60.26	60.26	0.88	1.64	Pass
		B	-28.17		0.08					1.13	2.82	
		C	-27.72		-24.42					0.87	2.15	
G	90	A	-28.28	-84.73	-24.55	-24.54	60.00	60.25	60.26	0.9	2.28	Pass
		B	-28.53		0.03					1.07	2.79	
		C	-27.92		-0.02					0.85	3.21	
H	90	A	-27.96	-83.81	-0.26	-24.64	60.00	60.25	60.26	0.92	3.77	Pass
		B	-28.20		-24.37					1.12	1.92	
		C	-27.65		-0.01					0.88	2.61	

Phases involved in load reduction.

1. Frequency measurements made using the Yokogawa 850DL scope recorder.
2. THD determined using PQView 12 Cycle Window.

Table 15: Unbalanced Load Test Results

Analysis

The ESS functions within acceptance criteria demonstrating the ability to smoothly transition to an unbalanced load condition in an islanded state. The system settles at a new frequency based on the total real power delivered by the ESS. The THD of the voltage waveform on the microgrid bus remains below 4%.

Figure 71 through Figure 76 show results from Test Event H, a transition from 90 kW balanced load to 30 kW on phase B. The RMS voltage, Figure 71, shows a voltage swell of 17.3% on phase A. The transient settles to a steady state approximately 0.9 seconds after the event. A steady state voltage unbalance of 8.2% results.

The frequency vs. time plot,

Figure 74, shows an initial frequency of 60.00 Hz and a final frequency of 60.25 Hz which agree well with the expected values of 60.02 Hz and 60.26 Hz respectively. The frequency transitions to its steady state value in 0.15 seconds or 9 cycles.

The steady state measured frequency is compared to the expected frequency for each event in Figure 75. The measured frequency agrees well with the expected values in all cases and does not deviate more than 0.02 Hz from the expected value.

The voltage THD response to each unbalanced load event is shown Figure 76. IEEE 519 recommends that the voltage THD, in general, remains below 5% at the point of common coupling with the utility. In all cases the voltage THD remains below 4% on the microgrid bus.

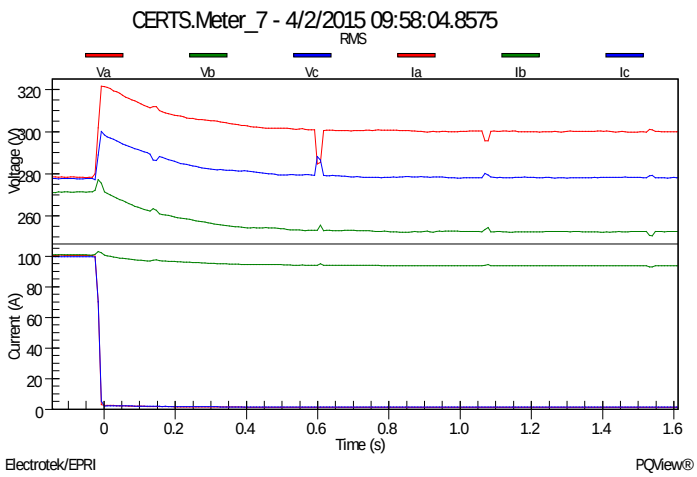

Figure 71 Event H, Unbalanced Load, RMS Voltage and Current, 90 kW to 30 kW, dropping phases A & C.

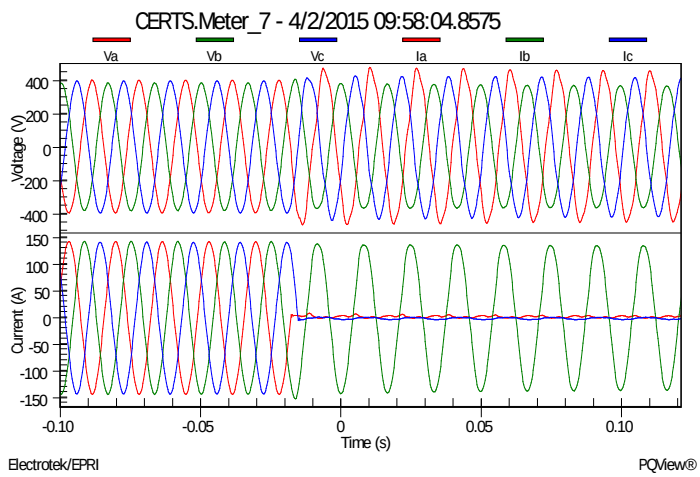

Figure 72 Event H, Unbalanced Load, Waveform Voltage and Current, 90 kW to 30 kW, dropping phases A & C.

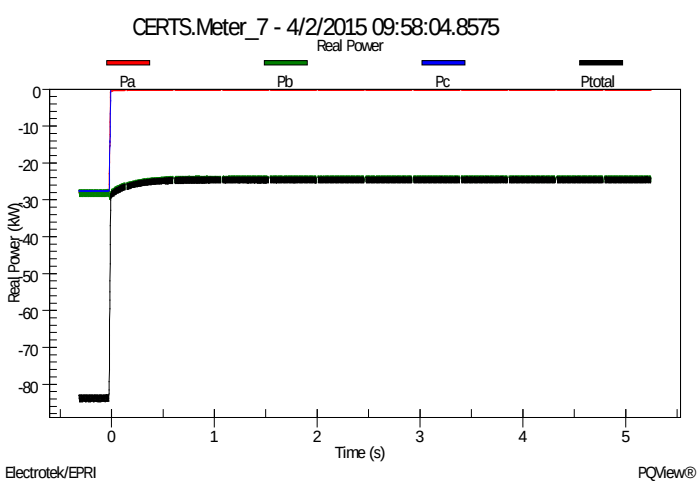

Figure 73 Event H, Unbalanced Load, Real Power, 90 kW to 30 kW, dropping phases A & C.

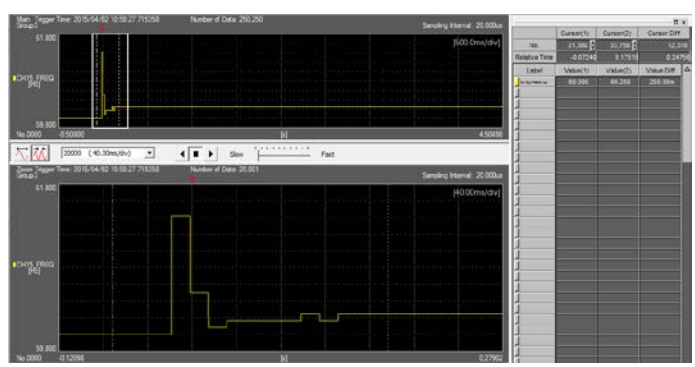

Figure 74 Event H, Unbalanced Load, Frequency, 90 kW to 30 kW, dropping phases A & C.

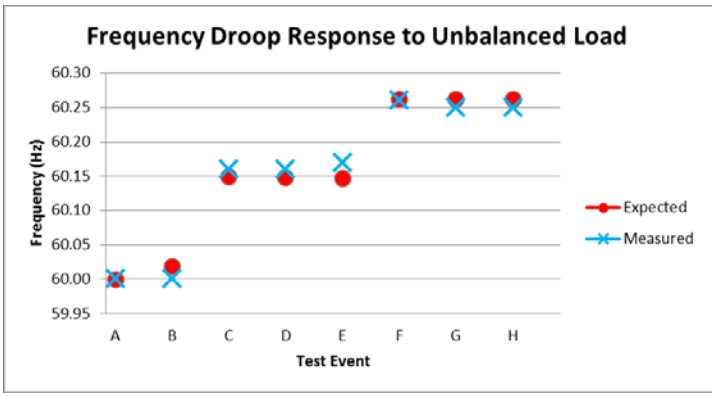

Figure 75 Frequency Droop Response to Unbalanced Load Conditions.

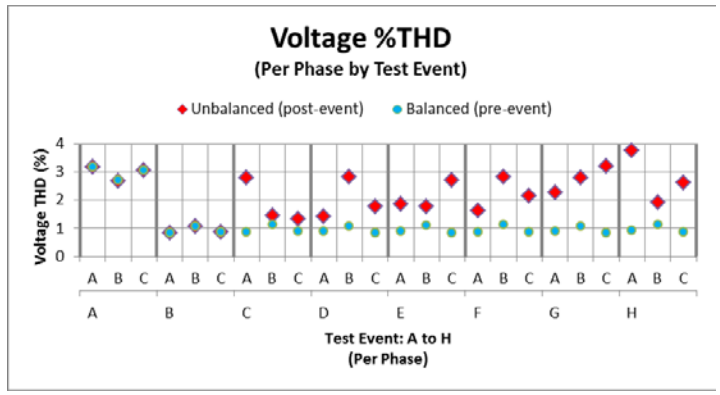

Figure 76 Voltage THD Response to Unbalanced Load Conditions.

5.8 Pmax Control – Stand Alone

Performance Goal

The intent of this testing is to ensure proper implementation of the CERTS P_{max} function. The P_{max} function is activated when the DER is operating at its limit of real power capability. This function responds to an overload condition by driving the output frequency down to allow other CERTS DERs in the microgrid the opportunity to pick up additional load and relieve the overloaded unit(s). The DER should demonstrate a predictable adjustment in frequency when the real power it is producing exceeds its P_{max} setting.

Description of Procedure

This test is performed by setting the P_{max} set point lower than its real power rating. For these tests P_{max} is set to 10 kW instead of 100 kW. The ESS is then loaded to various real power levels above P_{max} causing the P_{max} function to activate. This will allow investigation of the P_{max} controller separate from the ESS's ability and characteristics of serving such significant overloads. In addition, the ESS will be loaded to reactive power levels above P_{max}. In these cases the P_{max} functionality should not be activated.

The ESS is dispatched to 10 kW, 1% Frequency Droop, 480 V_{LL}, 5% Voltage Droop and operated islanded from the utility. The ESS is started and connected to the islanded microgrid electrical bus. Various real and reactive step loads are applied. At each load value the real power and frequency will be measured.

Test Settings

ESS parameters are set as follows:
$P_{dispatch}$ = 10 kW
Frequency Droop = 1% or -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 10 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)
AC Power Limit = 105 kW
Voltage Droop = 5% or -0.24 V/kVAr

Voltage Dispatch = 480 V_{LL} [Inverter Voltage Reference = 102.5 per PPS*]
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V.

Table 16 below lists the test cases. Load bank and total load transitions are indicated with an arrow (→).

Test Event	$P_{dispatch}$ (kW)	P_{max} (kW)	GIS	Load Bank 3	Load - P_{max}
A	10	10	Open	0→20 kW	10 kW
B	10	10	Open	0→30 kW	20 kW
C	10	10	Open	0→50 kW	40 kW
D	10	10	Open	0→70 kW	60 kW
E	10	10	Open	0→90 kW	80 kW
F	10	10	Open	0→30 kVAr	(-10+j30) kVA
G	10	10	Open	0→60 kVAr	(-10+j60) kVA

Table 16: Pmax Control Test Cases, ESS Stand Alone

Test Results

Table 17 below summarizes the results of the CERTS P_{max} tests including real power and frequency for all events.

Test Event	$P_{dispatch}$ (kW)	P_{max} (kW)	Step Load (kVA)	Pre-event		Post-event		P_{max}: Freq Slope (Hz/s)	P_{final}-P_{max} (kW)	P_{max} Activated	Pass/ Fail
				Real P (kW)	Freq (Hz)	Real P (kW)	Freq (Hz)				
A	10	10	0→20	0.10	59.96	18.67	50.03	-4.05	8.67	Yes	Pass
B	10	10	0→30	0.12	60.03	28.19	50.02	-6.43	18.19	Yes	Pass
C	10	10	0→50	0.12	60.03	46.42	50.03	-10.86	36.42	Yes	Pass
D	10	10	0→70	0.13	60.03	64.08	50.01	-16.49	54.08	Yes	Pass
E	10	10	0→90	0.14	60.03	81.52	50.02	-22.78	71.52	Yes	Pass
F	10	10	0→j30	0.14	60.03	1.67	60.03	n/a	-8.33	**No**	Pass
G	10	10	0→j60	0.13	60.03	2.93	60.03	n/a	-7.07	**No**	Pass

Table 17: Pmax Control Test Results, ESS Stand Alone

Analysis

The ESS functions within acceptance criteria demonstrating the ability to respond quickly and smoothly to a condition where P_{max} is exceeded. During the stand alone test when the load's real power exceeds the P_{max} set point the ESS responds with a gradual reduction in frequency to the minimum frequency set point of the inverter, 50 Hz for these tests. The 50 hz limit is not part of the CERTS algorithm which would otherwise allow for a continuous decline in frequency. The 50 Hz minimum frequency is a limit of the inverter. Under-frequency relays are not enabled during these tests. The P_{max} functionality is properly activated only when the real power output exceeds the P_{max} set point. As expected, the P_{max}

functionality is not activated on reactive power. This demonstrates proper dependence only on the real power load.

The RMS voltage is seen to vary significantly from approximately 250 Vrms to 310 Vrms in Figure 81 and Figure 86. This occurs after the P_{max} functionality is activated and the frequency drops below 59 Hz. A similar variation in the peak voltage is not exhibited when looking at the voltage waveforms. Neither is a significant change in the voltage waveforms apparent when examining them visually. The RMS voltage is examined in a separate software package, Yokogawa's Xviewer, using voltage data collected from the Yokogawa 850DL ScopeCorder and found not to exhibit wide variations in the RMS voltage. When the RMS voltages as provided by the PQView software from each phase are average at each time stamp the resulting plot indicates a very stable RMS voltage without the significant swings. It appears that the RMS voltage swings indicated in the PQView plots are an artifact of either the ION meter data collection or the processing of the data in PQView.

The frequency response for Events A through E is shown in Figure 77. The frequency response's slope increases as the amount of load in excess of P_{max} increases. The responses are linear however there is a detectable change in slope (knee) for each Event B through E (20 kW to 80 kW above P_{max}). The knee would appear to be a result of the PI controller where the proportional response is the first part of the slope and the integral response is the second part of the slope. Also, there appears to be a delay in the activation of P_{max} for Events A & B (10 kW and 20 kW over P_{max}) of approximately 165 ms and 89 ms respectively. The delay settles out at about 17 ms for Events D and E.

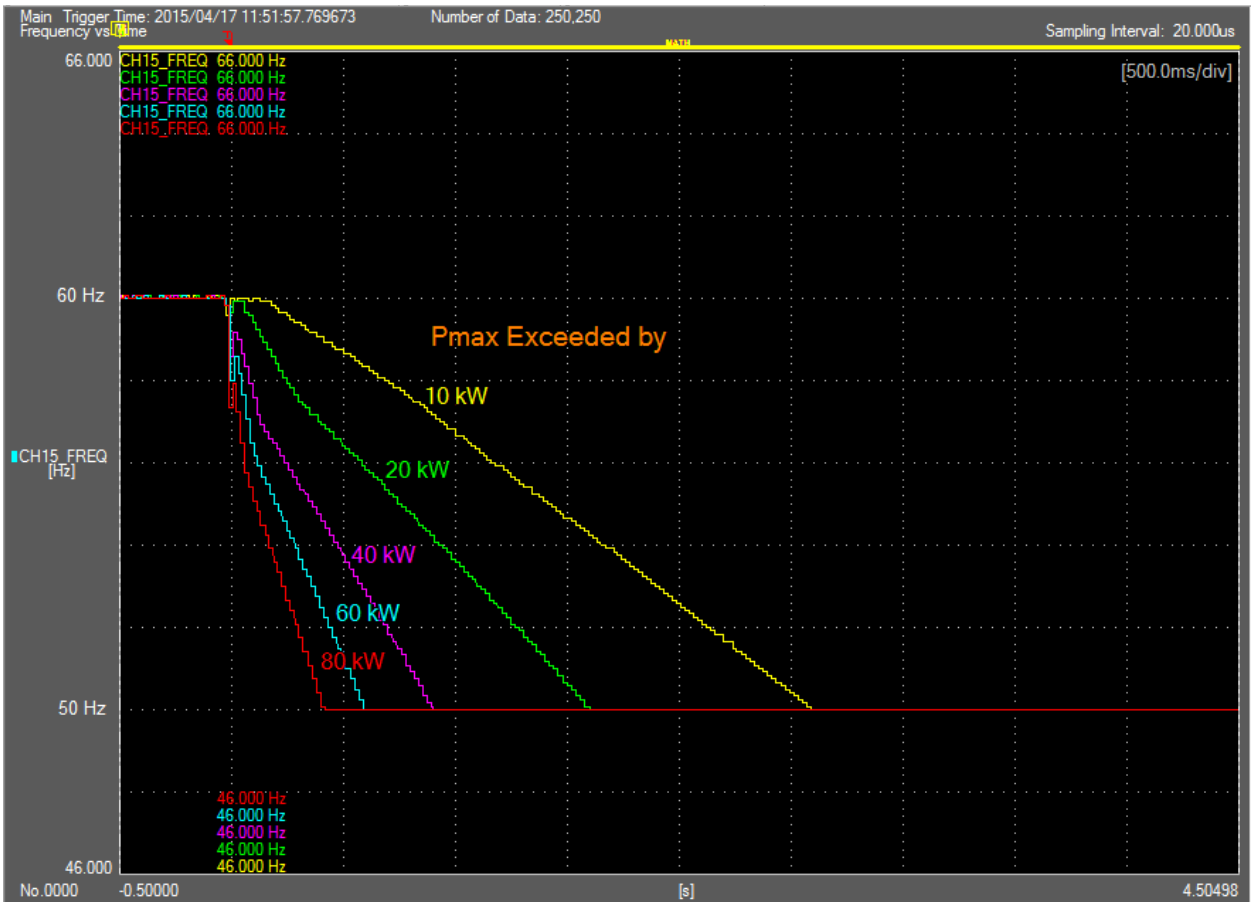

Figure 77: Events A to E, Frequency Response to Pmax Being Exceeded

Figure 78 shows the average slope for each frequency response as a function of the load amount in excess of P_{max}. The slope is seen to be approximately linearly proportional to the amount of load over the P_{max} set point with the slope of the trend line being 0.314 Hz/(s*kW).

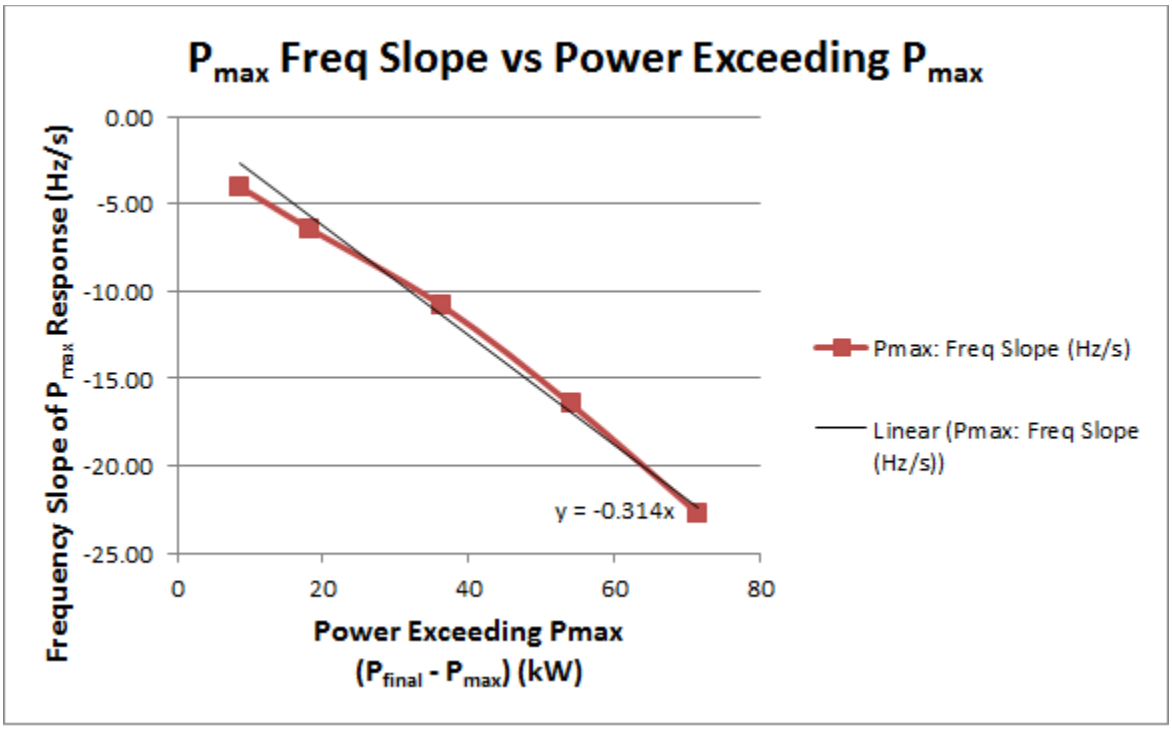

Figure 78: Events A to E, Pmax Average Frequency Slope vs. Power Exceeding Pmax Setting

Figure 79 through Figure 83 show the results of Event A, where the P_{max} set point is 10 kW and a step load of 0 kW to 20 kW is applied. The frequency response has a slope of -4.05 Hz/s and reaches the steady state frequency of 50 Hz in about 2.5 seconds. The ESS would continue to operate at this frequency until the load falls below the P_{max} set point or the unit is shut down. Under normal conditions an under-frequency relay would trip the unit.

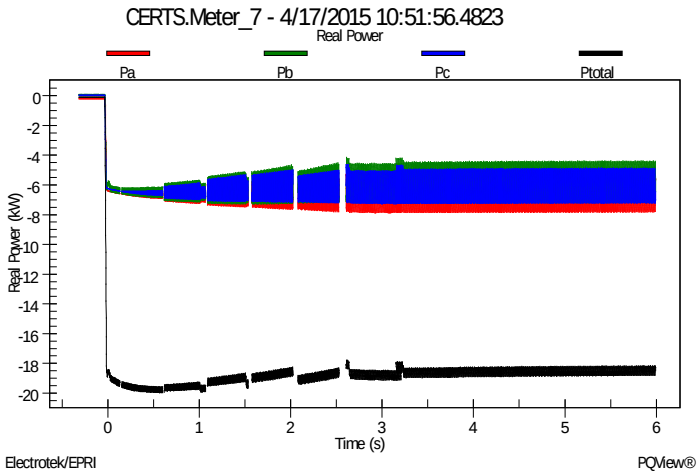

Figure 79: Event A, Pmax Exceeded by 10 kW, Real Power

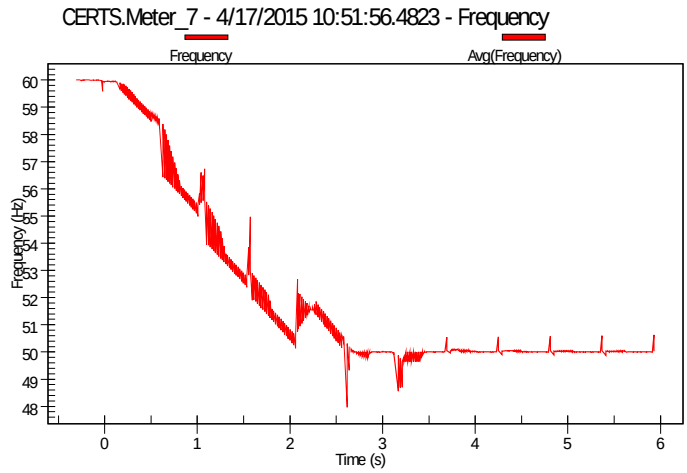

Figure 80: Event A, Pmax Exceeded by 10 kW, Frequency

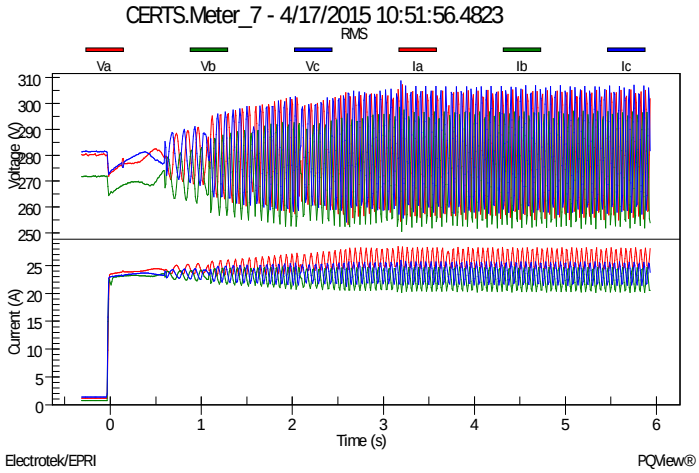

Figure 81: Event A, Pmax Exceeded by 10 kW, RMS Voltage & Current

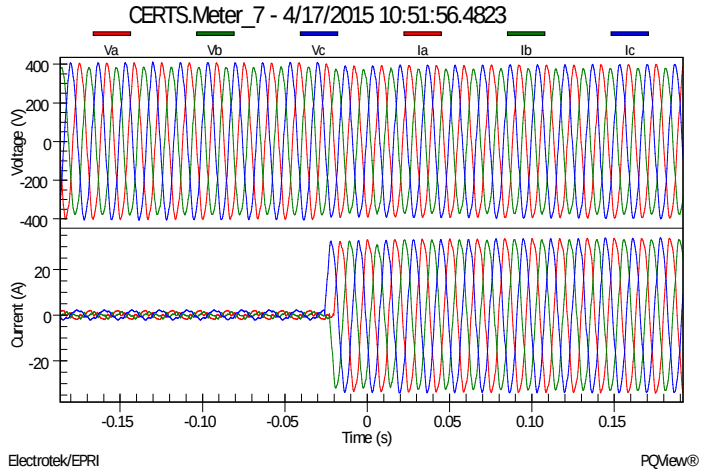

Figure 82: Event A, Pmax Exceeded by 10 kW, Waveform Voltage & Current Zoomed

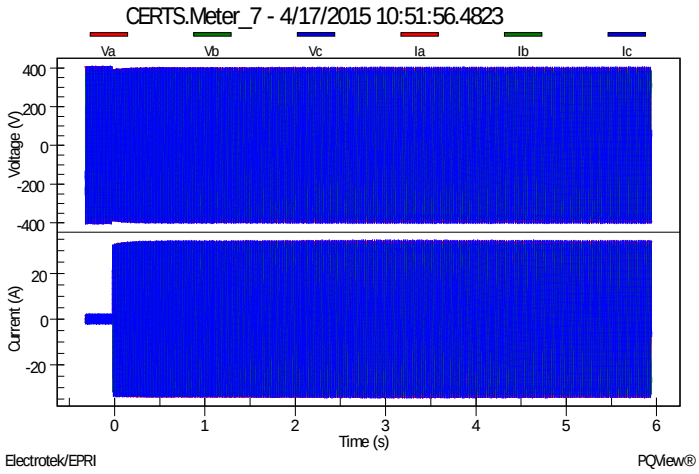

Figure 83: Event A, Pmax Exceeded by 10 kW, Waveform Voltage & Current

Figure 84 through Figure 88 show the results of Event D, where the P_{max} set point is 10 kW and a step load of 0 kW to 70 kW is applied. The frequency response has a slope of -16.49 Hz/s and reaches the steady state frequency of 50 Hz in about 0.6 seconds. The ESS would continue to operate at this frequency until the load falls below the P_{max} set point or the unit is shut down. Under normal conditions an under-frequency relay would trip the unit.

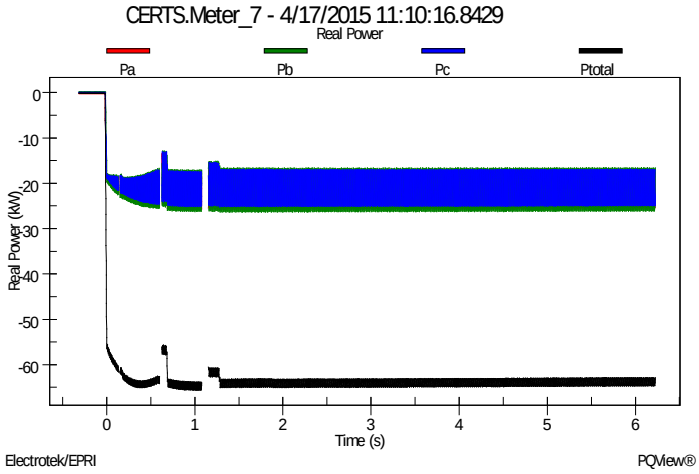

Figure 84: Event D, Pmax Exceeded by 60 kW, Real Power

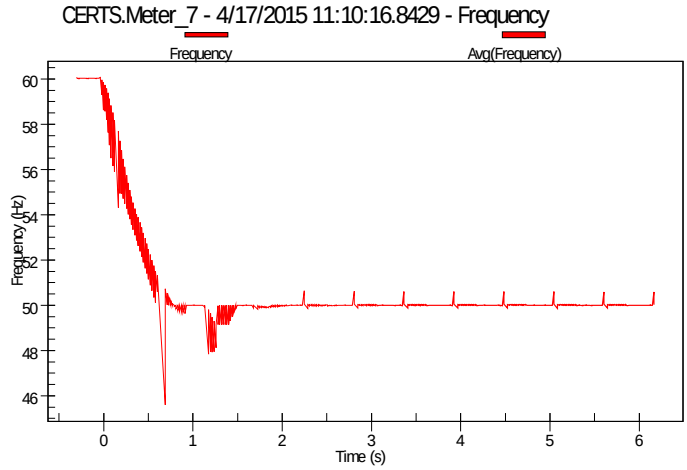

Figure 85: Event D, Pmax Exceeded by 60 kW, Frequency

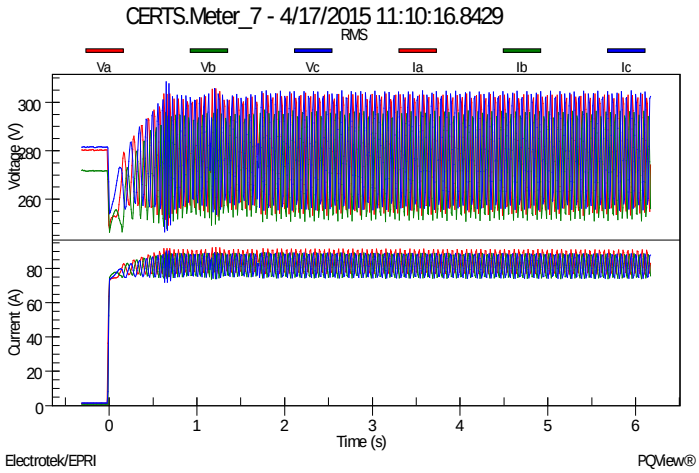

Figure 86: Event D, Pmax Exceeded by 60 kW, RMS Voltage & Current

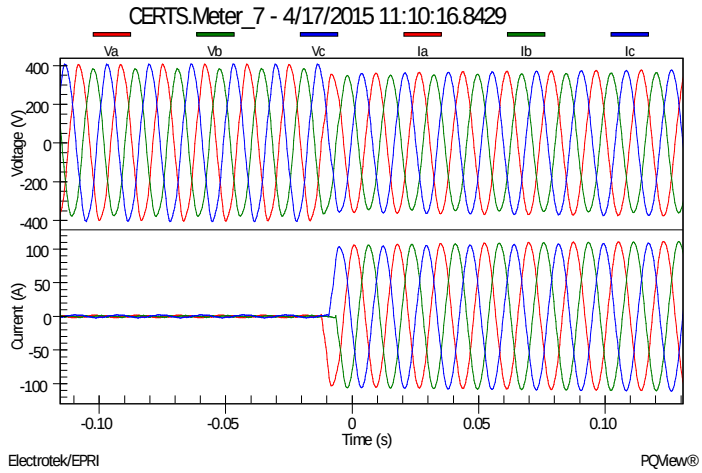

Figure 87: Event D, Pmax Exceeded by 60 kW, Waveform Voltage & Current Zoomed

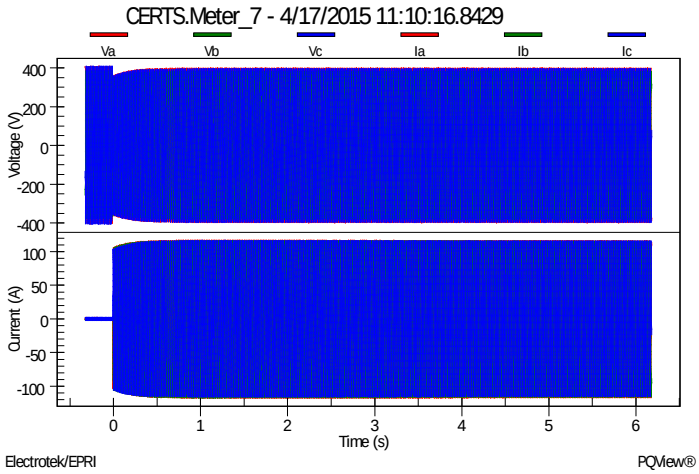

Figure 88: Event D, Pmax Exceeded by 60 kW, Waveform Voltage & Current

Figure 89 through Figure 93 show the results of Event G, where the P_{max} set point is 10 kW and a step load of 0 to 60 kVAr is applied. There is an initial spike in the real power which decays to 2.93 kW and accounts for the losses in supplying the reactive power. As expected, the P_{max} functionality is not activated since only a reactive load is applied and the real power remains below the P_{max} set point.

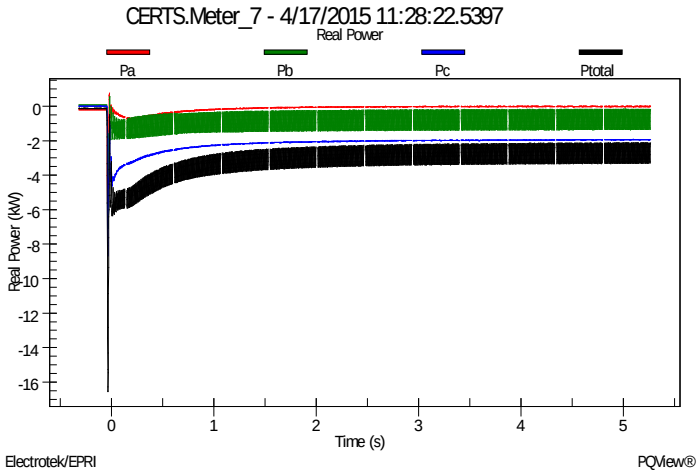

Figure 89: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, Real Power

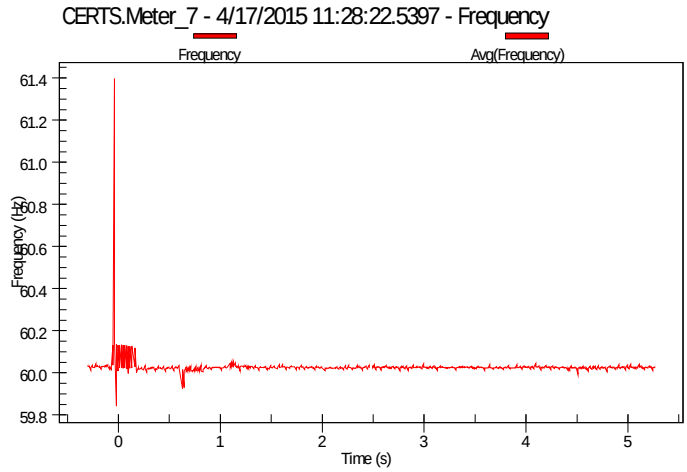

Figure 90: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, Frequency

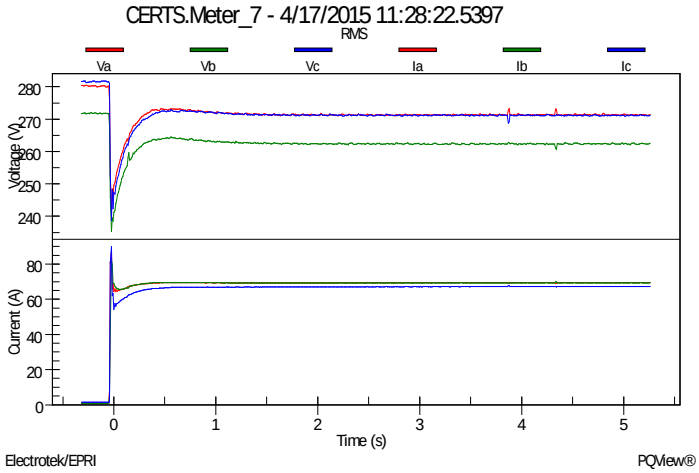

Figure 91: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, RMS Voltage & Current

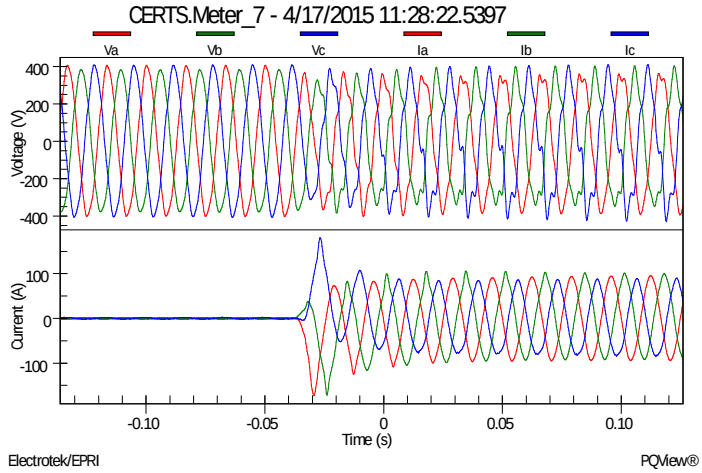

Figure 92: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, Waveform Voltage & Current (Zoomed)

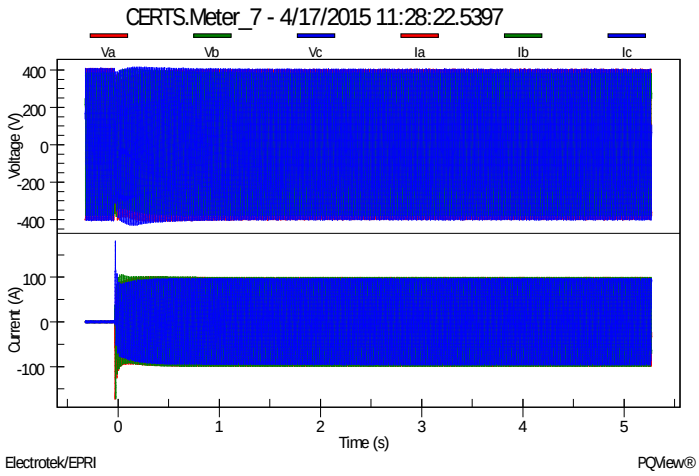

Figure 93: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, Waveform Voltage & Current

5.9 Pmin Control – Stand Alone

Performance Goal

The intent of this testing is to ensure proper implementation of the CERTS P_{min} function. The P_{min} function is activated when the DER is operating at its lower limit of real power capability. This function responds to a minimum load condition by driving the output frequency up to allow other CERTS DERs in the microgrid the opportunity to shed additional sourcing responsibilities and allow the microgrid to achieve a stable operating condition. The DER should demonstrate a predictable adjustment in frequency when the real power it is producing reaches its P_{min} setting.

Description of Procedure

This test is performed by setting the P_{min} set point higher than the ESS's minimum real power rating. For these tests P_{min} will be set to 80 kW or 10 kW instead of -50 kW. A declining step load is applied resulting in a transition from a real power load above P_{min} to a real power load below P_{min}. This should result in activation of the P_{min} functionality. This will allow investigation of the P_{min} controller separate from the ESS's ability and characteristics of serving loads at its minimum boundary. In addition, the ESS will be loaded with both real and reactive power levels above P_{min} and then have the real power lowered below P_{min} while leaving the reactive power greater than P_{min}. In these cases the P_{min} functionality should be activated.

The ESS is dispatched to 90 kW, 1% Frequency Droop, 480 V_{LL}, 5% Voltage Droop and operated islanded from the utility. P_{min} is set to either 80 kW or 10 kW depending on the test case. The ESS is started and connected to the islanded microgrid electrical bus. Various real and reactive step loads are applied. At each load value the real power and frequency is measured.

Test Settings

For these tests the following parameters are set as follows:

$P_{dispatch}$ = 90 kW

Frequency Droop = -.004 Hz/kW

P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)

P_{min} = Varies (80 kW or 10 kW) (P_{min} = Battery Power Limit Min parameter on inverter)

Voltage Set Point = 480 V (Inverter Voltage Reference = 102.5% per PPS)

Voltage Droop = -0.24 V/kVAr

Table 18 below lists the test cases. Load bank and total load transitions are indicated with an arrow (→).

Test Event	$P_{dispatch}$ (kW)	P_{min} (kW)	GIS	Load Bank 3	P_{min} - Load
A	90	80	Open	90→70 kW	10 kW
B	90	80	Open	90→60 kW	20 kW
C	90	80	Open	90→40 kW	40 kW
D	90	80	Open	90→20 kW	60 kW
E	90	80	Open	90→0 kW	80 kW
F	90	10	Open	20+j30→j30 kVA	(10-j30) kVA
G	90	10	Open	20+j60→j60 kVA	(10-j60) kVA

Table 18: Pmin Control Test Cases, ESS Stand Alone

Test Results

Table 19 below summarizes the results of the CERTS P_{min} tests including real power and frequency for all events.

Pmin Control Test Results, ESS Stand Alone												
Test Event	$P_{dispatch}$ (kW)	P_{min} (kW)	Step Load (kVA)	Pre-event		Post-event		P_{min}: Freq Slope (Hz/s)	P_{min}-P_{final} (kW)	P_{min} Activated	Pass/ Fail	Notes
				Real P (kW)	Freq (Hz)	Real P (kW)	Freq (Hz)					
A	90	80	90→70	82.81	60.09	57.16	69.98	5.09	22.84	Yes	Pass	
B	90	80	90→60	84.19	60.01	50.36	70.05	6.84	29.64	Yes	Pass	
C	90	80	90→40	83.44	60.3	33.53	70	10.51	46.47	Yes	Pass	
D	90	80	90→20	83.29	60.99	16.86	70.01	14.70	63.14	Yes	Pass	
E	90	80	90→0	81.69	59.99	0	-	n/a	n/a	-	Fail[1]	Inverter Tripped: IGBT Bridge Error
F	90	10	20+j30→j30	19.27	60.37	1.35	70.49	2.95	8.65	Yes	Pass	
G	90	10	20+j60→j60	19.49	60.44	2.33	70.01	2.48	7.67	Yes	Pass	
H	90	80	90→70	81.71	60.07	62.56	64.99	5.72	17.44	Yes	Pass	

1. This failure is not related to the CERTS algorithm but rather represents a limit of the operating capability of the inverter.

Table 19: Pmin Control Test Results, ESS Stand Alone

Analysis

The ESS functions within acceptance criteria demonstrating the ability to respond quickly and smoothly to a condition where the real power load falls below P_{min}. During the stand alone test when the real power load fell below the P_{min} set point the ESS responds with a gradual increase in frequency to the maximum frequency set point of the inverter, 70 Hz for these tests. Over-frequency relays are not enabled during these tests. The P_{min} functionality is not affected by reactive load demonstrating proper dependence only on the real power load.

Test Event E fails due to the ESS tripping as a result of the load step from 90 kW to 0 kW. This is a known issue with the inverter's inability to handle a declining load step of more than 85 kW and is documented earlier in the Load Step Response test case. This failure is not related to the CERTS algorithm but rather represents a limit of the operating capability of the inverter.

The frequency response for Events A through D is shown in Figure 94. The frequency response's slope increases as the amount of load below P_{min} increases. The responses are linear however there is a detectable change in slope (knee) for each Event B through D (20 kW to 60 kW below P_{min}). The knee would appear to be a result of the PI controller where the proportional response is the first part of the slope and the integral response is the second part of the slope. Also, there appears to be a delay in the activation of P_{min} for Event A (10 kW below P_{min}) of approximately 133 ms. A delay is not noticeable for the other events.

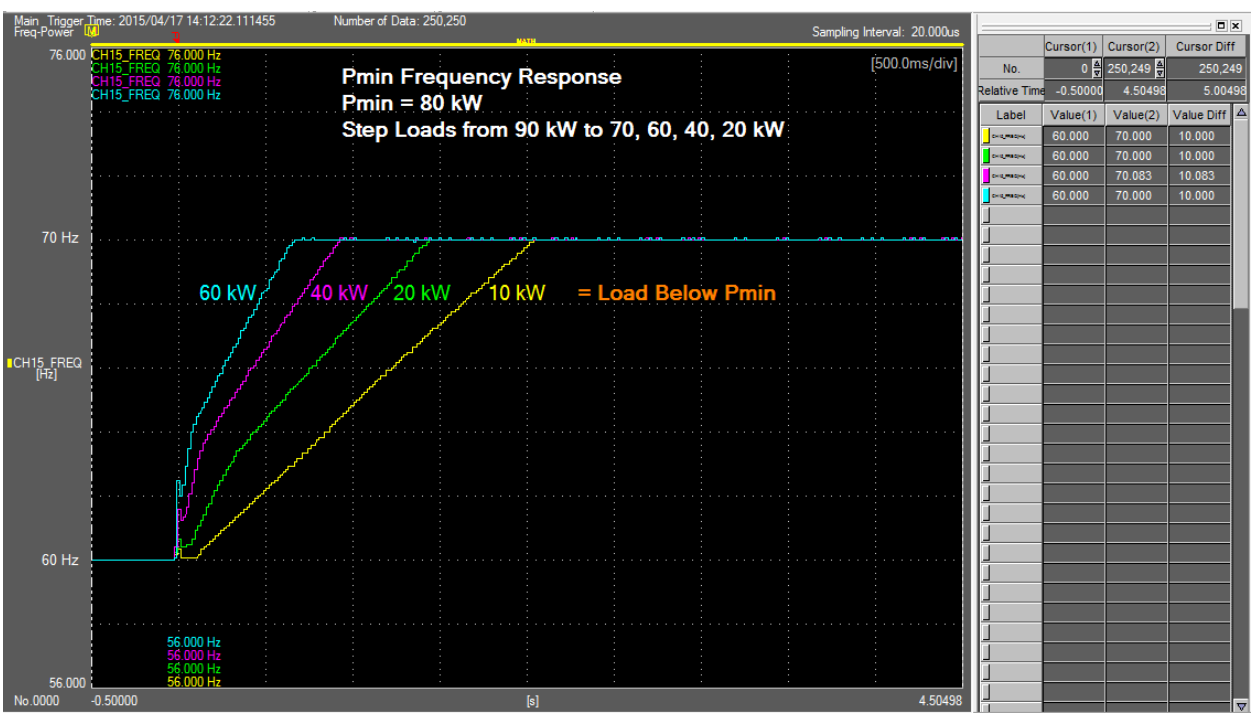

Figure 94: Events A to D, Frequency Response to Pmin Being Activated

Figure 95 shows the average slope for each frequency response as a function of the load below P_{min}. The slope is seen to be linearly proportional to the amount of load below the P_{min} set point with the slope of the trend line being 0.23 Hz/(s*kW).

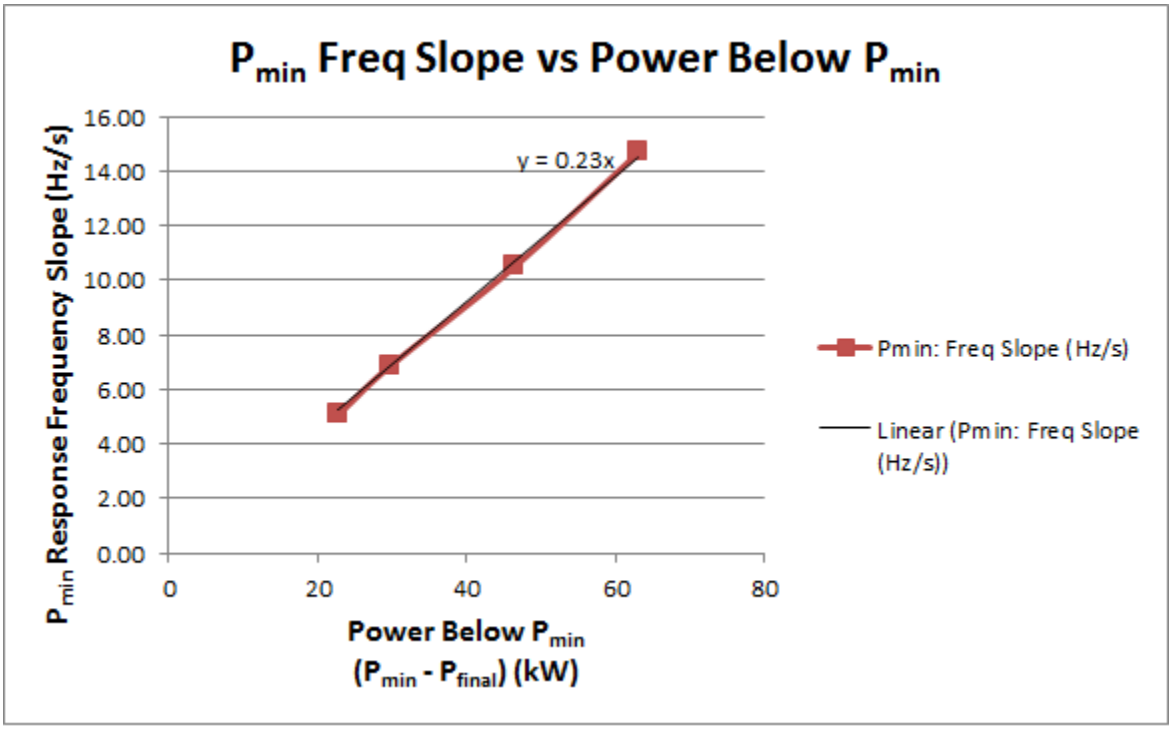

Figure 95: Events A to D, Pmin Average Frequency Slope vs. Power Below Pmin Setting

Note: The graphs shown below are produced from PQView and in some cases appear to be missing data. In addition, there appear to be significant swings in some of the data, particularly in the power and frequency plots. This does not appear to be the case in actuality and is likely an artifact of the post-processing performed by PQView on the raw data from the Ion metering system. The reason for this is not known but one possibility may be the post-event frequency of 70 Hz.

Figure 96 through Figure 100 show the results of Event A, where the P_{min} set point is 80 kW and a step load of 90 kW to 70 kW is applied. The frequency response has a slope of 5.09 Hz/s and reaches the steady state frequency of 70 Hz in about 2.1 seconds. The ESS would continue to operate at this frequency until the load rises above the P_{min} set point or the unit is shut down. Under normal conditions an over-frequency relay would trip the unit.

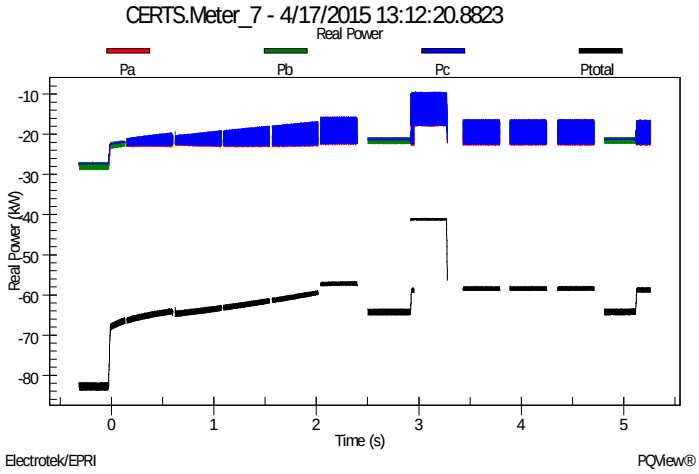

Figure 96: Event A, Load 10 kW Below Pmin, Real Power

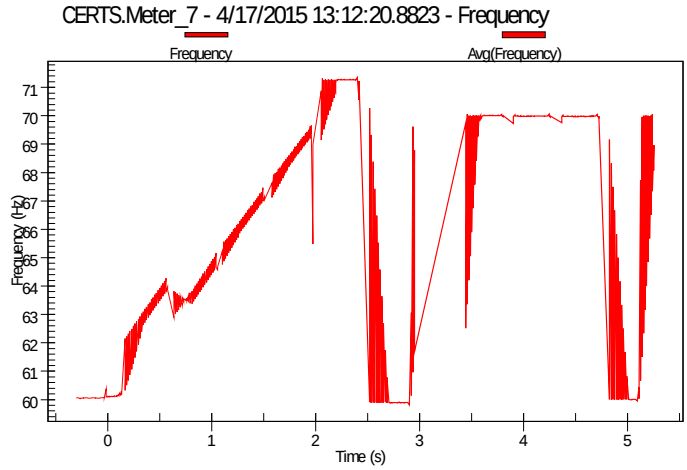

Figure 97: Event A, Load 10 kW Below Pmin, Frequency

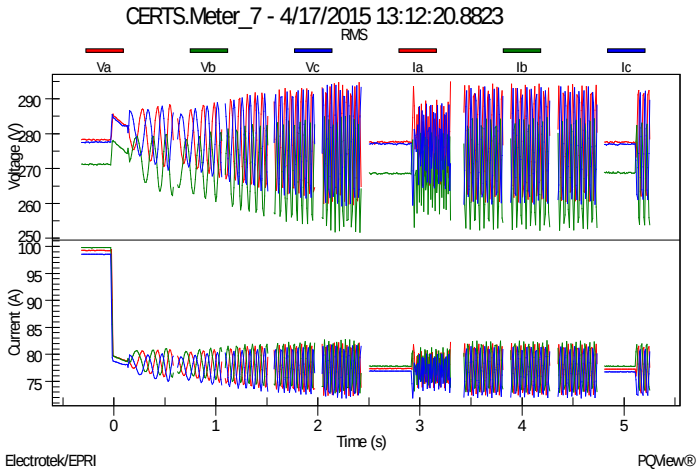

Figure 98: Event A, Load 10 kW Below Pmin, RMS Voltage & Current

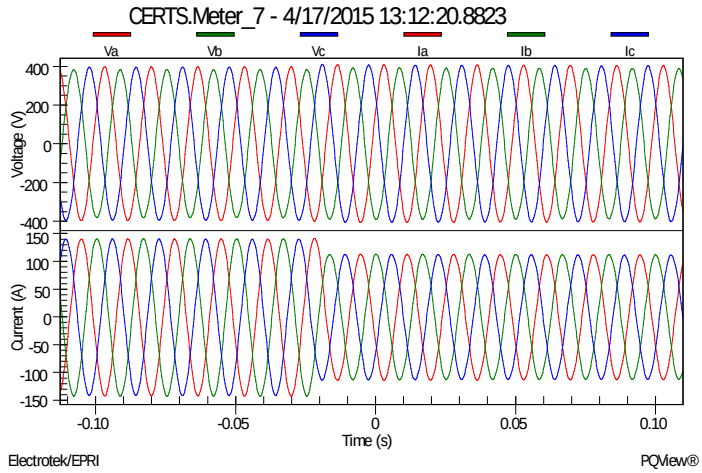

Figure 99: Event A, Load 10 kW Below Pmin, Waveform Voltage & Current (Zoomed)

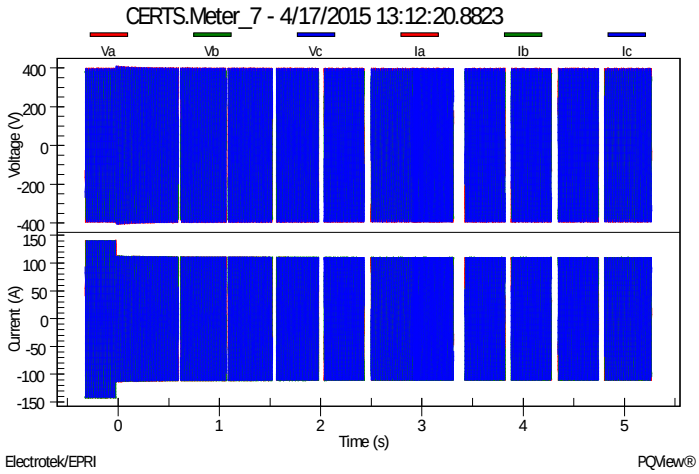

Figure 100: Event A, Load 10 kW Below Pmin, Waveform Voltage & Current

Figure 101 through Figure 105 show the results of Event D, where the P_{min} set point is 80 kW and a step load of 90 kW to 20 kW is applied. The frequency response has a slope of 14.7 Hz/s and reaches the steady state frequency of 70 Hz in about 0.7 seconds. The ESS would continue to operate at this frequency until the load rises above the P_{min} set point or the unit is shut down. Under normal conditions an over-frequency relay would trip the unit.

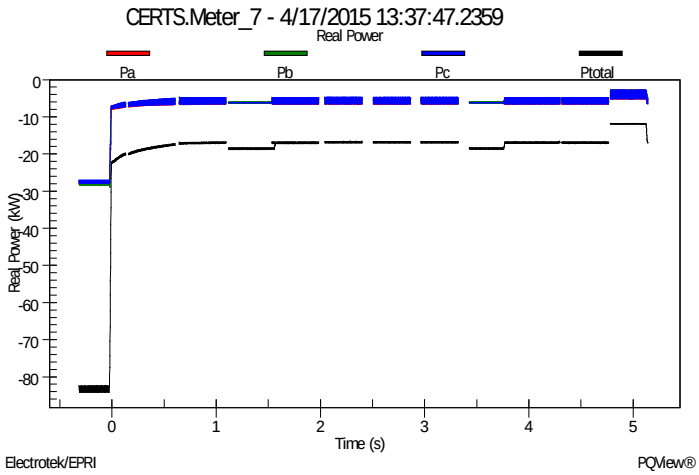

Figure 101: Event D, Load 60 kW Below Pmin, Real Power

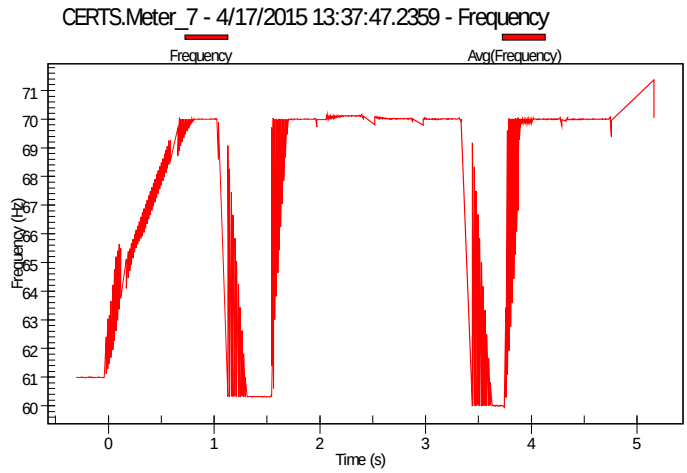

Figure 102: Event D, Load 60 kW Below Pmin, Frequency

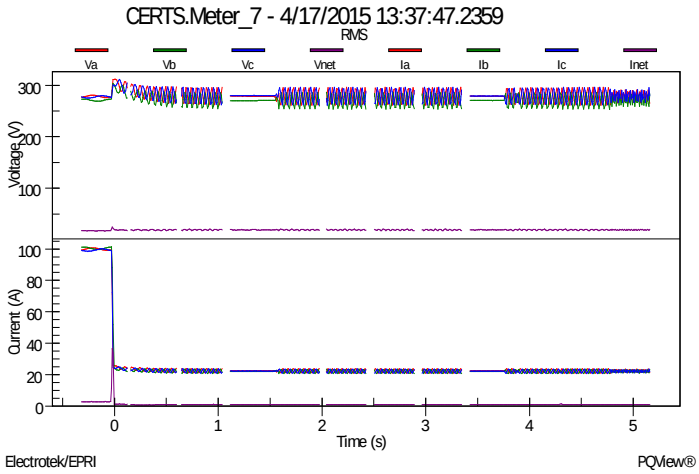

Figure 103: Event D, Load 60 kW Below Pmin, RMS Voltage & Current

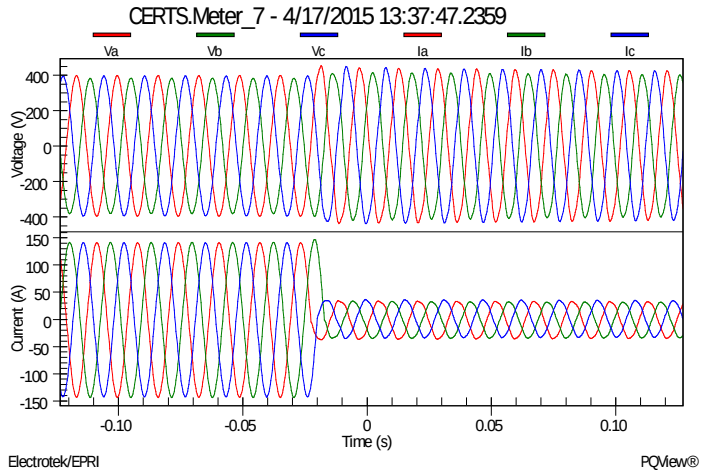

Figure 104: Event D, Load 60 kW Below Pmin, Waveform Voltage & Current (Zoomed)

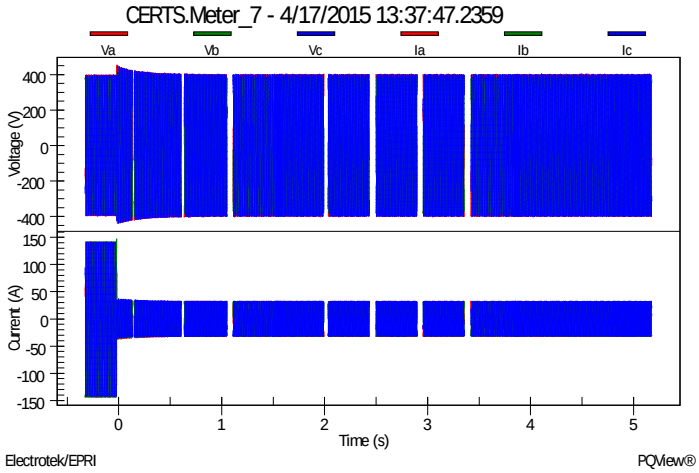

Figure 105: Event D, Load 60 kW Below Pmin, Waveform Voltage & Current

Figure 106 through Figure 111 show the results of Event G, where the P_{min} set point is 10 kW and a step load of (20+j60) kVA to j60 kVA is applied. As expected, the P_{min} functionality is activated and is not affected by reactive load demonstrating proper dependence only on the real power load.

It is interesting to note that the reactive power is reduced from approximately 55 kVAr to 43 kVAr. This is a reduction of 22% in the reactive power. Since the power is inversely proportional to the impedance (V^2/Z) and the impedance of the inductive load is directly proportional to the frequency ($j\omega L$) it follows that as the frequency increases, the impedance will increase, and the reactive power will decrease. In this case, the frequency increases by 16.7% (70 Hz/60 Hz) which does not fully account for the 22% reduction in reactive power. There is a slight, 0.1%, rise in the average RMS voltage due to reduction in reactive load but this would only have the effect of increasing the reactive load by approximately 0.2%.

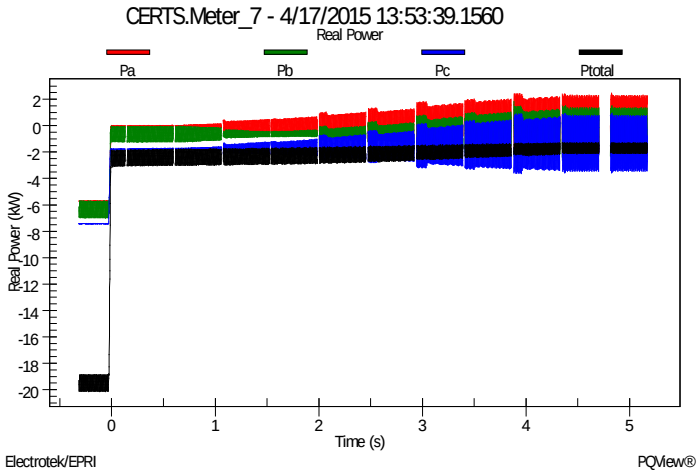

Figure 106: Event G, Pmin=10 kW, Load Step 20+j60 to j60 kVA, Real Power

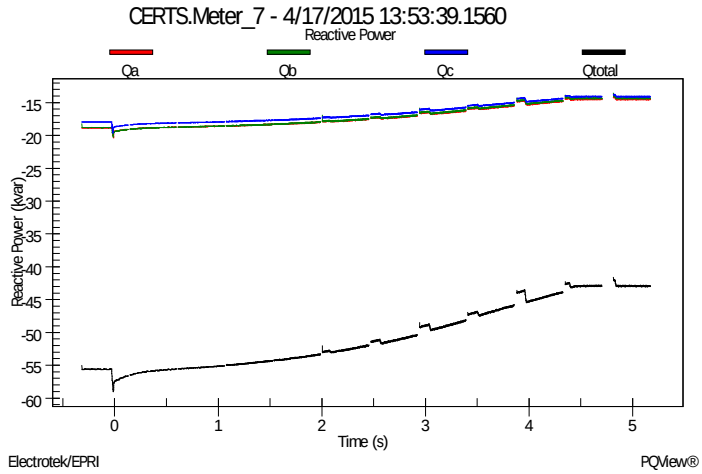

Figure 107: Event G, Pmin=10 kW, Load Step 20+j60 to j60 kVA, Reactive Power

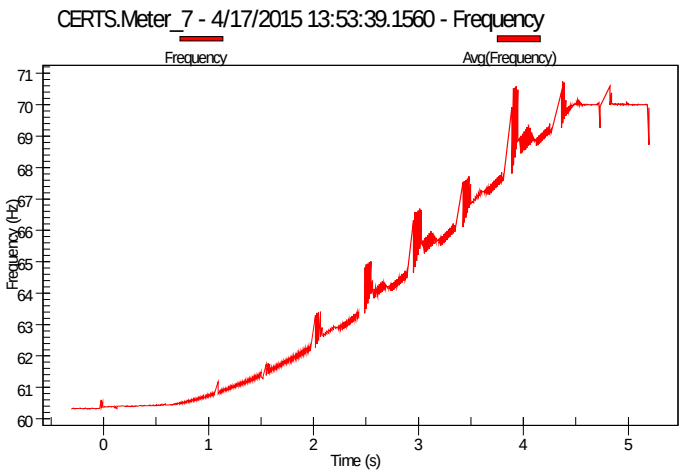

Figure 108: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, Frequency

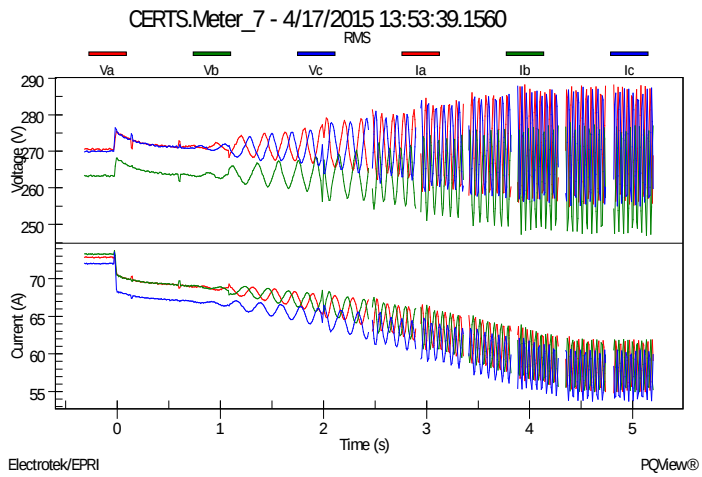

Figure 109: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, RMS Voltage & Current

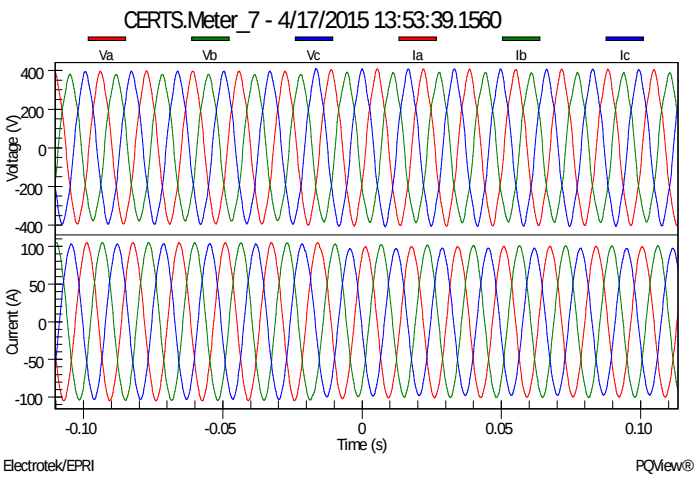

Figure 110: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, Waveform Voltage & Current (Zoomed)

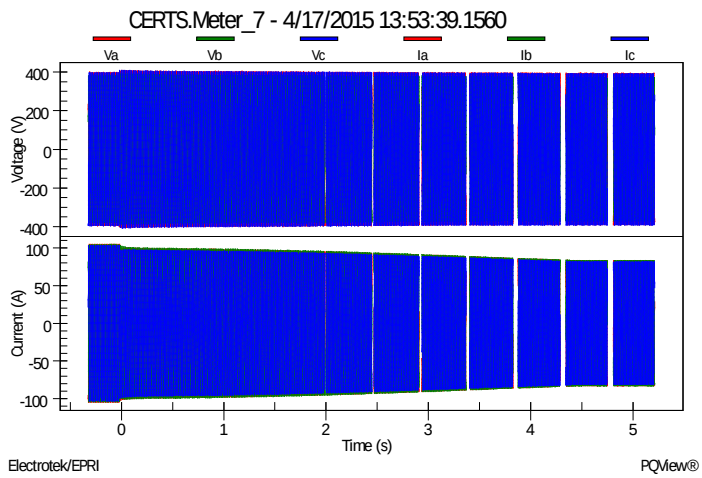

Figure 111: Event G, Pmax=10 kW, Load Step 0 to 60 kVAr, Waveform Voltage & Current

5.10 Inverter Voltage Regulation PI Controller – Tune Gains

Performance Goal

Tune the inverter's voltage regulation proportional and integral gains to reduce the voltage response's overshoot and settling time during a step load event. Previous tests have demonstrated voltage overshoots of approximately 12% during a significant step load of about 85 kW along with a settling time of 0.8 seconds. It is desired to reduce the overshoot to less than 10% and to improve the settling time. Also, determine if the new voltage regulation PI gains address the issue where the inverter trips on large declining step loads, typically those larger than 85 kW.

Description of Procedure

For all previous tests the voltage regulation gains have been set as follows:
Voltage Regulation P-gain = 0.1
Voltage Regulation I-gain = 0.46

The largest declining step load that does not result in the inverter tripping will be used which is approximately 85 kW to 0 kW. An initial step load will be performed with the current PI gains and used as the baseline response.

With the current I-gain of 0.46 held constant, P-gain is adjusted to determine the edge of instability. I-gain will then be set to a small value and P-gain will again be varied to determine the edge of instability. The P-gain will be set to approximately one half of the value that causes instability. The new P-gain setting will be held constant and I-gain will be adjusted. Based on the response characteristics from this set of tests a new I-gain value will be chosen.

Finally, a large declining load step (>85 kW) is performed to see if the new voltage regulation PI gains address the issue of the inverter tripping due in those cases.

Test Settings

ESS parameters arre set as follows:
$P_{dispatch}$ = 50 kW
Frequency Droop = 1% or -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)
AC Power Limit = 105 kW
Voltage Droop = 5% or -0.24 V/kVAr
Voltage Dispatch = 480 V_{LL} [Inverter Voltage Reference = 102.5 per PPS*]
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V.

Test Results

Table 20 below summarizes the results of voltage regulation PI gain tests including the tested PI gain combinations, calculated percent overshoot, and the settling time. Load bank transitions are indicated with an arrow (→**).**

Note that the load step size is reduced to 80 kW for test events B through S since the inverter started tripping on the 85 kW step load.

Test Event	Load Bank 3 (kW)	P-gain	I-gain	Percent Overshoot	Settling Time (s)	Comments
A	85 → 0	0.1	0.46	12.2%	0.80	Current PI gains / Baseline case
B	80 → 0	0.2	0.46	10.1%	0.76	Step reduced to 80 kW to avoid inverter tripping.
C	80 → 0	0.4	0.46	8.8%	0.78	
D	80 → 0	0.8	0.46	6.3%	1.20	On the edge of instability
E	80 → 0	0.05	0.46	12.7%	0.55	
F	80 → 0	0.1	0	-	-	Initial voltage conditions are not met (i.e. average voltage is 246 Vrms). With I-gain = 0 the initial voltage error is not driven to 0.
G	80 → 0	0.1	0.05	9.9%	4.83	
H	80 → 0	0.2	0.05	10.2%	4.59	
I	80 → 0	0.4	0.05	7.6%	4.84	
J	80 → 0	0.05	0.05	11.2%	4.13	
K	80 → 0	0.8	0.05	-	> 5.24	Edge of instability. Did not reach steady state.
L	80 → 0	0.4	1	8.7%	0.36	
M	80 → 0	0.4	1.5	8.0%	0.234	
N	80 → 0	0.4	2	7.8%	0.187	
O	80 → 0	0.4	3	6.7%	0.091	
P	80 → 0	0.4	4	6.3%	0.074	
Q	80 → 0	0.8	4	-	-	Edge of instability. Did not reach steady state.
R	80 → 0	0.4	8	6.9%	0.041	
S	80 → 0	0.4	16	6.1%	0.033	

Table 20: Voltage Regulation PI Control Test Cases

Analysis

Events A, shown in Figure 112, represents the test case where the inverter's PI gains are at the values set at the factory. In this case the overshoot is 12.2% and the settling time is 0.8 seconds. This is the baseline case.

Events B through E represent test cases where I-gain is held at its original value and P-gain is increased to determine the edge of instability of voltage regulation. This occurrs at P-gain = 0.8 and is shown in Figure 113, Event D. The graph shows the ESS struggling to maintain a constant voltage in contrast with the baseline case where the voltage is stable. In this case the overshoot is 6.3% and the settling time is 1.2 seconds. An attempt is made to set P-gain = 1.0 but this results in the inverter tripping most likely due to unstable voltage regulation.

Next the integral gain is set to a small value and P-gain is adjusted to determine an acceptable P-gain. Event F, shown in Figure 114, has I-gain set to 0. In this case, the initial voltage does not reach the nominal value of 277 V. Instead the ESS starts at 246 V. It is assumed that this is result of the I-gain being set to 0. This is not acceptable so the I-gain is changed to 0.05 for the test events to determine the proportional gain.

Events G through K represent test cases where I-gain is set to 0.05 and P-gain is adjusted to determine the edge of instability. This again occurs at P-gain = 0.8 and is shown in Figure 115, Event K. The graph shows the ESS struggling to maintain a constant voltage in contrast with the baseline case where the voltage is stable. In this case the overshoot is indeterminable because the settling time is greater than 5.24 seconds, the recording time of the meter, and therefore the final steady state voltage is not known.

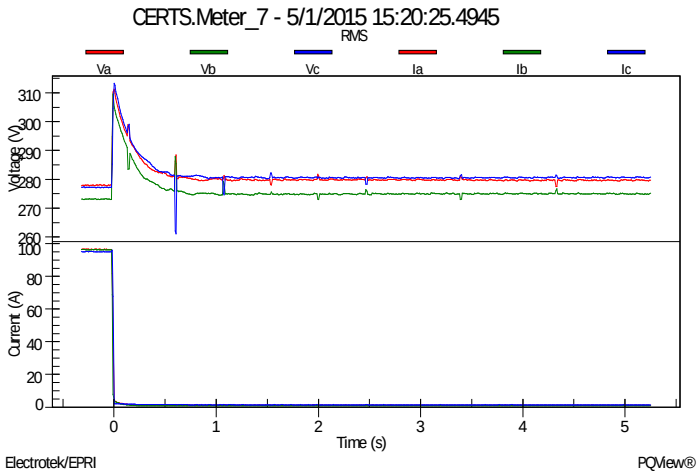

Figure 112: Voltage Regulation Gain Tuning, Event A, P=0.1, I=0.46, Baseline Case

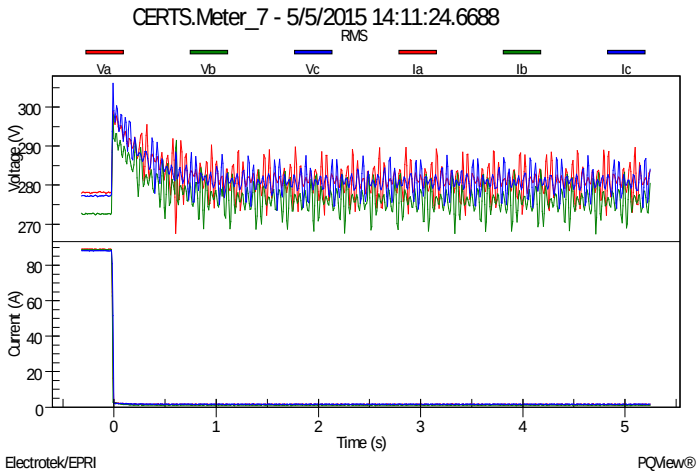

Figure 113: Voltage Regulation Gain Tuning, Event D, P=0.8, I=0.46, Edge of Instability

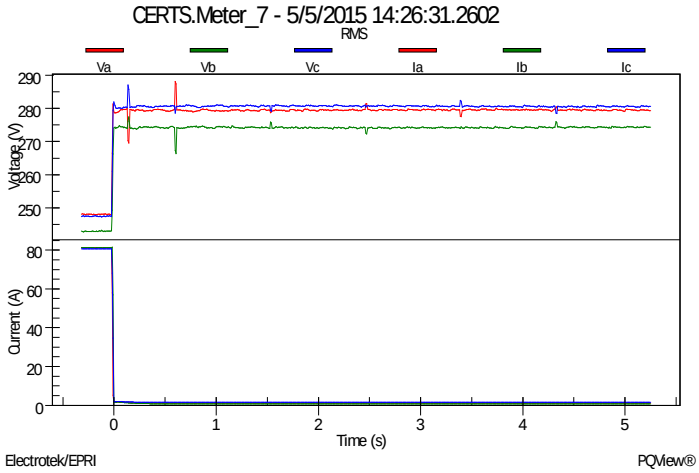

Figure 114: Voltage Regulation Gain Tuning, Event F, P=0.1, I=0.0, Integral Gain = 0

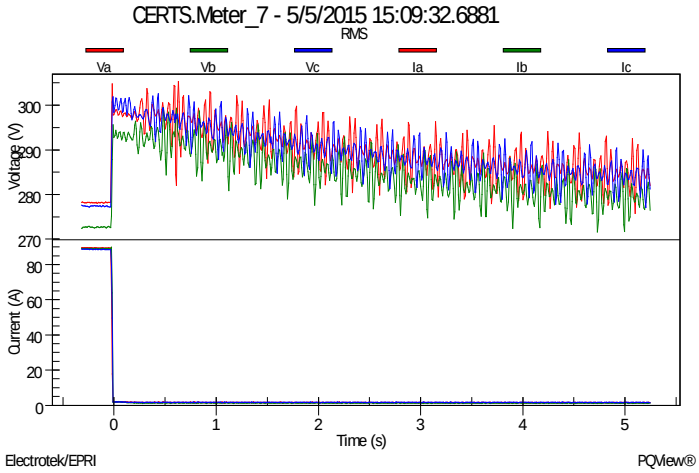

Figure 115: Voltage Regulation Gain Tuning, Event K, P=0.8, I=0.05, Edge of Instability

A P-gain of 0.8 is shown to be the edge of instability. Based on this, the new P-gain setting of 0.4 is chosen. Events L through S (excluding Q) hold P-gain = 0.4 and adjust the I-gain from 1 to 16 to determine the setting that gives the desired response of minimizing the overshoot and decreasing the settling time.

Figure 116 demonstrates how the overshoot and settling time due to a step load are affected as I-gain is varied while P-gain is held constant at 0.4. With I-gain = 16 the overshoot and settling time are minimized. The overshoot and settling time are 6.1% and 0.033 seconds with the new voltage regulation PI gain settings compared to 12.2% and 0.8 seconds with the original settings. These new settings are used for future testing unless indicated otherwise. The RMS voltage response can be seen in Figure 117.

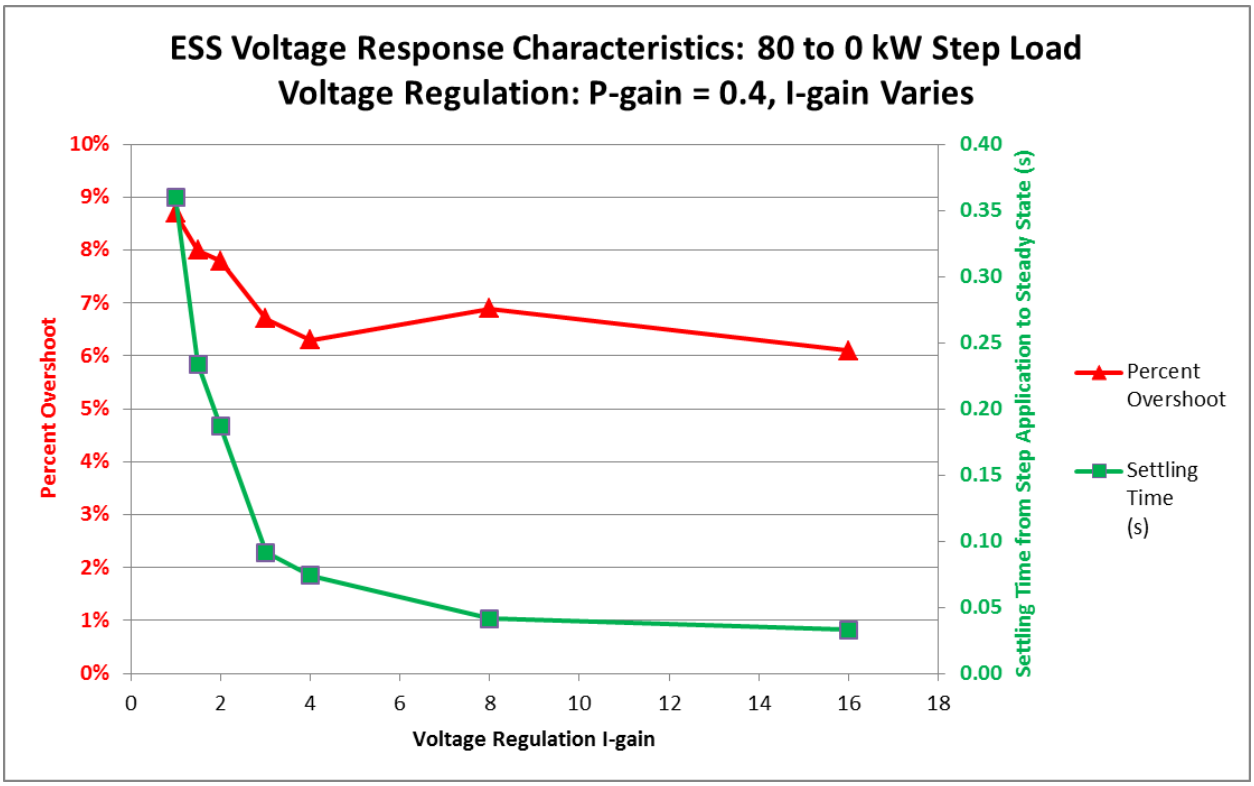

Figure 116: Voltage Response Characteristics, % Overshoot and Settling Time, P-gain = 0.4, I-gain Varies

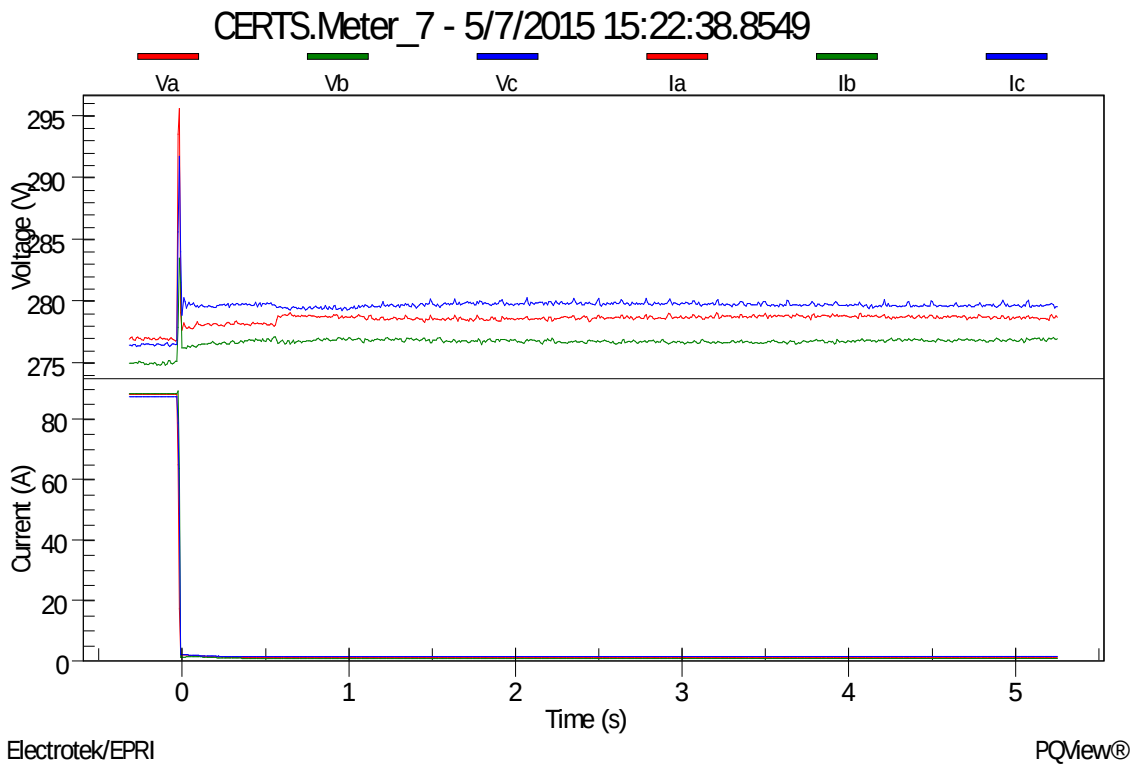

Figure 117: Voltage Regulation Gain Tuning, Event S, P=0.4, I=16, New PI Gains

Finally, a declining step load from 90 kW to 0 kW is performed to determine if the new PI gain settings would prevent the inverter from tripping due to a large load rejection. The result is that the inverter still trips under that condition.

5.11 Voltage Regulation Test with New Voltage Regulation PI Settings – Stand Alone

Performance Goal

Verify that the ESS is capable of holding the correct output voltage throughout its operating range. Voltage set points in the ESS are varied from 95% to 105% of nominal voltage (480V_{LL}). Actual voltage levels will be compared to expected values.

Description of Procedure

The ESS is dispatched to 50 kW, 1% Frequency Droop, a voltage range from 95% to 105% of 480 V_{LL} nominal, 5% Voltage Droop and operated islanded from the utility. The ESS is started and connected to the islanded microgrid electrical bus. For a given dispatch voltage, voltage measurements are taken at different loading values ranging from no load to approximately 100 kW.

Test Settings

ESS parameters are set as follows:
Pdispatch = 50 kW
Frequency Droop = -.004 Hz/kW (P1 = 100 kW, f1 = 59.8 Hz, P2 = -50 kW, f2 = 60.4 Hz)
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -50 kW (P_{min} = Battery Power Limit Min parameter on inverter)
AC Power Limit = 105 kW
Voltage Droop = -0.24 V/kVAr
Voltage Dispatch = Varies from 95% to 105% of nominal [Inverter Voltage Reference = 102.5 per PPS*]
Voltage Regulation P-gain = 0.4
Voltage Regulation I-gain = 16
* Note: Princeton Power Systems recommends that the Inverter Voltage Reference be set to 102.5% which is designed to produce 480 V_{LL}.

Table 21 below lists the test cases. Load bank and total load transitions are indicated with an arrow (→).

Test Event	ESS (Dispatch = 50 kW)	GIS	Load Bank 3 (kW)	Load Bank 4 (kW)	Total (kW)
A	480 V	Open	0	0	0
B	480 V	Open	0→30	0	0→30
C	480 V	Open	0→35	30	30→65
D	480 V	Open	35→70	30	65→100
E	504 V	Open	0	0	0
F	504 V	Open	0→30	0	0→30
G	504 V	Open	0→35	30	30→65
H	504 V	Open	35→70	30	65→100
I	456 V	Open	0	0	0
J	456 V	Open	0→30	0	0→30
K	456 V	Open	0→35	30	30→65
L	456 V	Open	35→70	30	65→100

Table 21: Voltage Regulation with New PI Gain Settings – Test Cases

Test Results

Table 22 below summarizes the results of initial voltage regulation tests including real and reactive power, voltage, and steady state voltage error for all events.

Test Event	ESS Real Power Observed	ESS Reactive Power Observed	ESS Voltage		Steady State Error (%)	Pass/Fail
			Target	Actual		
A	0.14	0.65	276.91	278.15	0.45%	**PASS**
B	23.57	0.79	276.89	277.52	0.23%	**PASS**
C	58.53	0.14	276.98	276.50	-0.17%	**PASS**
D	90.39	-0.75	277.10	275.47	-0.59%	**PASS**
E	2.00	0.51	290.93	292.17	0.43%	**PASS**
F	25.81	0.46	290.94	291.41	0.16%	**PASS**
G	64.33	-0.30	291.04	290.29	-0.26%	**PASS**
H	98.90	-1.12	291.16	289.17	-0.68%	**PASS**
I	0.09	0.70	262.90	264.14	0.47%	**PASS**
J	21.04	0.66	262.91	263.56	0.25%	**PASS**
K	52.76	0.08	262.99	262.51	-0.18%	**PASS**
L	81.18	-0.64	263.09	261.53	-0.59%	**PASS**

Table 22: Voltage Regulation with New PI Gain Settings – Test Results

Analysis

The ESS successfully passes the voltage regulation tests over its voltage and real power operating range. The results are essentially the same as the initial voltage regulation tests performed in Section 5.4.

The observed voltage at the ESS's meter deviated from its expected value by no more than 0.68% in all cases and ranged from -0.68% to 0.47%. The voltage is consistently slightly high at lighter loads and slightly low at heavier loads. This slight voltage droop is likely due to the impedance between the ESS and its meter. Figure 118 displays the measured and expected voltage response as a function of the real power provided from the ESS. The measured voltage response is seen to cross the target voltage response for each dispatch voltage at approximately the midpoint of each pair of graphs.

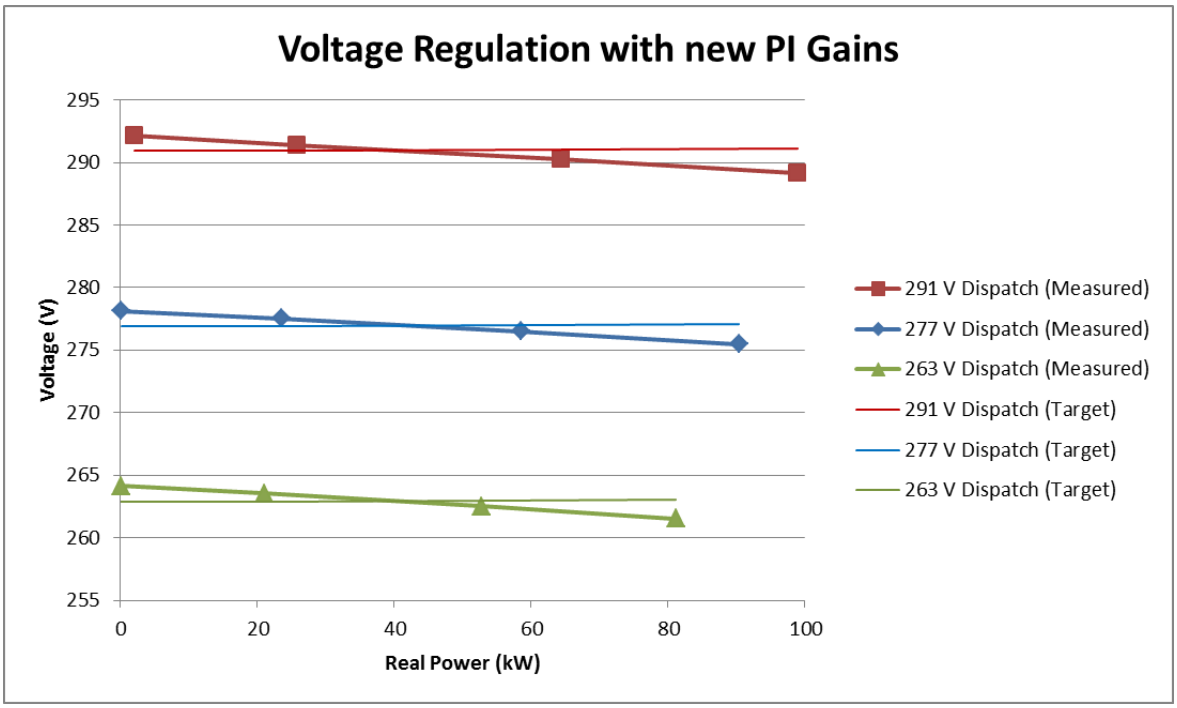

Figure 118: Voltage Regulation with New PI Gains

5.12 Transition between Charging Grid Connected and Discharging Islanded

Performance Goal

The intent of this testing is to ensure stable operation when transitioning between charging while grid connected and discharging islanded. A pass criterion for this test is the ability to transition between modes while maintaining acceptable steady state voltage and frequency.

Description of Procedure

The ESS is dispatched to various real power values all in the charging mode (i.e. $P_{dispatch}$ is negative), 1% Frequency Droop, 480 V_{LL}, 5% Voltage Droop. The ESS is started and connected to the utility-connected microgrid electrical bus. A load is placed on the microgrid and then the microgrid is disconnected from the utility resulting in the ESS transitioning from charge mode to discharge. After steady state conditions are established, the microgrid is reconnected to the utility resulting in the ESS transitioning from discharge mode to charge. For each event, real power, voltage, and frequency measurements are tabulated for both pre- and post-event.

Test Settings

The ESS settings for these tests are:

$P_{dispatch}$ = varies

$E_{dispatch}$ = 480 V_{ll}

Frequency Droop = 1.0%

Voltage Droop = 5%
P_{max} = 100 kW
P_{min} = -50 kW
Voltage Regulation P-gain = 0.4
Voltage Regulation I-gain = 16

Table 23 below lists the test cases. Transitions are indicated with an arrow (→).

Test Event	$P_{dispatch}$ (kW)	Load Bank 3	Load Bank 4	GIS	Swing
A	-25	50 kW		Closed → Open	75 kW
B	-25	50 kW		Open → Closed	75 kW
C	-25	75 kW		Closed → Open	100 kW
D	-25	75 kW		Open → Closed	100 kW
E	-25	90 kW		Closed → Open	115 kW
F	-25	90 kW		Open → Closed	115 kW
G	-50	10 kW	95 kW	Closed → Open	155 kW
H	-50	10 kW	95 kW	Open → Closed	155 kW
I	-50	(80+j60) kVA		Closed → Open	157 kVA
J	-50	(80+j60) kVA		Open → Closed	157 kVA
K	-50	5 kW		Closed → Open	55 kW
L	-50	5 kW		Open → Closed	55 kW
M	-50	0 kW		Closed → Open	50 kW
N	-50	0 kW		Open → Closed	50 kW
O	-1.5	5 kW		Closed → Open	6.5 kW
P	-1.5	5 kW		Open → Closed	6.5 kW
Q	-1.5	10 kW	95 kW	Closed → Open	106.5 kW
R	-1.5	10 kW	95 kW	Open → Closed	106.5 kW

Table 23: ESS Charging/Discharging Transition Test Cases

These tests are designed to test the boundaries of operation of the ESS as well as operation well inside of the boundaries. In addition, since the ESS has not yet demonstrated the ability to handle load rejection steps in excess of 85 kW, operation with load step changes both greater and less than 85 kW are performed. Thus, these tests look at different combinations of light or heavy loads and low or high rates of charging.

The boundaries of operation are:
Maximum Charge Rate = 50 kW (based on battery specifications, inverter capable of 100 kW)
Maximum Discharge Rate = 100 kW (inverter limit)
Minimum Charge Rate = 1.47 kW (3 A at 490 V, DC. Setting for full charge on battery)
Minimum Discharge Rate = 5 kW (smallest balanced load that can be applied in the test bed)

Test Events:
A & B: inside the boundaries, discharge < 85 kW, total swing < 85 kW

C & D: inside the boundaries, discharge < 85 kW, total swing > 85 kW
E & F: inside the boundaries, discharge > 85 kW, total swing > 85 kW
G & H: test swing between maximum charge and discharge rates, real power only
I & J: test swing between maximum charge and discharge rates, real and reactive power
K & L: test swing between maximum charge and minimum load
M & N: test swing between maximum charge and no load
O & P: test swing between minimum charge and minimum load
Q & R: test swing between minimum charge and maximum load

Test Results

The test results for transitioning between charging grid-connected and discharging islanded are summarized in Table 24. The ESS real power, and microgrid bus voltage and frequency are measured both prior to and after the event occurred.

Test Event	$P_{dispatch}$ (kW)	Desired Load Swing (kVA)	ESS Pre-Event			ESS Post-Event			Pass/Fail
			Real Power (kW)	Voltage (V)	Frequency (Hz)	Real Power (kW)	Voltage (V)	Frequency (Hz)	
A	-25	-25→50	-27.52	274.88	59.85	40.31	277.21	59.73	**Pass**
B	-25	50→-25	40.10	277.16	59.84	-30.25	274.90	60.01	**Pass**
C	-25	-25→75	-30.82	274.11	60.01	62.78	276.49	59.65	**Pass**
D	-25	75→-25	62.40	276.41	59.64	-23.83	273.93	59.98	**Pass**
E	-25	-25→90	-26.02	273.69	59.84	84.55	275.55	59.55	**Pass**
F	-25	90→-25	83.65	275.51	59.56	-28.53	274.06	59.98	**Pass**
G	-50	-50→100	-52.53	273.52	59.99	98.82	274.98	59.39	**Pass**
H2	-50	100→-50	100.24	275.31	59.39	-49.84	274.37	59.98	**Pass**
I	-50	-50→ (80+j60)	-53.27	270.46	59.99	76.26	266.12	59.49	**Pass**
J	-50	(80+j60) → -50	76.02	266.04	59.48	-53.94	270.51	59.99	**Pass**
K	-50	-50→5	-51.20	275.20	59.99	5.37	277.81	59.77	**Pass**
L	-50	5→-50	5.32	277.83	59.77	-51.72	275.25	59.98	**Pass**
M	-50	-50→0	-53.39	275.27	60.00	0.16	278.01	59.79	**Pass**
N	-50	0→-50	0.12	278.03	59.79	56.23	275.43	60.03	**Pass**
O	-1.5	-1.5→5	-7.51	275.11	60.02	5.31	277.91	59.95	**Pass**
P1	-1.5	5→-1.5	5.29	277.92	59.96	-16.47	274.60	60.05	**Pass**
Q	-1.5	-1.5→100	-1.04	273.45	59.98	99.48	275.17	59.58	**Pass**
R2	-1.5	100→-1.5	100.05	275.29	59.57	-6.38	274.41	60.00	**Pass**

Table 24: ESS Charging/Discharging Transition Test Results

Analysis

The ESS successfully passes all transitions between charging grid-connected and discharging islanded.

Previous large step load rejection tests (> 85 kW to 0 kW) resulted in the ESS inverter tripping. Several tests are conducted as part of this use case where a load rejection is greater than 85 kW, including the most severe case of 100 kW to -50 kW or a load swing of 150 kW. In all cases the transition occurs successfully and the ESS inverter enters the charging state. In these cases it appears that the presence of the utility grid provides the necessary support to sustain the transition.

Some of the test results are presented below in graphical form.

Figure 119 through Figure 124 show the results of Test Event G, a transition from charging at 50 kW grid-connected to discharging at 100 kW islanded. This is the most severe load increase within operating specifications that can be performed. PQView indicates in Figure 120 that the frequency takes approximately 1.5 to 2.0 seconds to reach steady state, however the Yokogawa ScopeCorder in Figure 124 indicates that this occurs in 2 cycles. Also, Figure 121 indicates a significant transient in the RMS voltage. This appears to be the result of the distortion in the voltage waveform during the cycle that the transition occurs and is not an indication of an actual dip in the peak voltage. The voltage waveform distortion can be seen in Figure 124 where the phase C voltage is shown in green in the bottom half of the figure. Similar observations regarding the frequency and transient RMS voltages can be made for the other tests for this use case. The RMS voltage transient is generally worse when transitioning from charging to discharging.

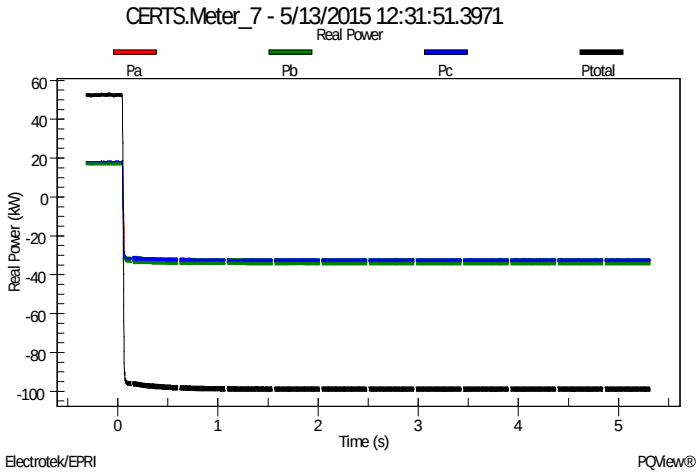

Figure 119: Event G, 50 kW Charge to 100 kW Discharge, Real Power

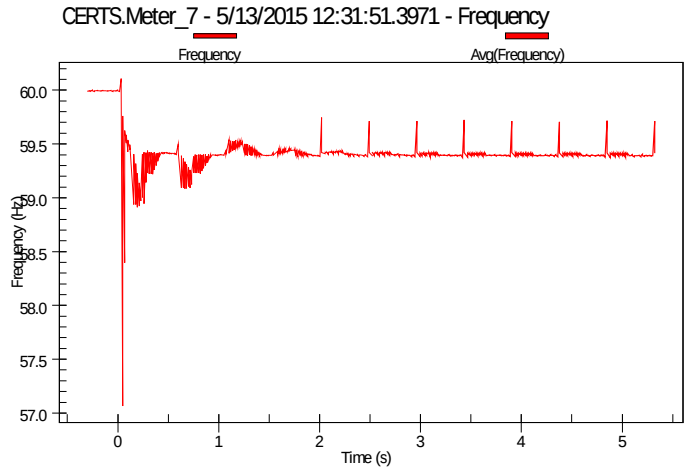

Figure 120: Event G, 50 kW Charge to 100 kW Discharge, Frequency

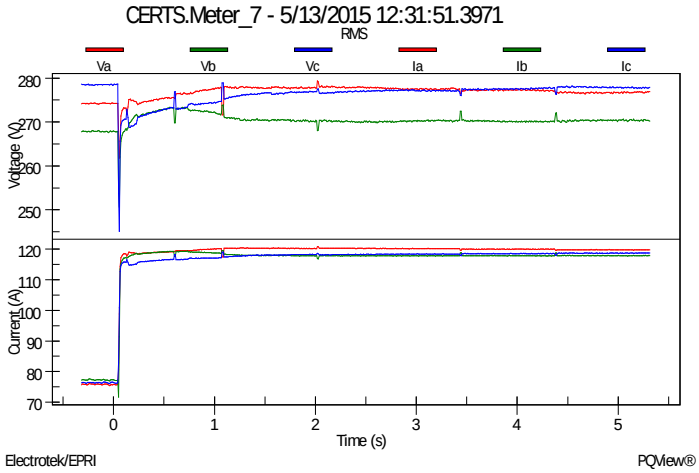

Figure 121: Event G, 50 kW Charge to 100 kW Discharge, RMS Voltage & Current

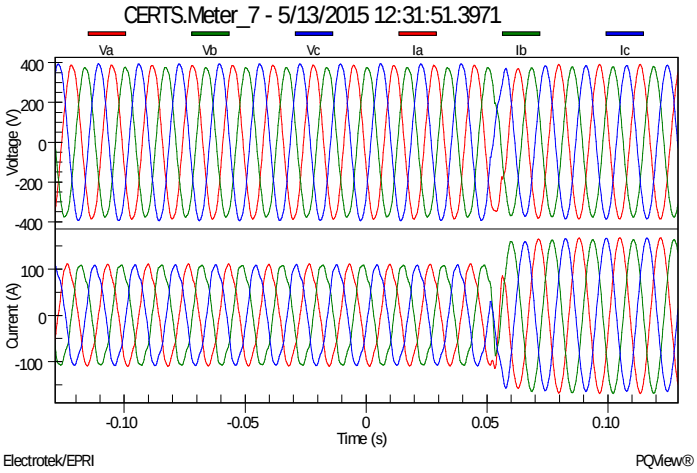

Figure 122: Event G, 50 kW Charge to 100 kW Discharge, Waveform Voltage & Current (Zoomed)

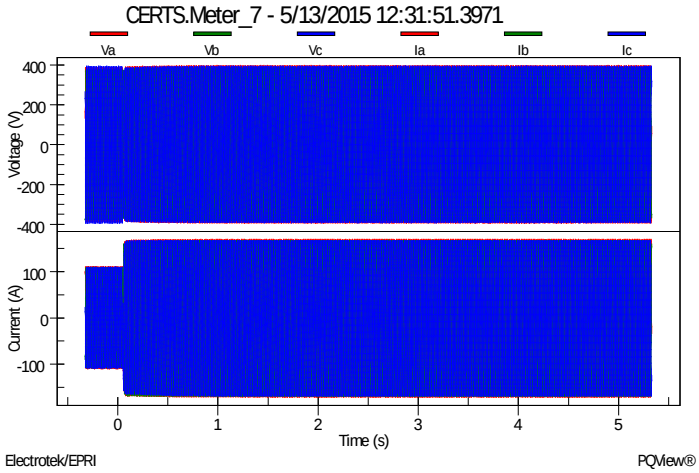

Figure 123: Event G, 50 kW Charge to 100 kW Discharge, Waveform Voltage & Current

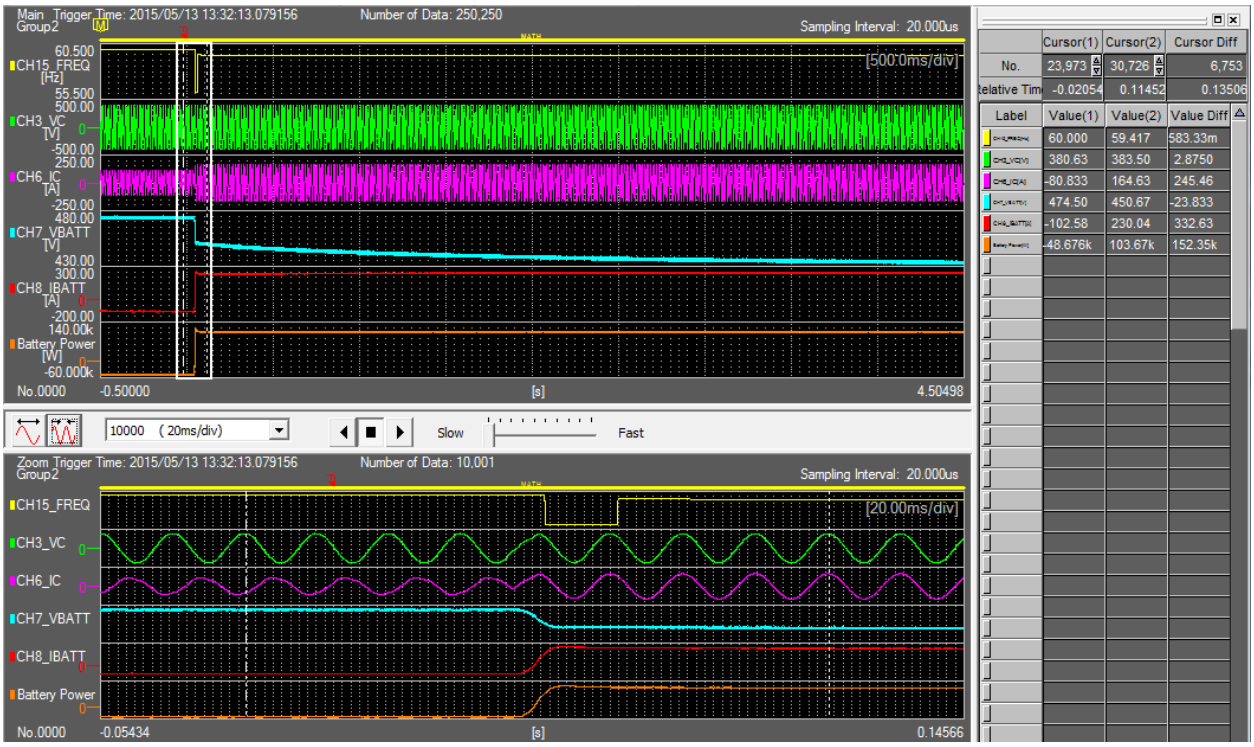

Figure 124: Event G, 50 kW Charge to 100 kW Discharge, Yokogawa ScopeCorder

Figure 125 through Figure 130 show the results of Test Event H2, a transition from discharging at 100 kW islanded to charging at 50 kW grid-connected. This is the most severe load rejection within operating specifications that can be performed. As mentioned earlier, it is interesting to note that this decreasing load swing of 150 kW does not cause the inverter to trip presumably due to the presence of the grid connection whereas previous declining load steps > 85 kW, during a stand-alone condition, always resulted in the inverter tripping.

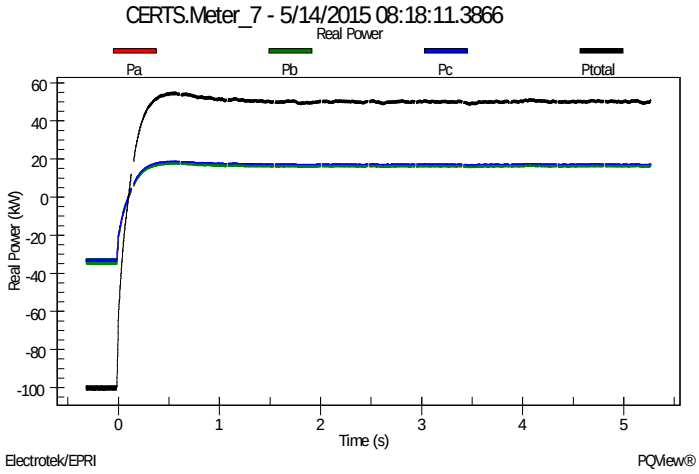

Figure 125: Event H2, 100 kW Discharge to 50 kW Charge, Real Power

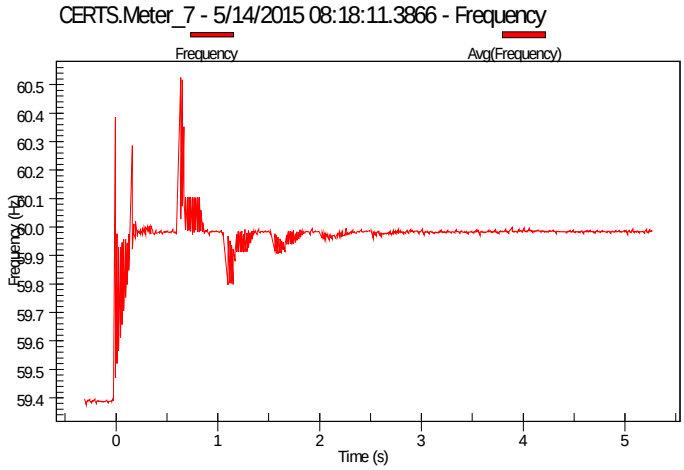

Figure 126: Event H2, 100 kW Discharge to 50 kW Charge, Frequency

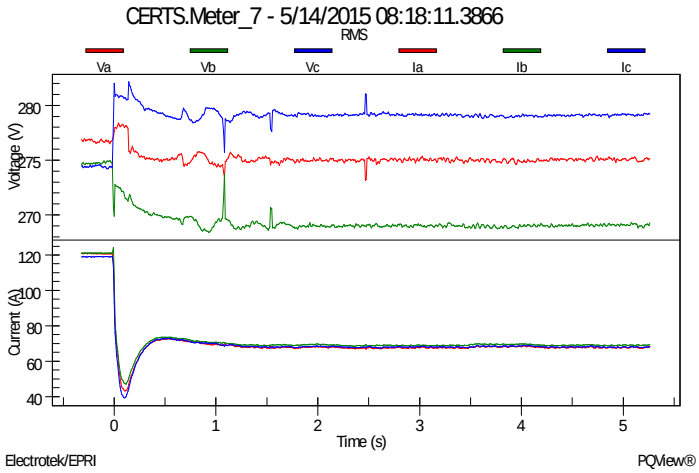

Figure 127: Event H2, 100 kW Discharge to 50 kW Charge, RMS Voltage & Current

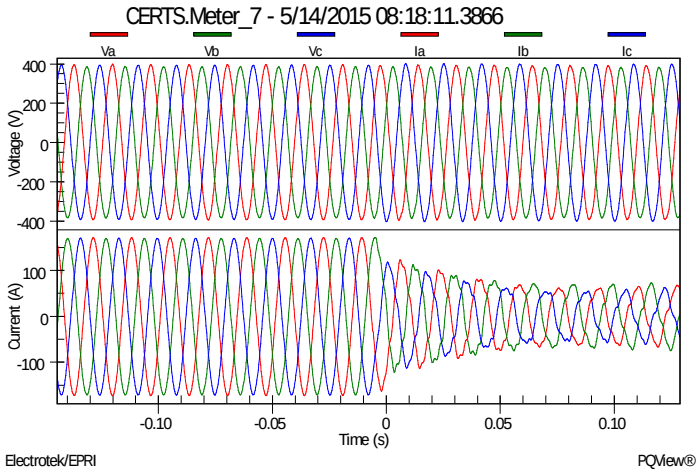

Figure 128: Event H2, 100 kW Discharge to 50 kW Charge, Waveform Voltage & Current (Zoomed)

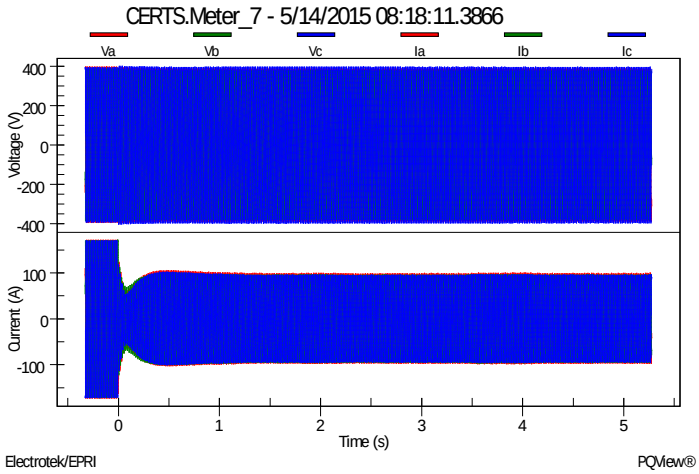

Figure 129: Event H2, 100 kW Discharge to 50 kW Charge, Waveform Voltage & Current

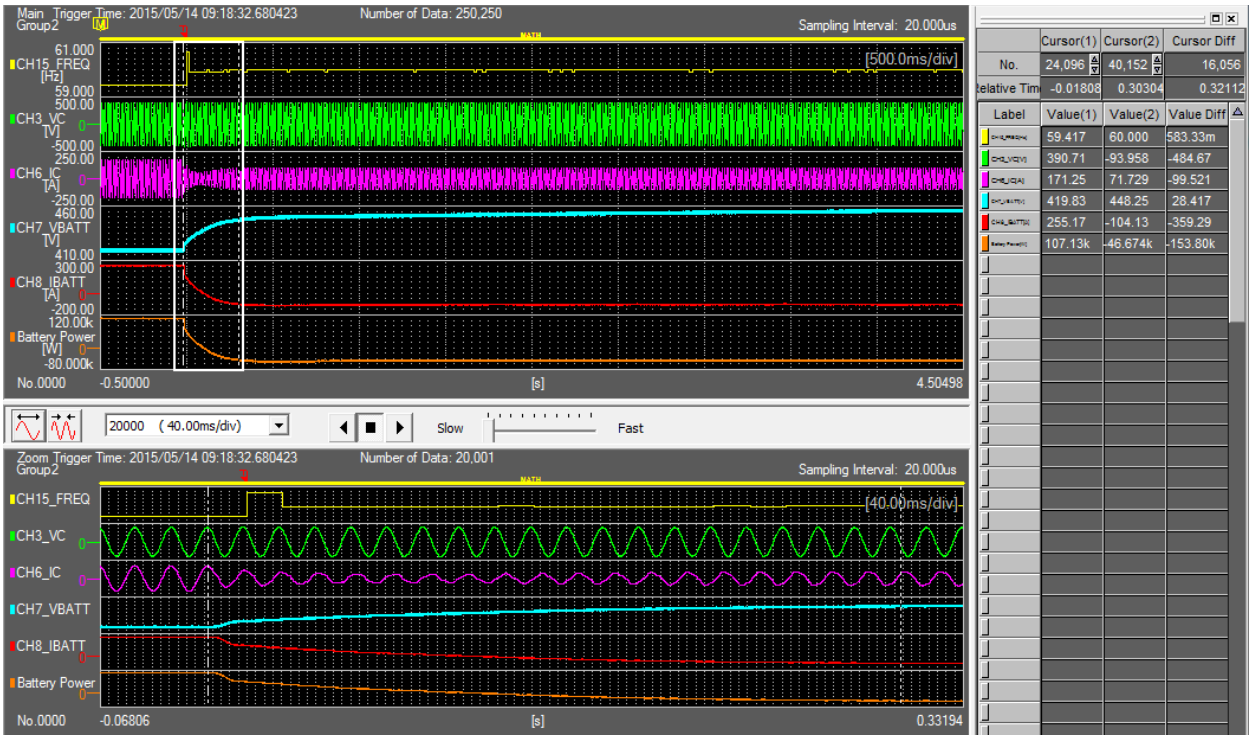

Figure 130: Event H2, 100 kW Discharge to 50 kW Charge, Yokogawa ScopeCorder

Figure 131 through Figure 136 show the results of Test Event I, a transition from charging at 50 kW grid-connected to discharging at (80+j60) kVA islanded. These results are similar to other transitions of this magnitude and the 60 kVAr reactive load does not affect the ability of the ESS to make this transition. Note that the initial condition of the ESS is intended to be supplying 0 kVAr; it is in fact supplying 50 kVAr. This is a result of the lower than nominal voltage provided at the point of common coupling from the utility and also to the reactive load on the microgrid bus.

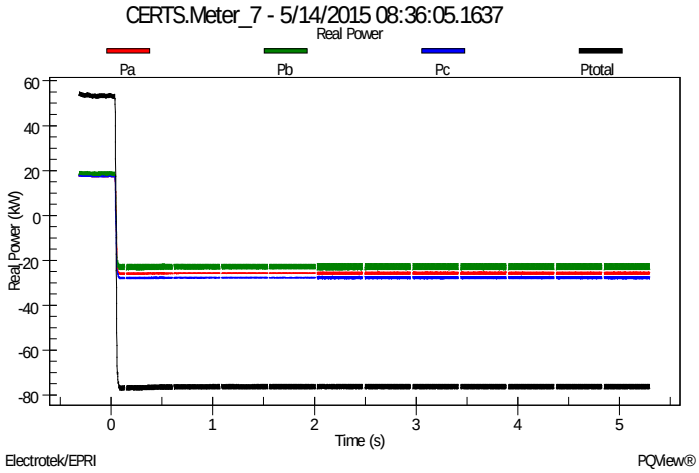

Figure 131: Event I, 50 kW Charge to (80+j60) kVA Discharge, Real Power

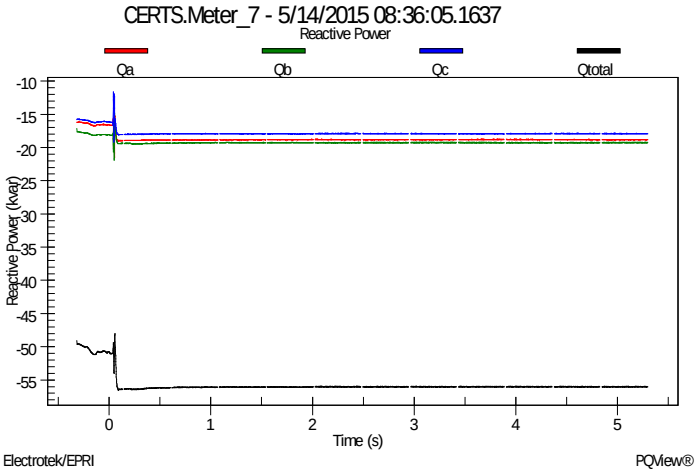

Figure 132: Event I, 50 kW Charge to (80+j60) kVA Discharge, Reactive Power

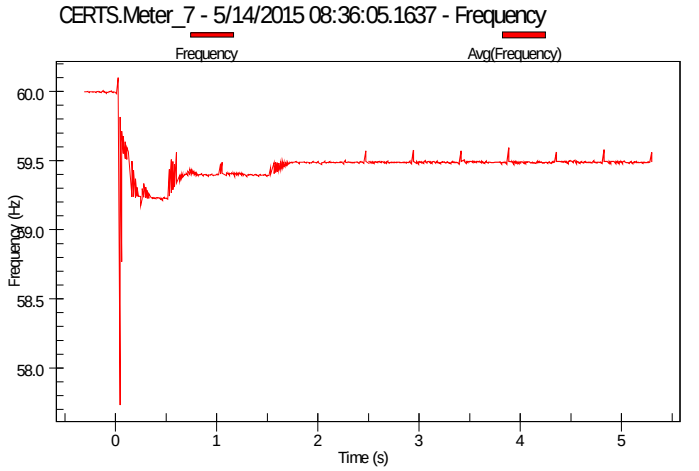

Figure 133: Event I, 50 kW Charge to (80+j60) kVA Discharge, Frequency

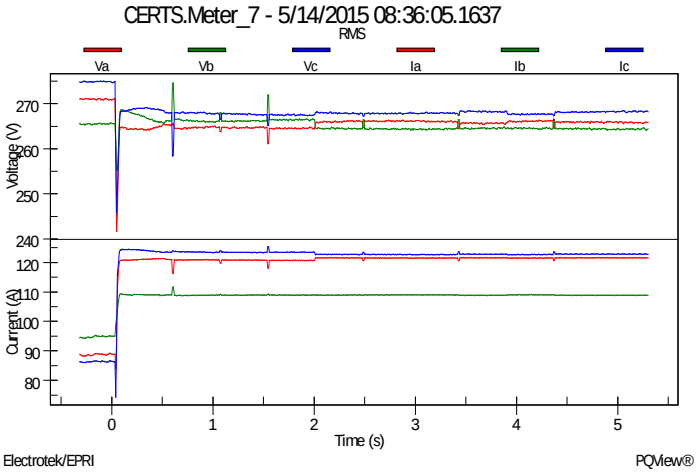

Figure 134: Event I, 50 kW Charge to (80+j60) kVA Discharge, RMS Voltage & Current

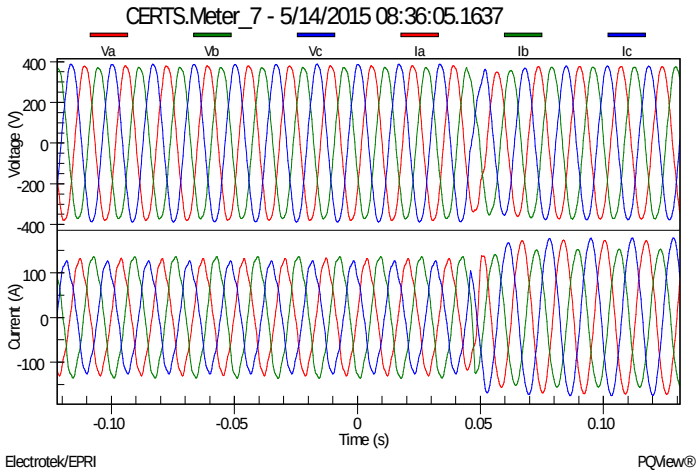

Figure 135: Event I, 50 kW Charge to (80+j60) kVA Discharge, Waveform Voltage & Current (Zoomed)

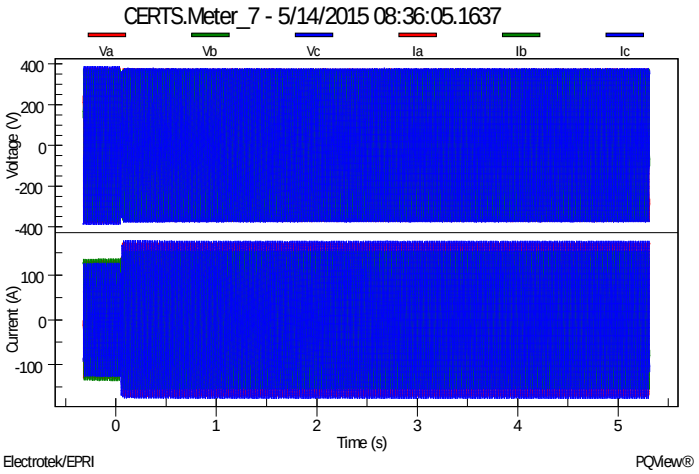

Figure 136: Event I, 50 kW Charge to (80+j60) kVA Discharge, Waveform Voltage & Current

Figure 137 through Figure 142 show the results of Test Event J, a transition from discharging at (80+j60) kVA islanded to charging at 50 kW grid-connected. These results are similar to other transitions of this magnitude and the 60 kVAr reactive load does not affect the ability of the ESS to make this transition. Here again it is desired for the ESS to provide 0 kVAr when grid-tied but due to the lower utility voltage and the reactive load on the microgrid, the grid-tied reactive load is 50 kVAr which is close to the initial 55 kVAr supplied by the ESS when islanded.

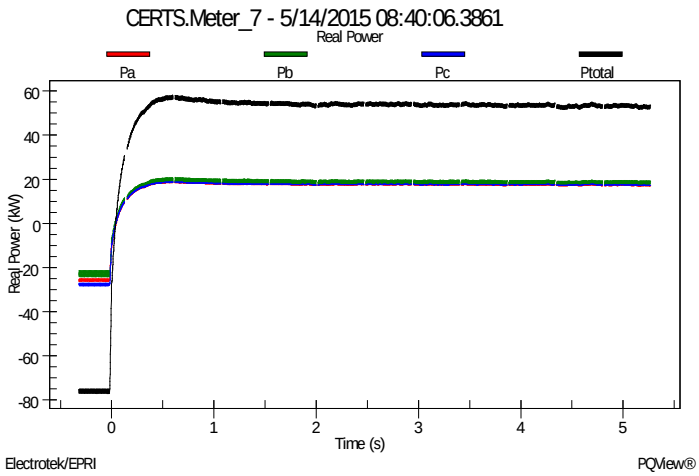

Figure 137: Event J, (80+j60) kVA Discharge to 50 kW Charge, Real Power

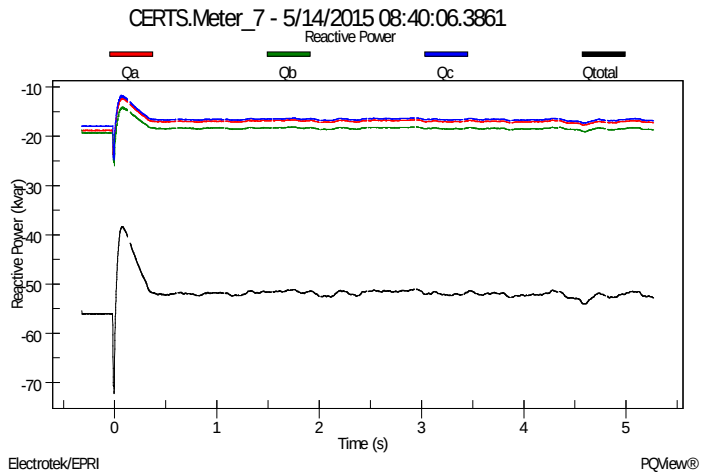

Figure 138: Event J, (80+j60) kVA Discharge to 50 kW Charge, Reactive Power

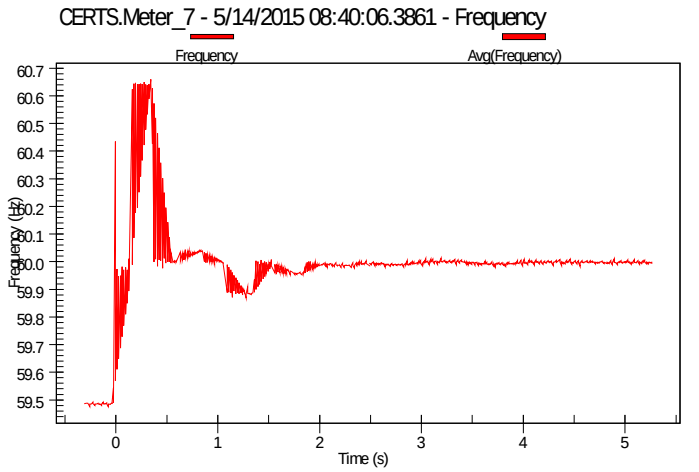

Figure 139: Event J, (80+j60) kVA Discharge to 50 kW Charge, Frequency

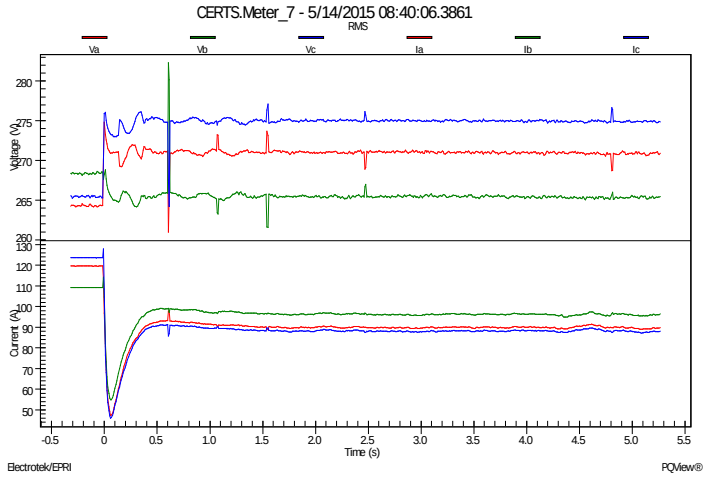

Figure 140: Event J, (80+j60) kVA Discharge to 50 kW Charge, RMS Voltage & Current

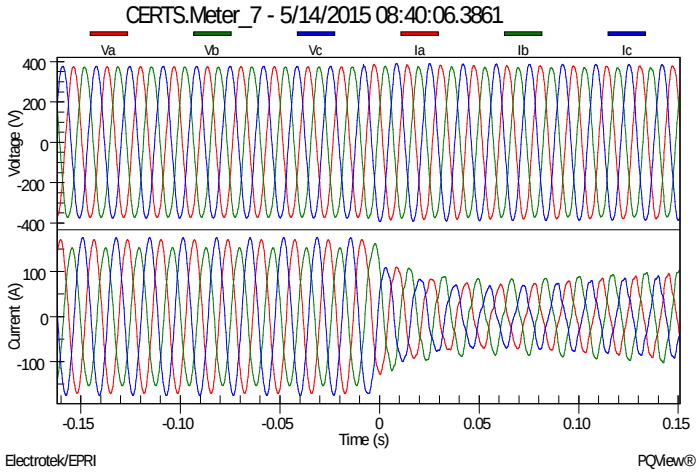

Figure 141: Event J, (80+j60) kVA Discharge to 50 kW Charge, Waveform Voltage & Current (Zoomed)

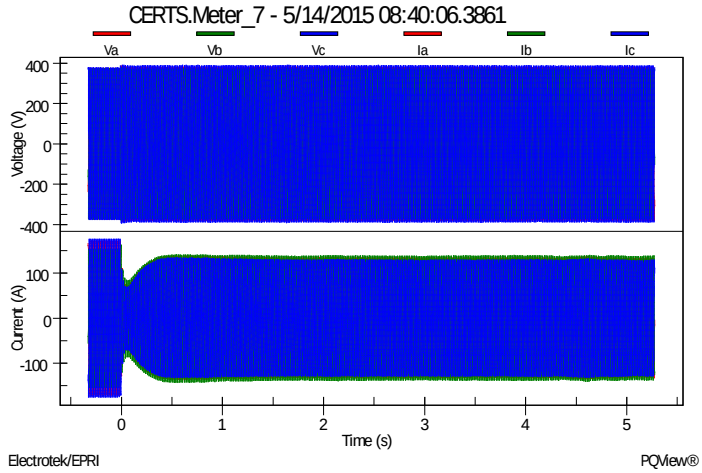

Figure 142: Event J, (80+j60) kVA Discharge to 50 kW Charge, Waveform Voltage & Current

Figure 143 through Figure 147 show the results of Test Event K, a transition from charging at 50 kW grid-connected to discharging at 5 kW islanded. This test represents a transition from the maximum charge rate to a light load case.

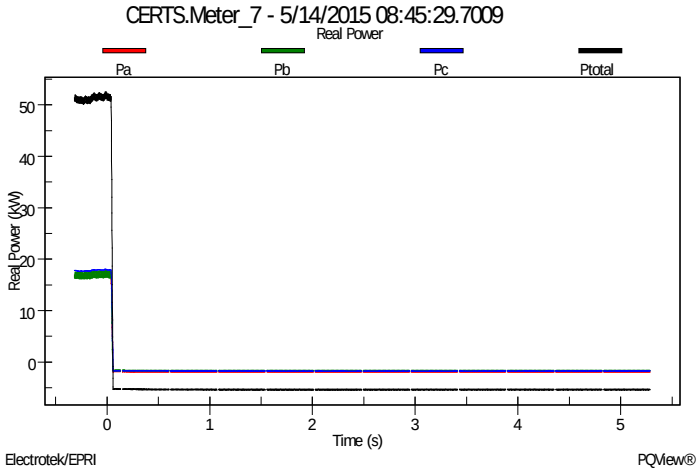

Figure 143: Event K, 50 kW Charge to 5 kW Discharge, Real Power

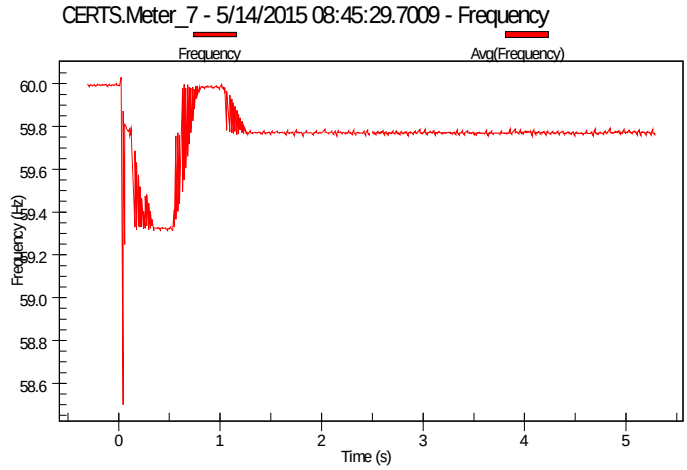

Figure 144: Event K, 50 kW Charge to 5 kW Discharge, Frequency

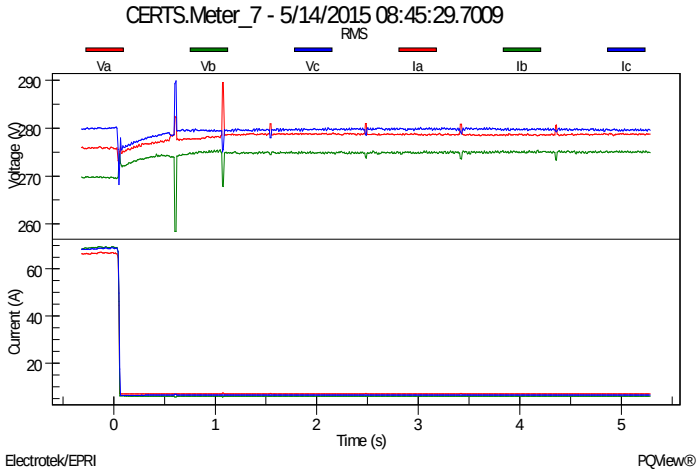

Figure 145: Event K, 50 kW Charge to 5 kW Discharge, RMS Voltage & Current

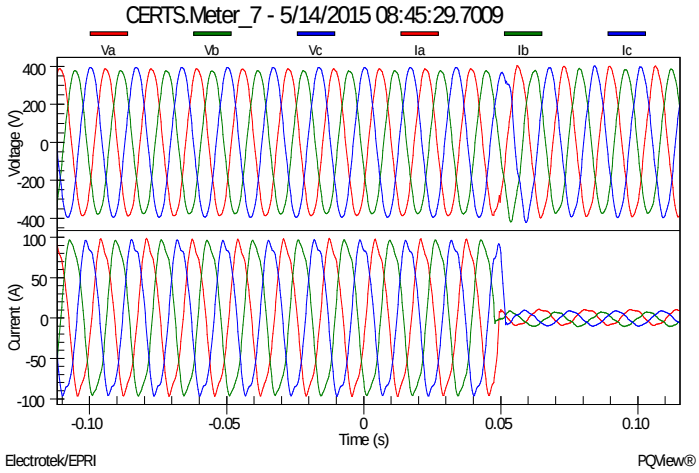

Figure 146: Event K, 50 kW Charge to 5 kW Discharge, Waveform Voltage & Current (Zoomed)

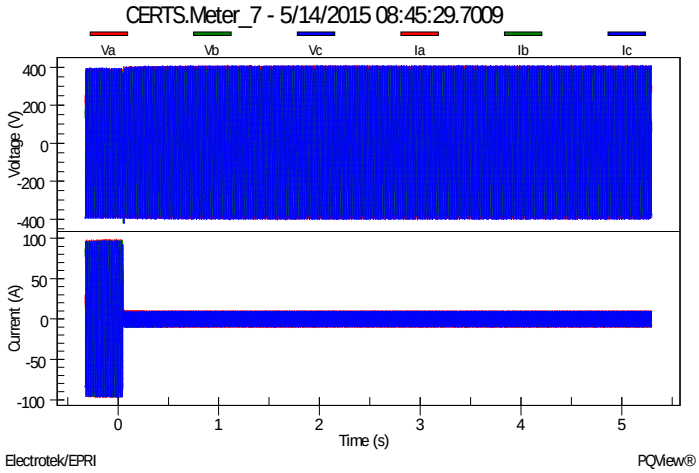

Figure 147: Event K, 50 kW Charge to 5 kW Discharge, Waveform Voltage & Current

Figure 148 through Figure 152 show the results of Test Event L, a transition from discharging at 5 kW islanded to charging at 50 kW grid-connected. This test represents a transition from a light load to the maximum charge rate.

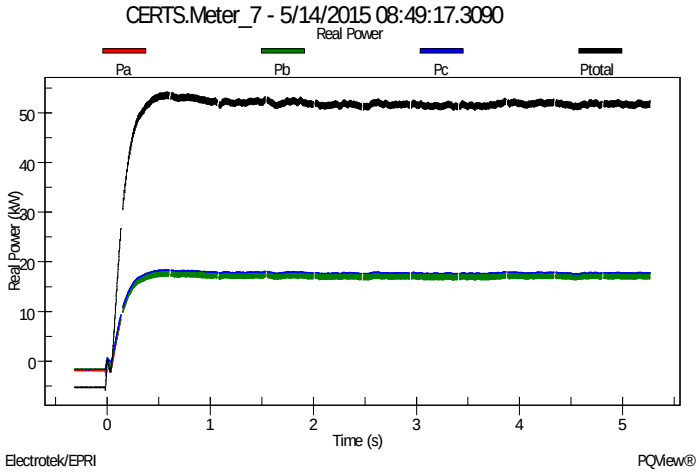

Figure 148: Event L, 5 kW Discharge to 50 kW Charge, Real Power

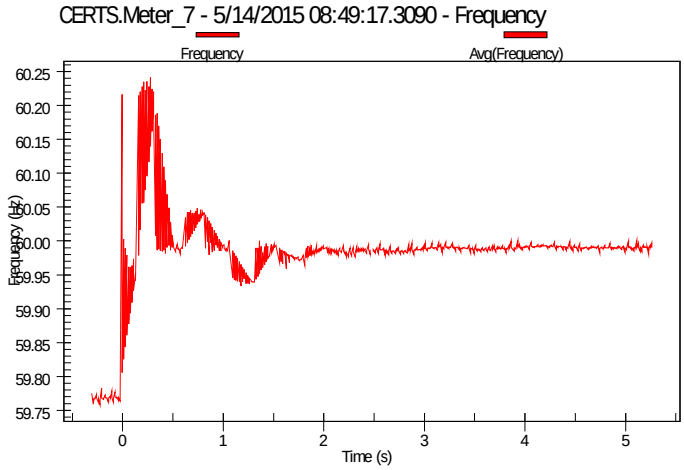

Figure 149: Event L, 5 kW Discharge to 50 kW Charge, Frequency

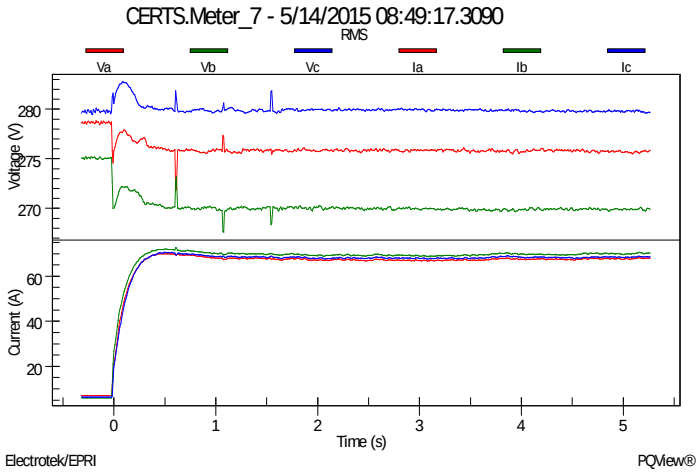

Figure 150: Event L, 5 kW Discharge to 50 kW Charge, RMS Voltage & Current

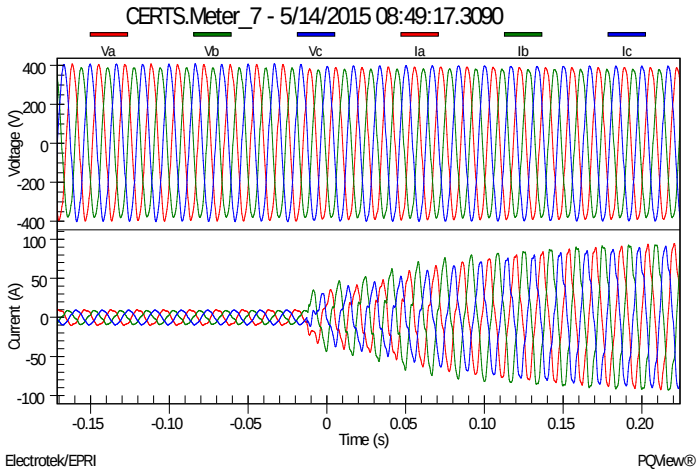

Figure 151: Event L, 5 kW Discharge to 50 kW Charge, Waveform Voltage & Current (Zoomed)

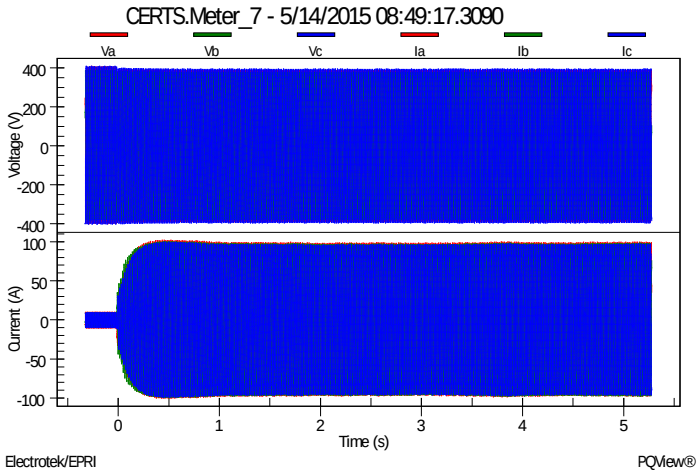

Figure 152: Event L, 5 kW Discharge to 50 kW Charge, Waveform Voltage & Current

Figure 153 through Figure 157 show the results of Test Event Q, a transition from charging at 1.5 kW grid-connected to discharging at 100 kW islanded. This test represents a transition from the minimum charge rate to the maximum load case.

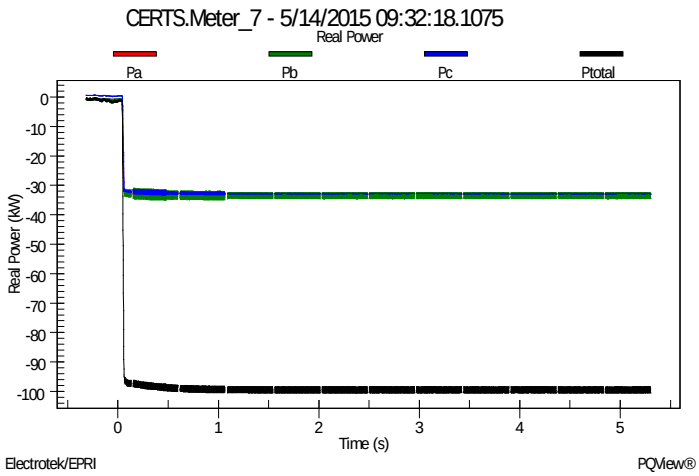

Figure 153: Event Q, 1.5 kW Charge to 100 kW Discharge, Real Power

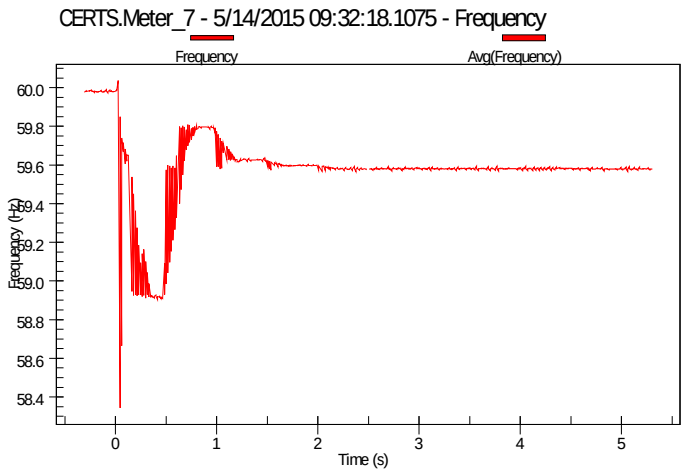

Figure 154: Event Q, 1.5 kW Charge to 100 kW Discharge, Frequency

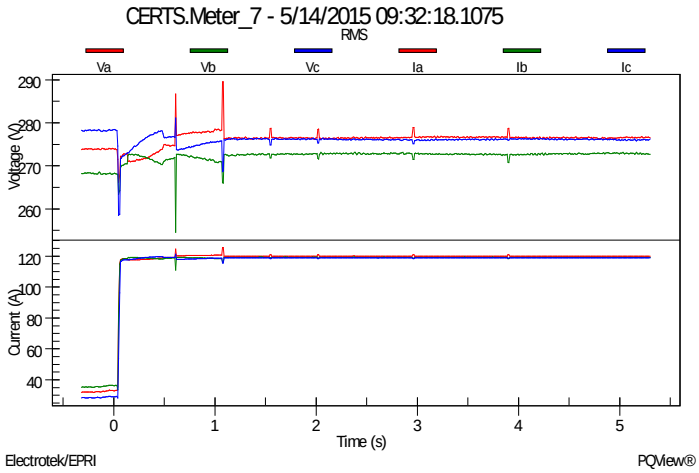

Figure 155: Event Q, 1.5 kW Charge to 100 kW Discharge, RMS Voltage & Current

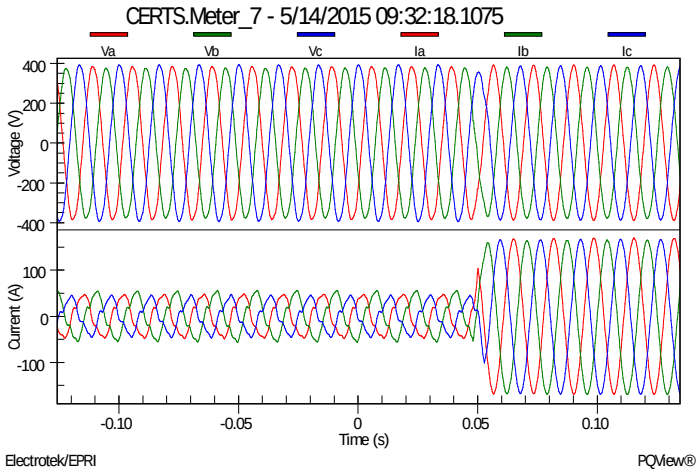

Figure 156: Event Q, 1.5 kW Charge to 100 kW Discharge, Waveform Voltage & Current (Zoomed)

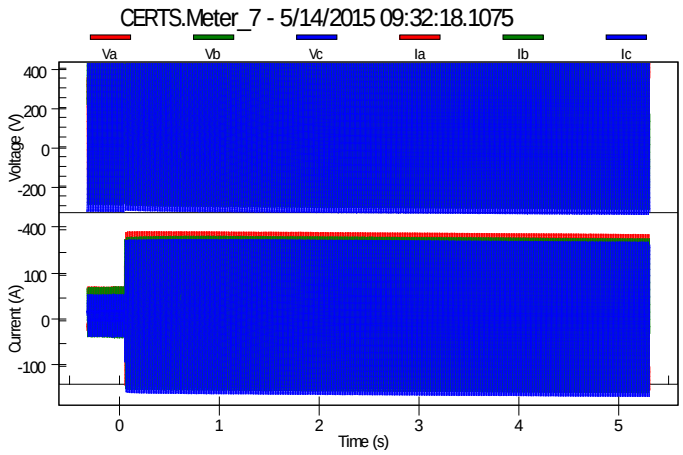

Figure 157: Event Q, 1.5 kW Charge to 100 kW Discharge, Waveform Voltage & Current

Figure 158 through Figure 162 show the results of Test Event R, a transition from discharging at 100 kW islanded to charging at 1.5 kW grid-connected. This test represents a transition from the maximum load to the minimum charge rate. This is another example of the case where a load rejection of greater than 85 kW is successful when transitioning to being grid-connected. Similar transitions when islanded results in the ESS tripping.

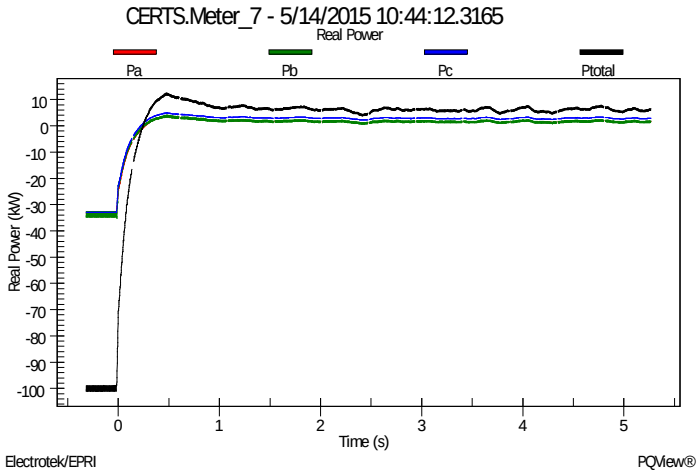

Figure 158: Event R2, 100 kW Discharge to 1.5 kW Charge, Real Power

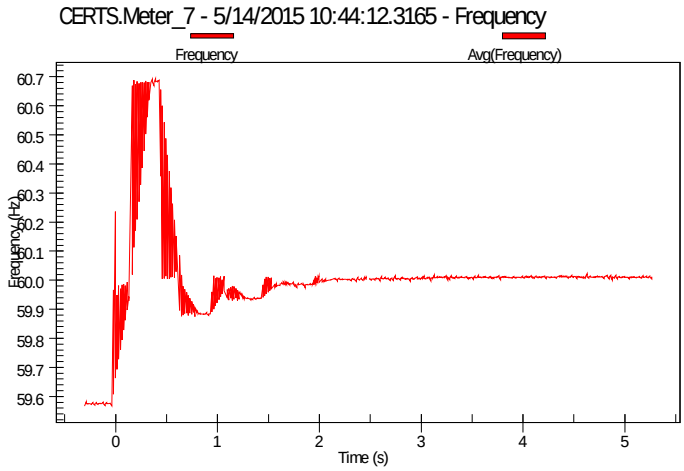

Figure 159: Event R2, 100 kW Discharge to 1.5 kW Charge, Frequency

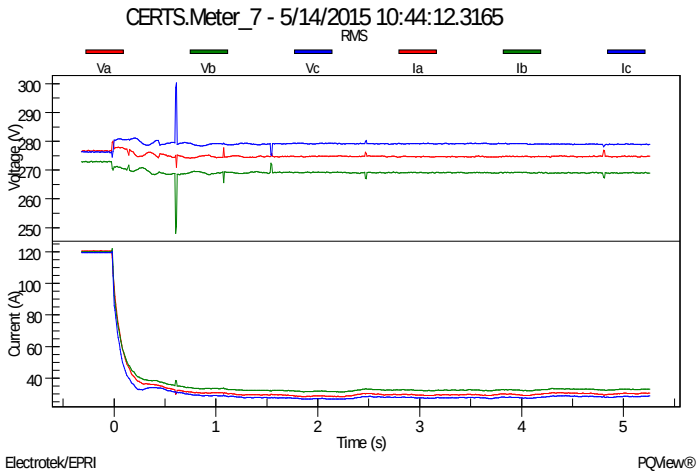

Figure 160: Event R2, 100 kW Discharge to 1.5 kW Charge, RMS Voltage & Current

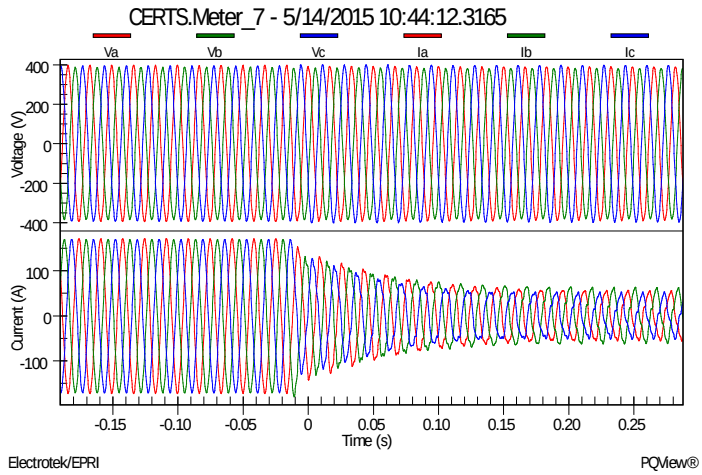

Figure 161: Event R2, 100 kW Discharge to 1.5 kW Charge, Waveform Voltage & Current (Zoomed)

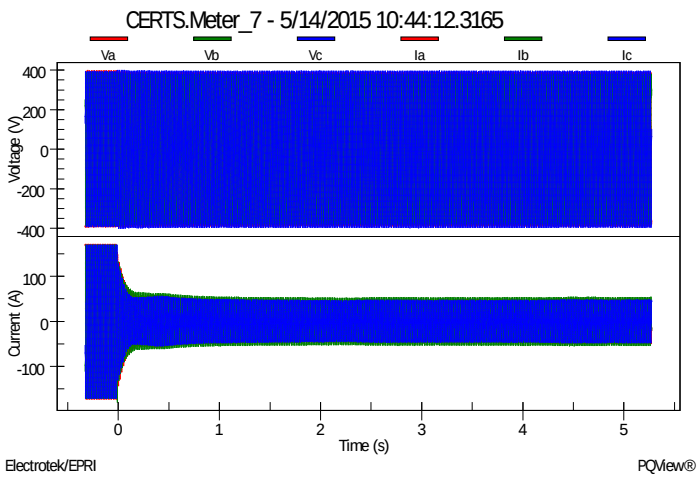

Figure 162: Event R2, 100 kW Discharge to 1.5 kW Charge, Waveform Voltage & Current

5.13 Multiple Unit Load Sharing

Performance Goal

The intent of this test set is to observe how two sources share load during transitions within their normal operating droop range, i.e. without activating P_{max} or P_{min}. These tests are performed with the Tecogen InVerde 100 (A1) and the ESS pair as well as the MTU synchronous gen-set, B1, and the ESS. This will provide an opportunity to evaluate the behavior of two inverter-tied units, A1 and ESS, and a directly coupled and inverter-tied pair, B1 and ESS.

Description of Procedure

Test Events A through P investigate the behavior between A1 and the ESS, both inverter-tied units, while Test Events Q through FF look at B1 and the ESS with B1 being a synchronous gen-set. Initially the microgrid is grid-connected and then transitions to islanded mode. The real power dispatch values for

the units are set both the same and differently during the test to determine if initial loading has an effect on load sharing. Microgrid load values are set both above and below total dispatch levels to confirm behavior of the droop curves in both directions. Finally, tests are conducted to cause the ESS to transition between charging and discharging.

Figure 163, below, shows an example of two units' (ESS and A1) frequency vs. real power droop characteristics and the composite droop curve created by their interaction. This particular example corresponds to Test Events E-H where the ESS is dispatched at 30 kW and A1 at 80 kW. The composite droop curve can be used to determine how the units will share the total load and what the microgrid frequency should be in the islanded case. The composite droop curve is determined by summing the real power output from each unit at each frequency in the system's frequency operating range. For example, looking at the frequency of 59.9 Hz in Figure 163 below it is shown that the ESS would output 50 kW and A1 96 kW for a total of 146 kW (the green Composite Droop line). Once this is done for all frequencies the composite droop line can be drawn. The composite droop line can then be used to determine the system's frequency for a given system load. Once the system frequency is known, each unit's real power contribution can also be determined. This method can be extended to any number of units in a microgrid system.

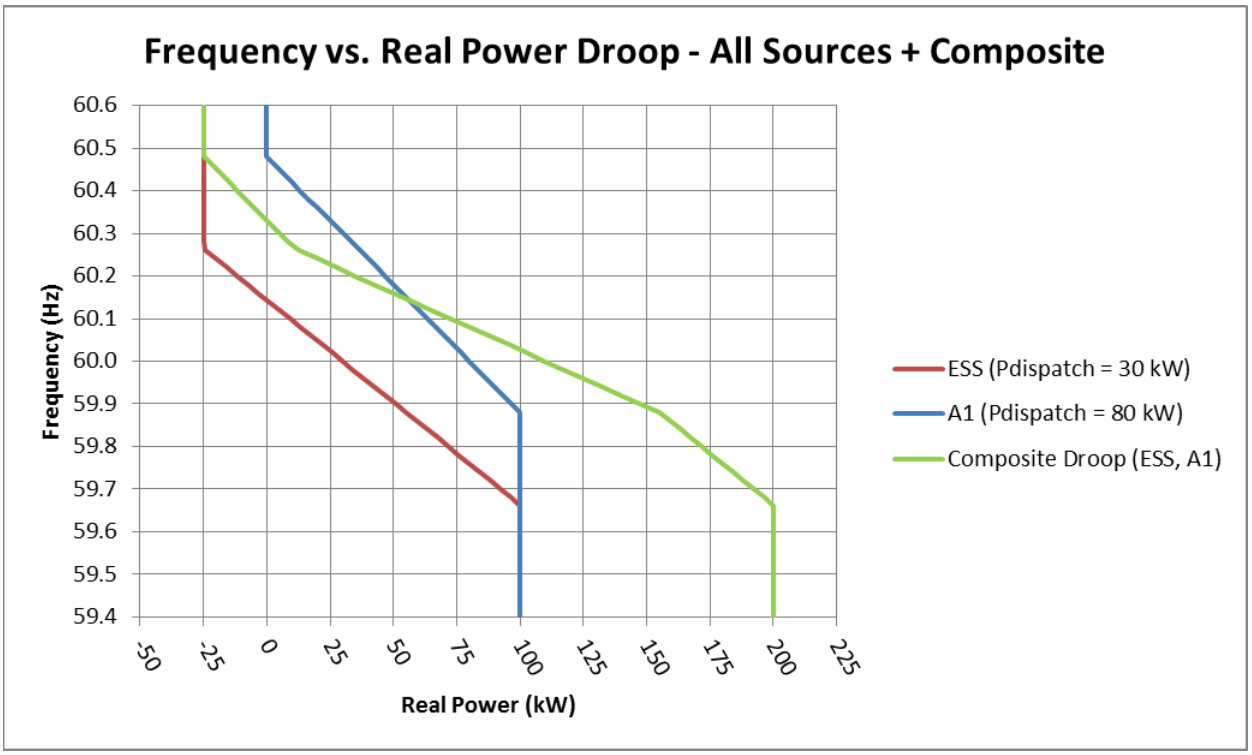

Figure 163: Composite Droop Characteristic Example (Test Events E-H)

Test Settings

For these tests the following parameters are set as follows:

<u>ESS</u>

Pdispatch = Varies

Frequency Droop = 1%
Real Power-Frequency Droop = -.0048 Hz/kW
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -25 kW (P_{min} = Battery Power Limit Min parameter on inverter)
Voltage Set Point = 480 V_{LL} (Inverter Voltage Reference = 102.5 per PPS)
Voltage Droop = -0.24 V_{LL}/kVAr (5%)
Voltage Regulation P-gain = 0.4
Voltage Regulation I-gain = 16

<u>A1 (Inverde 100)</u>
Pdispatch = Varies
Frequency Droop = 1%
Real Power-Frequency Droop = -.006 Hz/kW
P_{max} = 100 kW
P_{min} = 0 kW
Voltage Set Point = 480 V_{LL}
Voltage Droop = -0.14 V_{LN}/kVAr (5%)

<u>B1 (Sync Gen)</u>
Pdispatch = Varies
Frequency Droop = 1%
Real Power-Frequency Droop = -.006452 Hz/kW
P_{max} = 93 kW
P_{min} = 0 kW
Voltage Set Point = 480 V_{LL}
Voltage Droop = -0.24 V_{LL}/kVAr (5%)

During each sequence of tests in Table 25, a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers “Closed”; all load banks initially set at zero; load banks are set as close as possible to the prescribed values; reactive load is set to achieve a power factor of approximately 0.9 lagging inside the microgrid (excludes load bank 6 which is outside of the microgrid); and events are triggered based on the transition of the GIS.

	Dispatch			Pre-Event Loads (pf = 0.9)			Pre-Event Meter Values					Islanded	
Test Event	A1 (kW)	ESS (kW)	B1 (kW)	L3 (A1) or L5 (B1) (kW)	L 4 (kW)	L 6 (kW)	A1 (kW)	Meter 3 (kW)	B1 (kW)	Meter 7 (kW)	SS (kW)	Freq (Hz)	GIS
A	50	50	-	30	30	60	50	10	0	-50	-40	60.107	Closed → Open
B	50	50	-	30	30	60	32.2	27.8	0	-27.8	-	60.107	Open → Closed
C	50	50	-	70	70	0	50	90	0	-50	40	59.893	Closed → Open
D	50	50	-	70	70	0	67.8	72.2	0	-72.2	-	59.893	Open → Closed
E	80	30	-	70	70	0	80	60	0	-30	30	59.92	Closed → Open
F	80	30	-	70	70	0	93.3	46.7	0	-46.7	-	59.92	Open → Closed
G	80	30	-	40	40	50	80	0	0	-30	-30	60.08	Closed → Open
H	80	30	-	40	40	50	67.7	13.3	0	-13.3	-	60.08	Open → Closed
I	30	80	-	30	30	70	30	30	0	-80	-50	60.133	Closed → Open
J	30	80	-	30	30	70	7.8	52.2	0	-52.2	-	60.133	Open → Closed
K	30	80	-	65	65	0	30	100	0	-80	20	59.947	Closed → Open
L	30	80	-	65	65	0	38.9	91.1	0	-91.1	-	59.947	Open → Closed
M	50	-10	-	65	65	0	50	80	0	10	90	59.76	Closed → Open
N	50	-10	-	65	65	0	90	40	0	-40	-	59.76	Open → Closed
O	65	10	-	30	0	65	65	-35	0	-10	-45	60.12	Closed → Open
P	65	10	-	30	0	65	45	-15	0	15	-	60.12	Open → Closed
Q	-	50	50	30	30	60	0	60	50	-50	-40	60.11	Closed → Open
R	-	50	50	30	30	60	0	60	32.9	-27.1	-	60.11	Open → Closed
S	-	50	50	70	70	0	0	140	50	-50	40	59.89	Closed → Open
T	-	50	50	70	70	0	0	140	67.1	-72.9	-	59.89	Open → Closed
U	-	30	80	70	70	0	0	140	80	-30	30	59.917	Closed → Open
V	-	30	80	70	70	0	0	140	-2.8	-47.2	-	59.917	Open → Closed
W	-	30	80	40	40	50	0	80	80	-30	-30	60.083	Closed → Open

	Dispatch			Pre-Event Loads (pf = 0.9)			Pre-Event Meter Values					Islanded	
Test Event	A1 (kW)	ESS (kW)	B1 (kW)	L3 (A1) or L5 (B1) (kW)	L 4 (kW)	L 6 (kW)	A1 (kW)	Meter 3 (kW)	B1 (kW)	Meter 7 (kW)	SS (kW)	Freq (Hz)	GIS
X	-	30	80	40	40	50	0	80	67.2	-12.8	-	60.083	Open → Closed
Y	-	80	30	30	30	70	0	60	30	-80	-50	60.138	Closed → Open
Z	-	80	30	30	30	70	0	60	8.7	-51.3	-	60.138	Open → Closed
AA	-	80	30	65	65	0	0	130	30	-80	20	59.945	Closed → Open
BB	-	80	30	65	65	0	0	130	38.5	-91.5	-	59.945	Open → Closed
CC	-	-10	50	65	65	0	0	130	50	10	90	59.752	Closed → Open
DD	-	-10	50	65	65	0	0	130	88.4	-41.6	-	59.752	Open → Closed
EE	-	10	65	30	0	65	0	30	65	-10	-45	60.124	Closed → Open
FF	-	10	65	30	0	65	0	30	45.8	15.8	-	60.124	Open → Closed

Table 25: Multiple Unit Load Sharing

Test Results

The test results for multiple unit load sharing between the ESS and A1 are summarized in Table 26.

Test Event	Pre-Event							Post-Event														Pass/ Fail
	Generator A1			Energy Storage System			Freq (Hz)	Generator A1				Energy Storage System				Total		Voltage (V)	Actual Freq (Hz)	Expected Freq (Hz)	Freq Delta (Hz)	
	Dispatch (kW)	Real Power (kW)	Reactive Power (kVAr)	Dispatch (kW)	Real Power (kW)	Reactive Power (kVAr)		Actual Real Power (kW)	Actual Reactive Power (kVAr)	Expected Real Power (kW)	Real Power Delta (kW)	Actual Real Power (kW)	Actual Reactive Power (kVAr)	Expected Real Power (kW)	Real Power Delta (kW)	Actual Real Power (kW)	Actual Reactive Power (kVAr)					
A	50	45.20	6.05	50	49.60	25.35	59.99	31.72	6.12	34.36	-2.64	33.10	23.72	30.46	2.64	64.82	29.84	273.72	60.08	60.09	-0.01	Pass
B	50	31.57	6.12	50	33.05	23.57	60.07	43.48	5.95	46.11	-2.63	47.77	25.62	45.14	2.63	91.25	31.57	272.94	60.00	60.02	-0.02	Pass
C	50	46.07	15.68	50	50.50	37.99	59.98	66.33	17.09	68.32	-1.99	74.90	50.58	72.91	1.99	141.23	67.67	267.72	59.87	59.89	-0.02	Pass
D	50	66.34	17.36	50	74.67	50.41	59.87	47.34	15.05	49.80	-2.46	52.22	39.71	49.76	2.46	99.56	54.76	270.62	60.00	60.00	0.00	Pass
E	80	77.99	8.54	30	33.05	44.66	59.97	91.55	10.18	93.45	-1.90	48.72	57.54	46.82	1.90	140.27	67.72	267.42	59.90	59.92	-0.02	Pass
F	80	91.58	10.06	30	48.76	57.64	59.89	80.31	7.60	82.57	-2.26	35.48	43.27	33.22	2.26	115.79	50.87	270.28	59.97	59.98	-0.01	Pass
G	80	73.19	2.59	30	26.57	34.20	60.00	65.02	4.18	67.18	-2.16	16.14	34.74	13.98	2.16	81.16	38.92	275.52	60.06	60.08	-0.02	Pass
H	80	64.95	4.05	30	16.27	34.77	60.05	75.66	2.47	77.92	-2.26	29.65	35.03	27.39	2.26	105.31	37.50	272.08	60.00	60.01	-0.01	Pass
I	30	28.14	11.19	80	81.22	22.27	59.97	5.16	11.04	7.48	-2.32	54.18	18.16	51.86	2.32	59.34	29.20	273.97	60.11	60.14	-0.03	Pass
J	30	5.18	11.00	80	53.99	18.15	60.09	23.71	11.67	25.54	-1.83	76.26	21.87	74.43	1.83	99.97	33.54	272.65	60.00	60.03	-0.03	Pass
K	30	26.87	15.99	80	80.52	25.90	59.98	37.48	20.06	39.28	-1.80	93.41	37.49	91.61	1.80	130.89	57.55	269.20	59.92	59.94	-0.02	Pass
L	30	37.31	20.58	80	92.96	37.07	59.91	26.96	16.23	28.99	-2.03	80.76	25.34	78.73	2.03	107.72	41.57	271.51	60.00	60.01	-0.01	Pass
M	50	40.69	13.87	-10	-16.17	45.11	59.84	87.11	8.56	89.78	-2.67	42.39	49.30	39.72	2.67	129.50	57.86	268.79	59.75	59.76	-0.01	Pass
N	50	87.28	8.44	-10	42.15	49.42	59.78	43.86	13.85	46.15	-2.29	-12.53	45.87	-14.82	2.29	31.33	59.72	271.18	60.00	60.02	-0.02	Pass
O	65	59.36	-2.34	10	9.73	24.69	60.06	42.53	-6.20	45.09	-2.56	-12.33	16.46	-14.89	2.56	30.20	10.26	276.19	60.10	60.12	-0.02	Pass
P	65	42.57	-7.15	10	-12.01	17.32	60.10	61.62	-1.74	64.46	-2.84	12.16	25.48	9.32	2.84	73.78	23.74	273.91	60.00	60.00	0.00	Pass

Table 26: Multiple Unit Load Sharing Test Results (ESS & A1)

The test results for multiple unit load sharing between the ESS and B1 are summarized in Table 27.

Test Event	Pre-Event							Post-Event														Pass/ Fail
	Generator B1			Energy Storage System			Freq (Hz)	Generator B1				Energy Storage System				Total		Voltage (V)	Actual Freq (Hz)	Expected Freq (Hz)	Freq Delta (Hz)	
	Dispatch (kW)	Real Power (kW)	Reactive Power (kVAr)	Dispatch (kW)	Real Power (kW)	Reactive Power (kVAr)		Actual Real Power (kW)	Actual Reactive Power (kVAr)	Expected Real Power (kW)	Real Power Delta (kW)	Actual Real Power (kW)	Actual Reactive Power (kVAr)	Expected Real Power (kW)	Real Power Delta (kW)	Actual Real Power (kW)	Actual Reactive Power (kVAr)					
Q	50	46.15	26.59	50	45.48	7.21	60.02	28.85	18.00	32.88	-4.03	31.03	12.04	27.00	4.03	59.88	30.04	274.35	60.08	60.11	-0.03	Pass
R	50	32.40	18.61	50	27.46	11.91	60.09	49.96	29.02	47.79	2.17	44.86	5.76	47.03	-2.17	94.82	34.78	275.51	60.00	60.01	-0.01	Pass
S	50	49.87	44.12	50	48.74	20.84	60.01	75.93	43.63	68.17	7.76	66.67	29.55	74.43	-7.76	142.60	73.18	270.99	59.92	59.88	0.03	Pass
T	50	68.47	44.45	50	73.71	28.60	59.87	51.67	44.68	52.44	-0.77	54.04	18.15	53.27	0.77	105.71	62.83	273.07	60.00	59.98	0.02	Pass
U	80	77.34	35.67	30	23.53	17.61	59.99	94.02	35.70	90.80	3.22	41.29	25.57	44.51	-3.22	135.31	61.27	272.17	59.92	59.93	-0.01	Pass
V	80	92.32	34.93	30	42.92	26.21	59.93	87.46	35.00	81.14	6.32	25.21	17.53	31.53	-6.32	112.67	52.53	273.94	60.00	59.99	0.01	Pass
W	80	75.56	35.44	30	21.46	16.36	60.03	67.21	20.69	68.73	-1.52	16.38	19.20	14.86	1.52	83.59	39.89	273.50	60.08	60.07	0.01	Pass
X	80	69.62	22.68	30	14.45	18.13	60.06	76.50	36.42	75.73	0.77	23.48	16.31	24.25	-0.77	99.98	52.73	274.52	60.00	60.03	-0.03	Pass
Y	30	26.06	36.66	80	74.37	8.68	60.02	3.20	20.72	10.72	-7.52	61.60	9.55	54.08	7.52	64.80	30.27	273.93	60.08	60.12	-0.04	Pass
Z	30	10.71	21.13	80	53.68	9.33	60.11	33.77	38.69	30.68	3.09	77.82	4.19	80.91	-3.09	111.59	42.88	274.97	60.00	60.00	0.00	Pass
AA	30	28.28	44.55	80	74.57	14.51	60.02	42.68	38.77	39.64	3.04	89.91	21.86	92.95	-3.04	132.59	60.63	271.63	59.92	59.94	-0.02	Pass
BB	30	39.85	40.72	80	92.92	20.08	59.95	24.47	48.35	26.32	-1.85	76.91	14.22	75.06	1.85	101.38	62.57	273.23	60.00	60.02	-0.02	Pass
CC	50	48.56	45.50	-10	-11.24	28.39	59.99	94.11	38.87	90.63	3.48	41.12	22.35	44.60	-3.48	135.23	61.22	272.30	59.76	59.74	0.02	Pass
DD	50	90.39	34.50	-10	42.56	26.55	59.73	38.19	47.51	43.92	-5.73	-12.44	29.48	-18.17	5.73	25.75	76.99	273.18	60.00	60.04	-0.04	Pass
EE	65	67.49	24.07	10	10.67	10.35	60.00	41.21	2.66	45.36	-4.15	-12.25	7.47	-16.40	4.15	28.96	10.13	275.52	60.09	60.13	-0.04	Pass
FF	65	47.64	3.89	10	-18.01	7.65	60.13	68.48	27.83	65.87	2.61	8.57	9.94	11.18	-2.61	77.05	37.77	276.41	60.00	59.99	0.01	Pass

Table 27: Multiple Unit Load Sharing Test Results (ESS & B1)

Analysis

The ESS in combination with A1 successfully passes all multiple unit load sharing test cases related to real power load sharing and frequency expectations when transitioning between grid-tied and islanded modes of operation. This includes the ability of the ESS to transition between charging and discharging during a disconnection or reconnection between the microgrid and the utility.

The sources share the real power load according to their frequency vs. real power droop settings. There is an average bias of 2.29 kW toward the ESS sourcing more real power than expected and A1 sourcing less than expected. This bias is relatively consistent, ranging from 1.8 kW to 2.84 kW, over the range of dispatch and loading values. A comparison of the actual and expected amounts of real power provided by each source is shown in Figure 164.

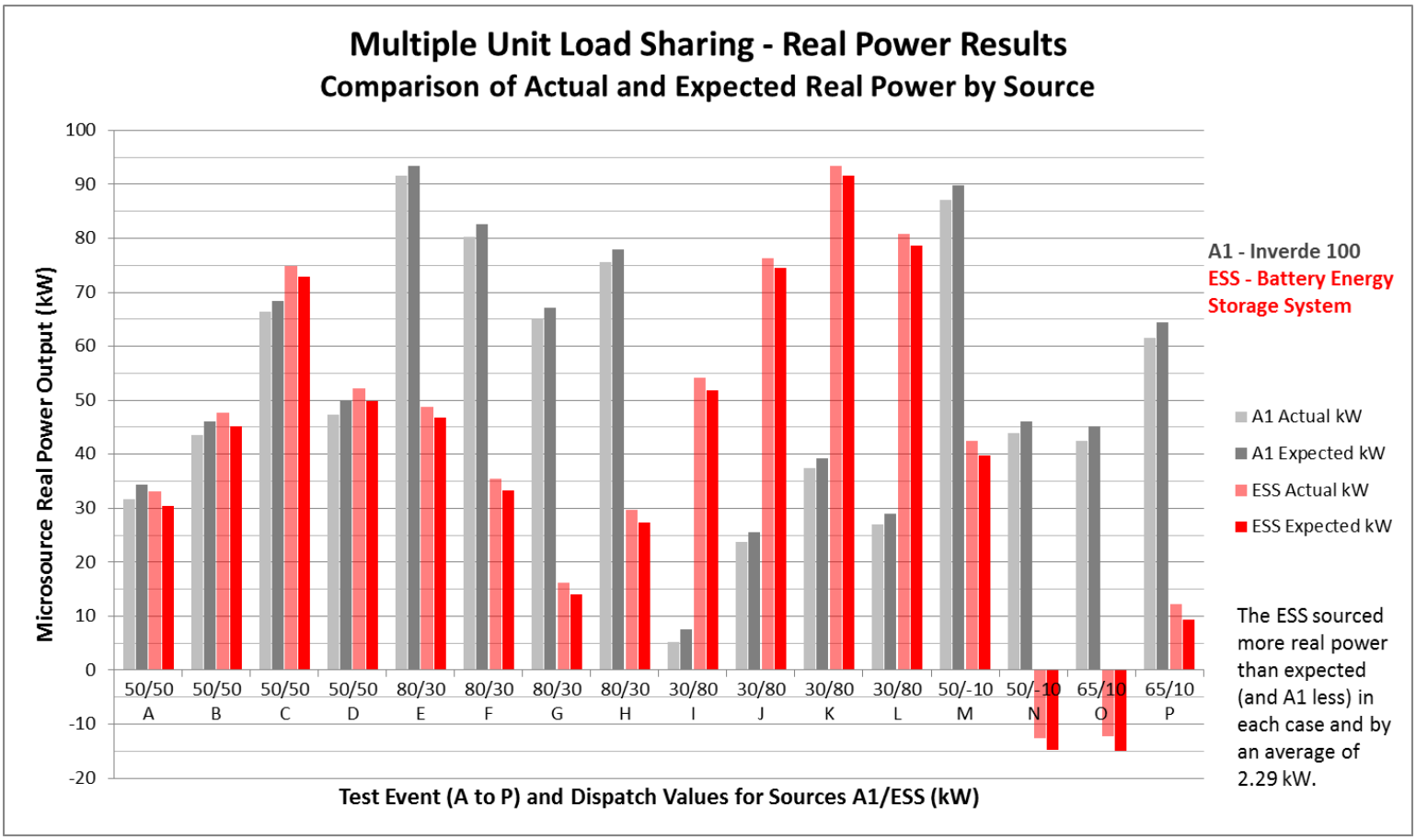

Figure 164 - Multiple Unit Load Sharing, ESS & A1, Real Power

The microgrid frequency also reaches a steady state value within acceptable performance criteria. On average, the actual frequency is 0.017 Hz, or 0.027%, less than the expected frequency based on the total power sourced by the ESS and A1. A comparison of the actual and expected frequencies for each test case is shown in Figure 165.

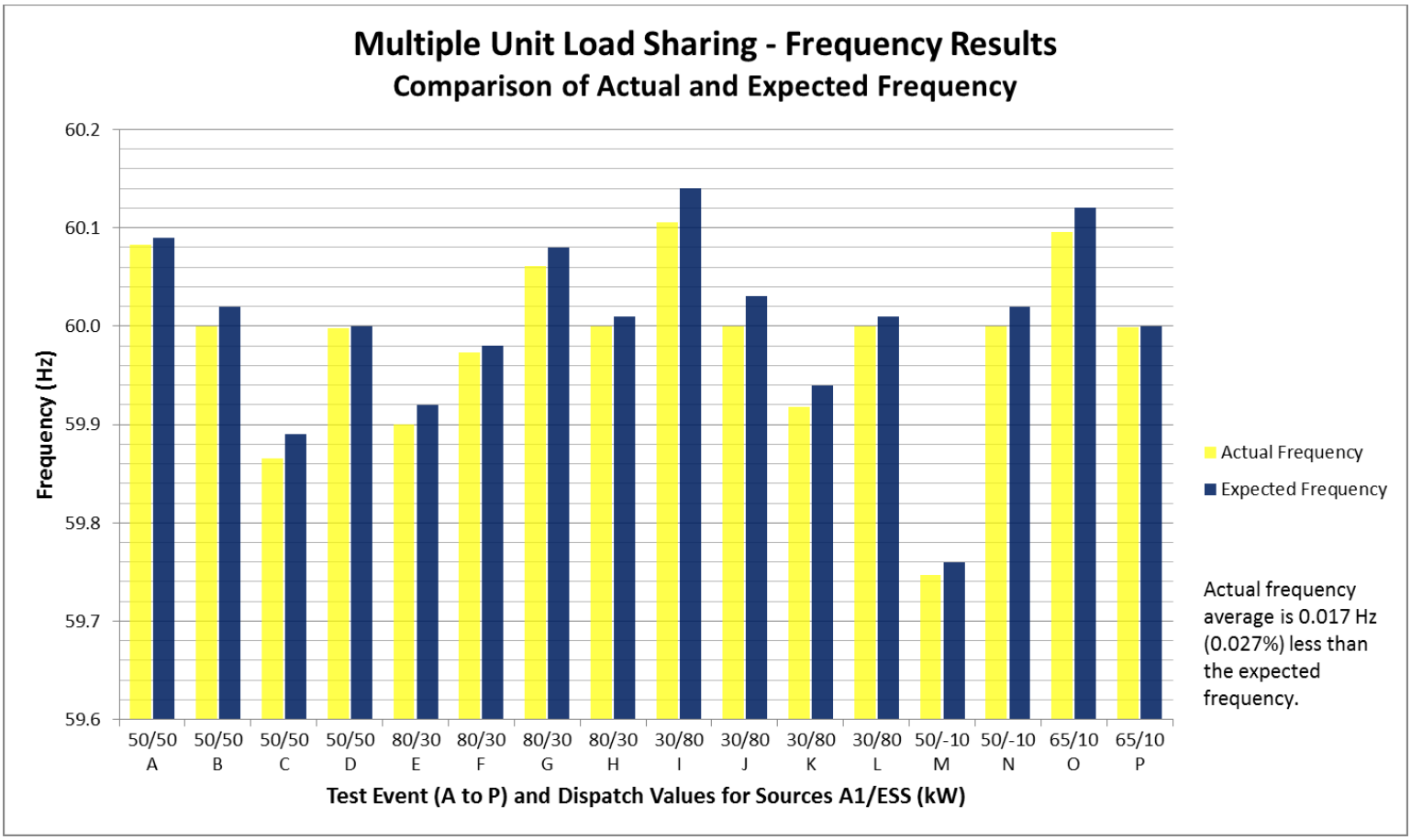

Figure 165 - Multiple Unit Load Sharing, ESS & A1, Frequency

The reactive load is not shared as expected in any of the test cases. Both sources have the same voltage vs. reactive power droop settings of 480V, 5% droop, +/- 100 kVAr. Given the network topology in this case where A1 is electrically closer the loads (i.e. has a lower impedance path) than the ESS, it is reasonable to assume that A1 would provide more reactive power than the ESS in general with the possible exceptions of when the ESS is in the charging mode or A1 is providing significantly more power than the ESS. However, in all cases the ESS supplies the majority of the reactive power. This is shown in Figure 166. This is due to A1's voltage droop not behaving as it should and having an effective droop slope larger than its set point. It should be noted that A1 did not originally pass its voltage droop acceptance test which is reported in "CERTS Microgrid Tecogen InVerde INV100 Test Report", dated March 5, 2012.

A1's voltage droop characteristics are revisited under a separate test plan. It is confirmed that the unit does not exhibit the expected droop behavior. In all cases, the slope of the voltage droop characteristics are significantly more negative than expected meaning that the voltage is lowered more than expected for a given reactive load.

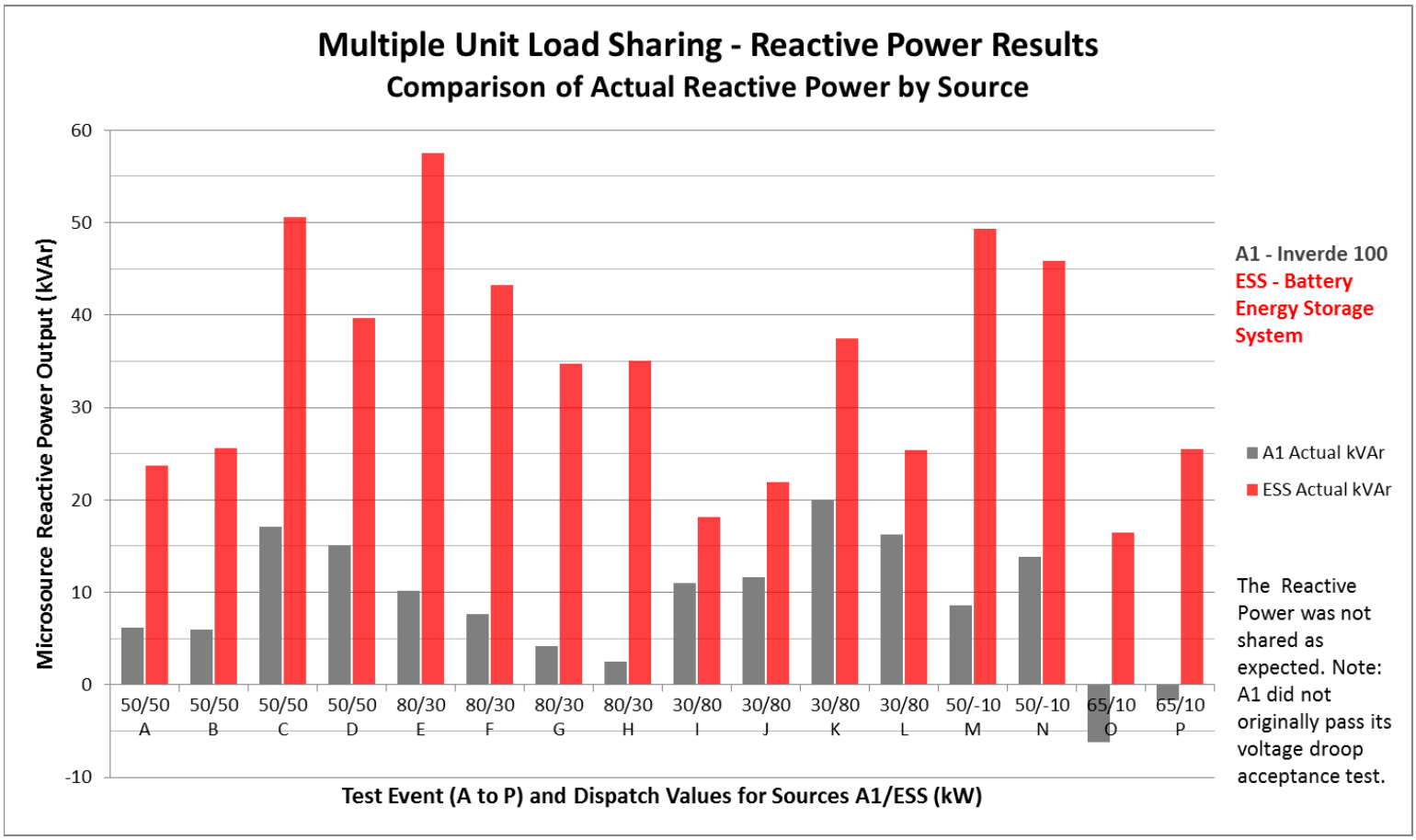

Figure 166: Multiple Unit Load Sharing, ESS & A1, Reactive Power

An oscillation of approximately 9 Hz is observed in the voltage and current RMS values as well as the real and reactive power from the sources in some of the events. This is exemplified in Figure 167 which shows the RMS voltage and current graphs for Event A, where both the ESS and A1 are dispatched to 50 kW (100 kW total) and the microgrid test bed has an approximate load of (60 + j30) kVA. The oscillation is seen both before and after the transition to the islanded state.

This phenomenon generally occurs when the reactive load of the microgrid is less than 45 kVAr. The oscillation exists regardless of whether the microgrid is operating islanded or grid-tied. The oscillation disappears when the reactive load of the microgrid exceeds approximately 45 kVAr. Events where the reactive load of the microgrid is less than 45 kVAr include: A, B, G, H, I, J, L, O, and P.

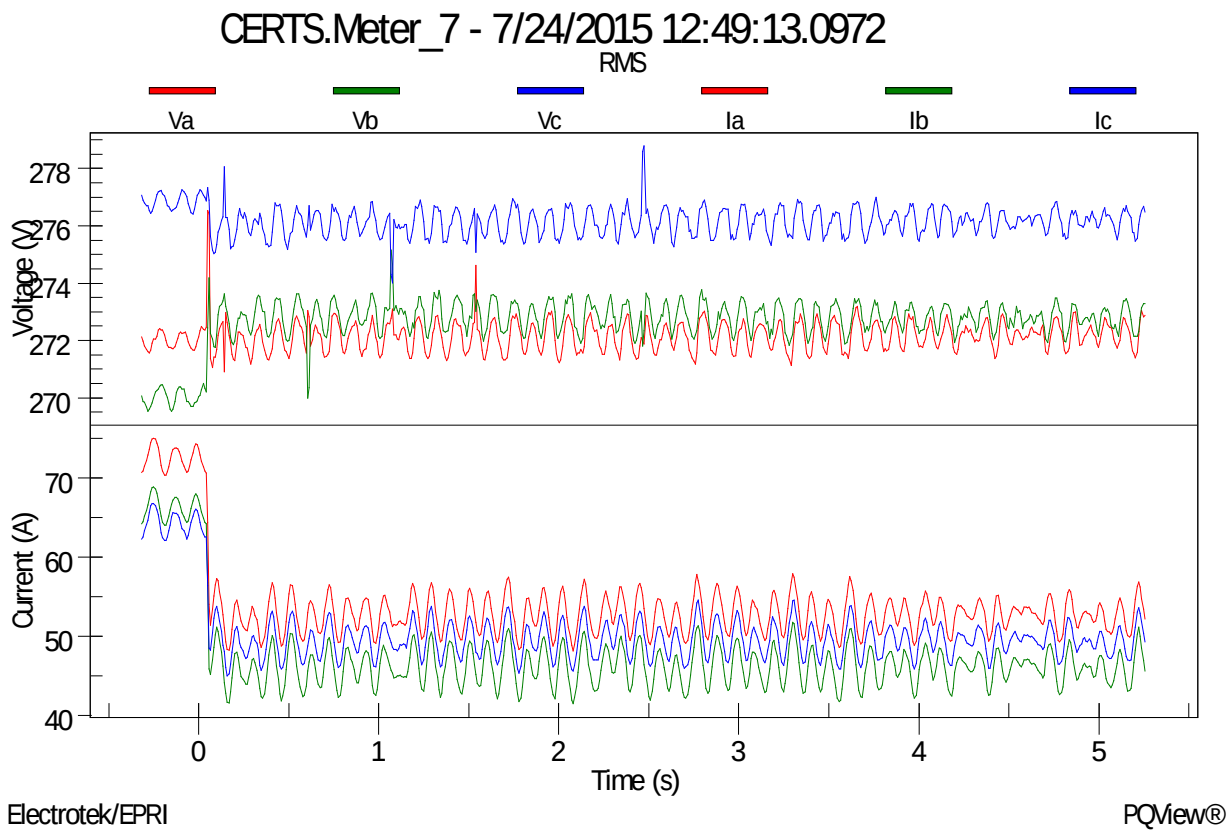

Figure 167 - Event A, RMS Voltage & Current, A1 & ESS Dispatched at 50 kW Each, Transition to Islanded State with 60 kW Load

The ESS in combination with B1 successfully passes all multiple unit load sharing test cases related to real power load sharing and frequency expectations when transitioning between grid-tied and islanded modes of operation. This includes the ability of the ESS to transition between charging and discharging during a disconnection or reconnection between the microgrid and the utility.

The sources share the real power load according to their frequency vs. real power droop settings. There is a slight average bias of 0.43 kW toward B1 sourcing more real power than expected and A1 sourcing less than expected. However, in 7 of the 16 test events the ESS sources more real power than B1. The bias in favor of B1 ranges from 7.76 kW to -7.52 kW. A comparison of the actual and expected amounts of real power provided by each source is shown in Figure 168. It should be noted that in three of the eight test events that resulted in the islanded condition, the system does not quite reach steady for real power flow in the 5 second recording time of the data acquisition system. This would result in an increase in the difference between the actual and expected power values listed in Table 27 on page 106.

The reason for the delay in reaching steady state within the 5 second window seems to be the difference between the speed of the controllers for each DER. The ESS's controller is much faster than B1's so it tends to take on the change in power when an event occurs. B1's controller then gradually responds to difference in frequency between the two units. While these tests are designed not to

activate the P_{max} functionality on either unit, P_{max} is activated in some cases primarily due to the difference in the speed of the controllers.

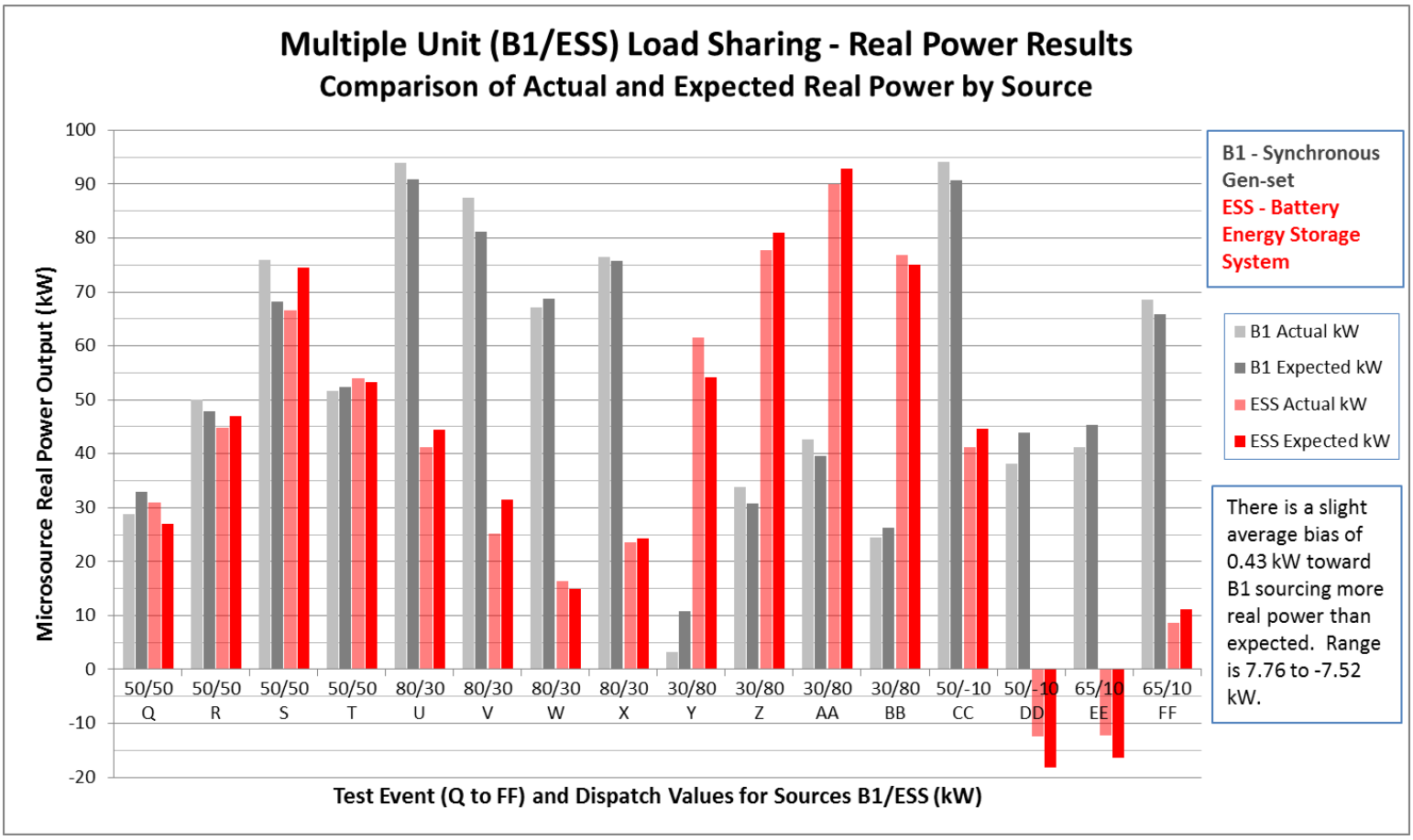

Figure 168: Multiple Unit Load Sharing, ESS & B1, Real Power

The microgrid frequency also reaches a steady state value within acceptable performance criteria. On average, the actual frequency is 0.009 Hz, less than the expected frequency based on the total real power sourced by the ESS and B1. The difference between the actual and expected frequency ranges from -0.04 Hz to 0.03 Hz. The average variation is 0.035%. A comparison of the actual and expected frequencies for each test case is shown in Figure 169.

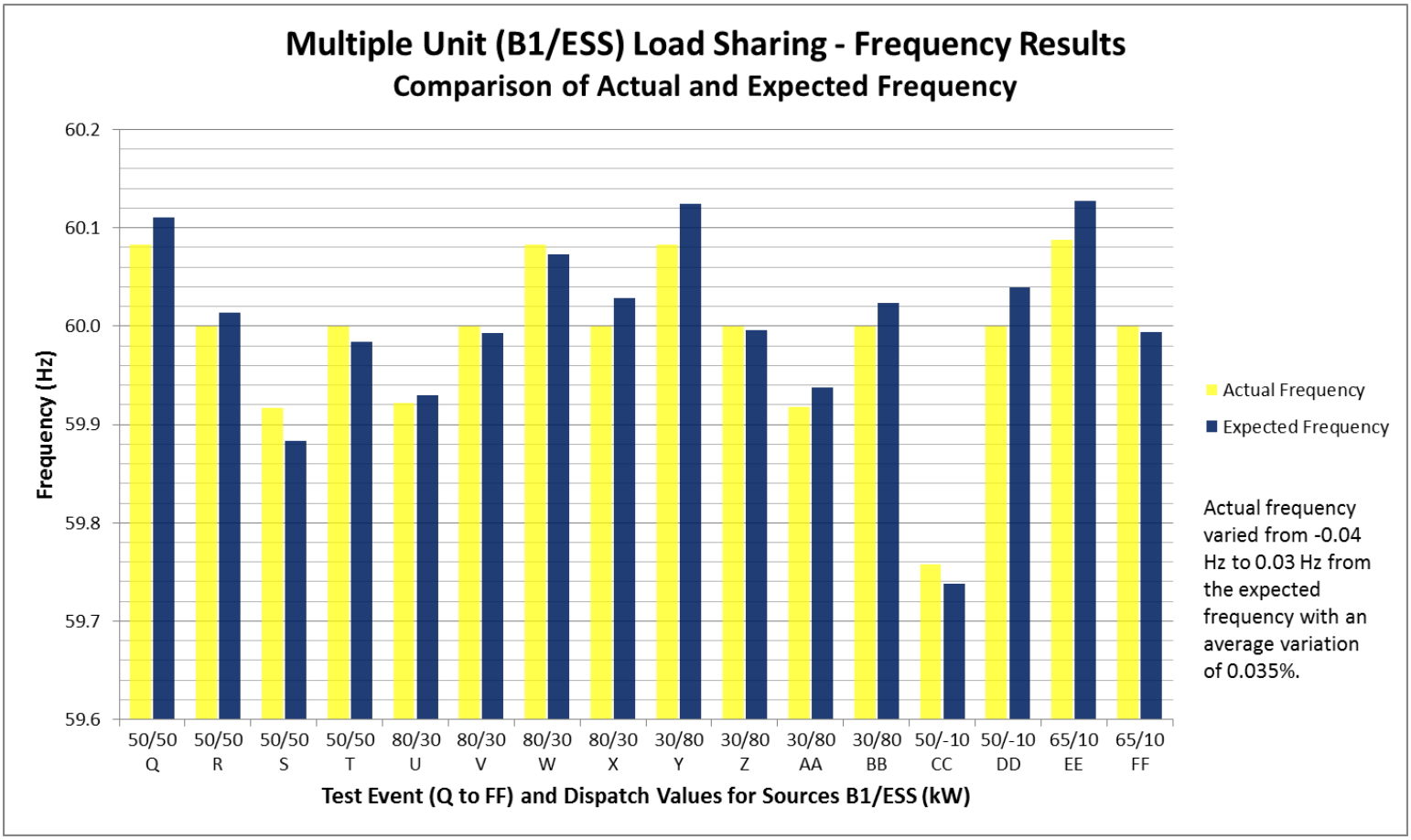

Figure 169: Multiple Unit Load Sharing, ESS & B1, Frequency

The reactive load is shared as expected between B1 and the ESS. Both sources have the same voltage vs. reactive power droop settings of 480V, 5% droop, +/- 100 kVAr. Given the network topology in this case where B1 is electrically closer the loads (i.e. has a lower impedance path) than the ESS, it is reasonable to assume that B1 would provide more reactive power than the ESS in general with the possible exceptions of when the ESS is in the charging mode or B1 is providing significantly more power than the ESS. Figure 170 shows the results of the reactive power sharing between B1 and the ESS.

B1, as expected, supplies more reactive power than the ESS in all cases except Event EE which is an islanded case where the ESS is in charge mode consuming 12 kW and B1 is supplying 41 kW.

It should be noted that in five of the eight test events that result in the islanded condition, the system does not quite reach steady for reactive power flow in the 5 second recording time of the data acquisition system. However, in all such cases the system is headed toward steady state and the data in Figure 170 is representative of the expected results. The five events that had not quite reached steady state include Q, W, Y, CC, and EE.

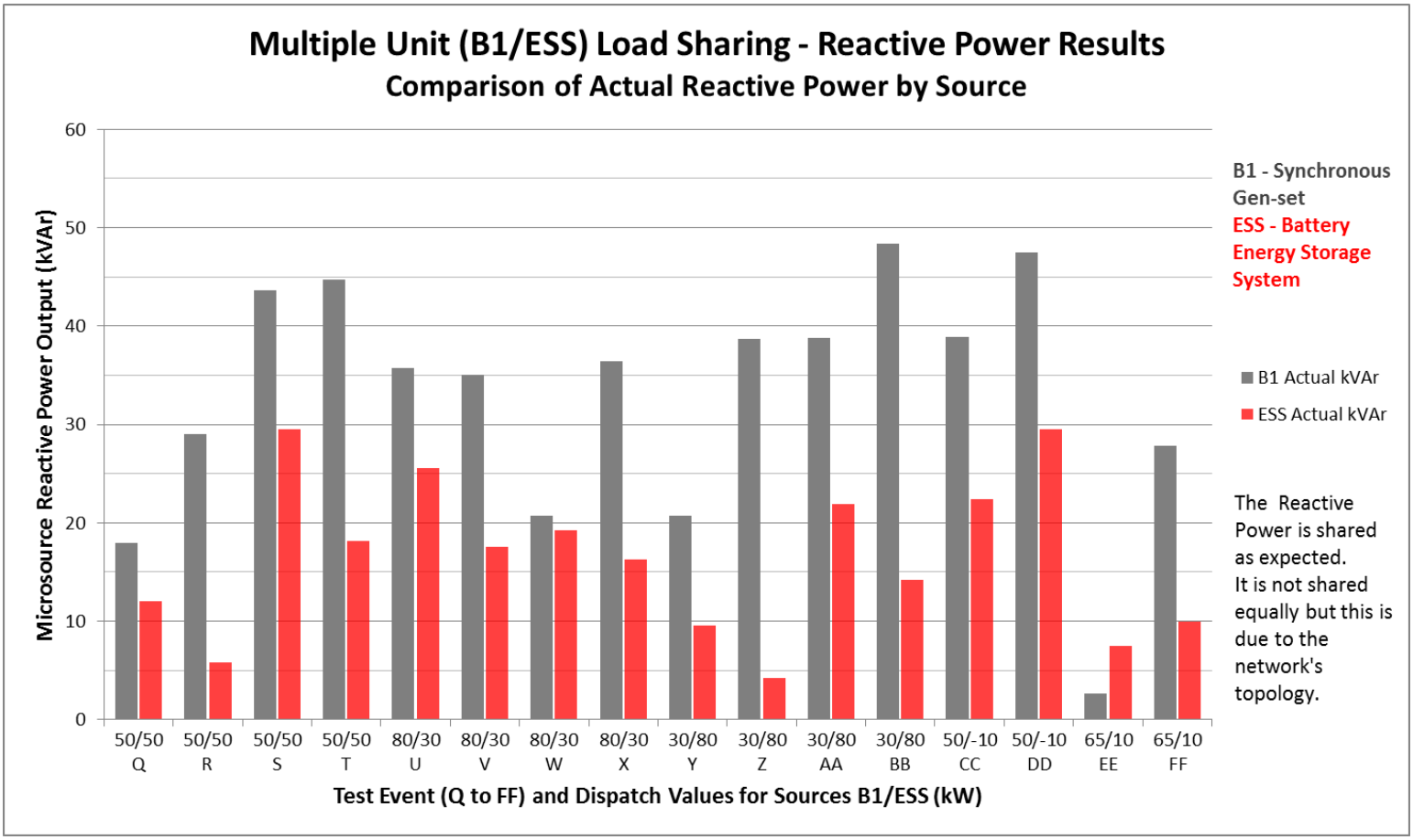

Figure 170: Multiple Unit Load Sharing, ESS & B1, Reactive Power

Figure 171 through Figure 178 show the results of Event A where the ESS and A1 are both dispatched to 50 kW, microgrid load is (65 + j30) kVA, and the microgrid transitions from grid-tied to islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 2.64 kW (33.10 kW instead of the expected 30.46 kW) as discussed earlier in this section. The microgrid frequency achieves an acceptable steady state value of 60.08 Hz which is 0.01 Hz less than the expected 60.09 Hz.

As indicated earlier, the reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplies 23.72 kVAr while A1 supplies 6.12. This test case is an example where the test bed reactive load of 29.84 kVAr is less than 45 kVAr and results in the 9 Hz oscillations that can been seen in the real and reactive power graphs as well as the RMS voltage and current plots.

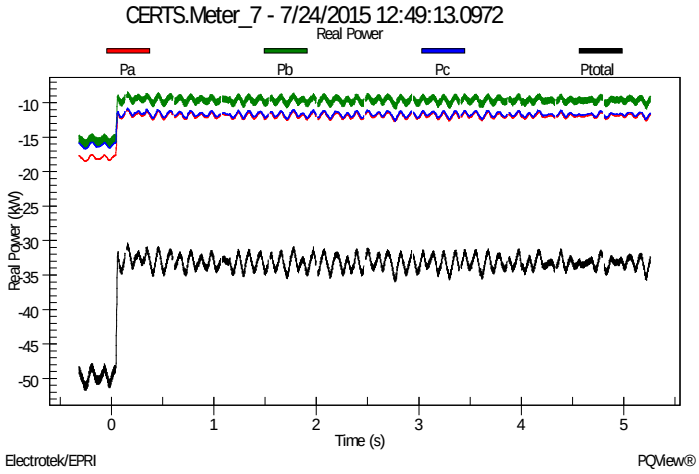

Figure 171: Event A, ESS Real Power

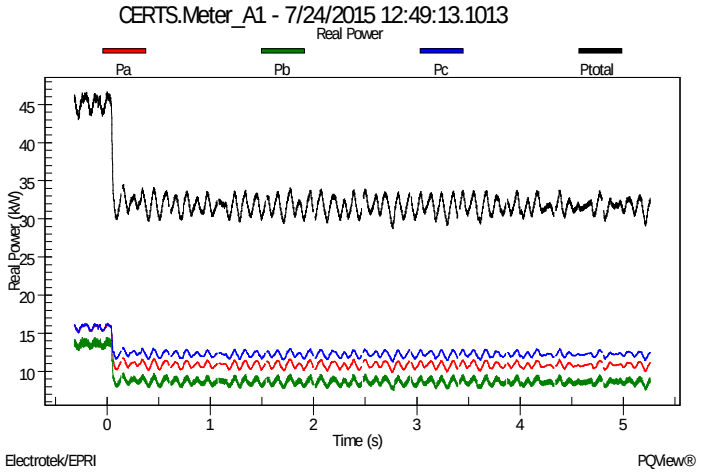

Figure 172: Event A, A1 Real Power

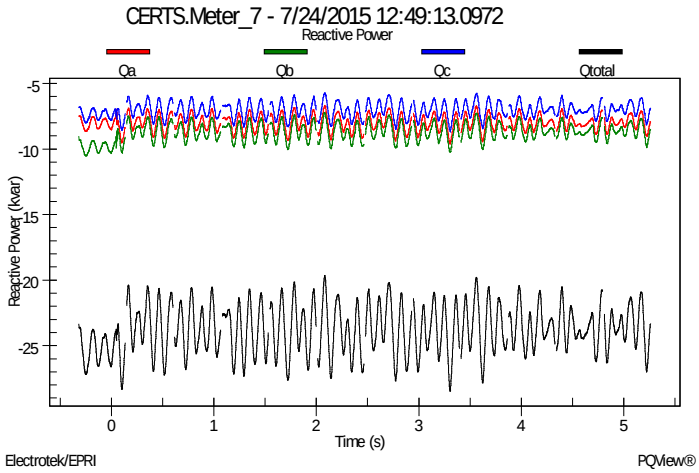

Figure 173: Event A, ESS Reactive Power

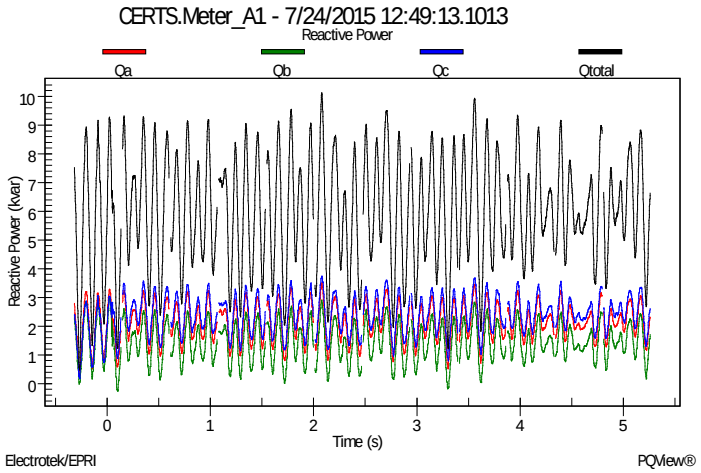

Figure 174: Event A, A1 Reactive Power

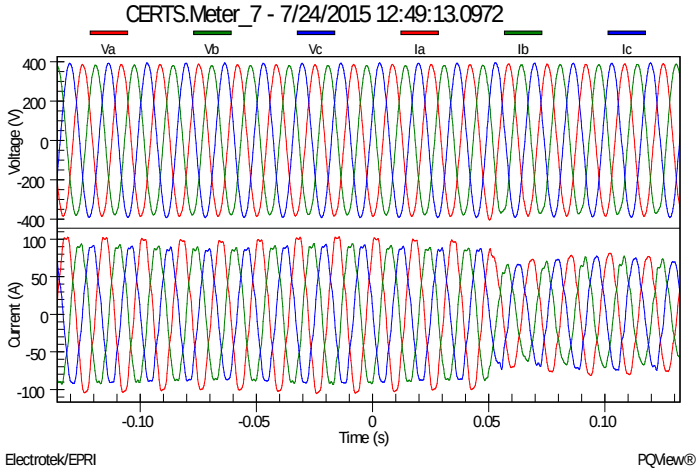

Figure 175: Event A, ESS Voltage & Current Waveform (Zoomed)

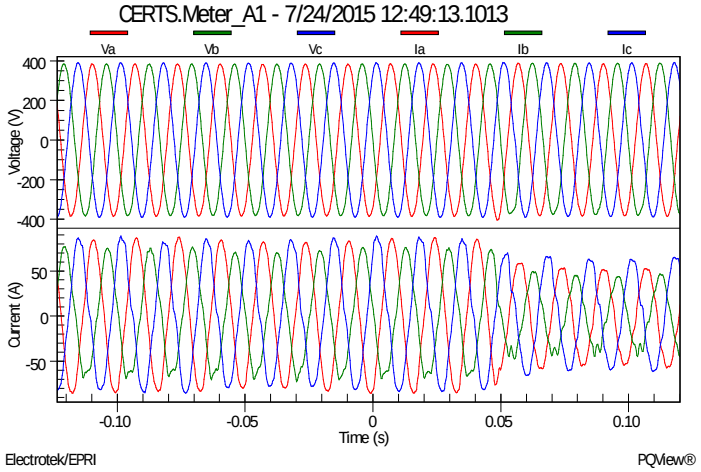

Figure 176: Event A, A1 Voltage & Current Waveform (Zoomed)

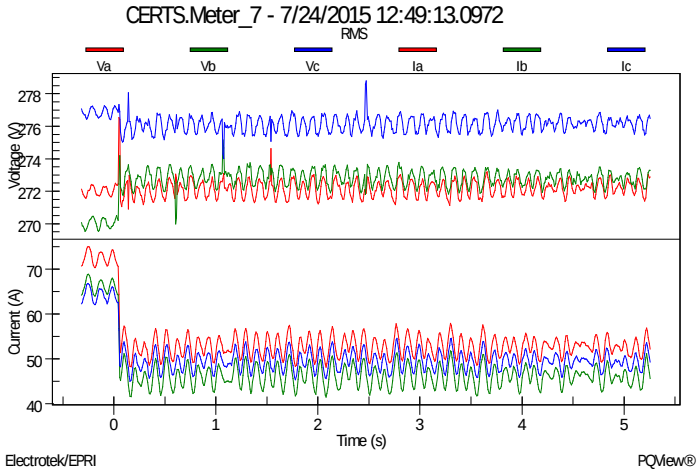

Figure 177: Event A, ESS RMS Voltage & Current

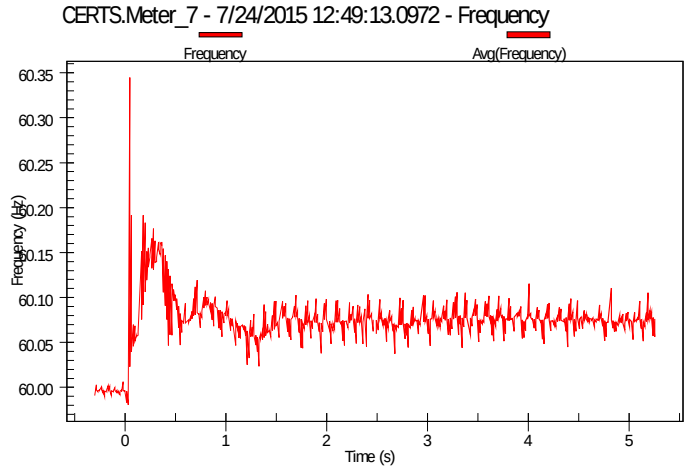

Figure 178: Event A, ESS Frequency

Figure 179 through Figure 186 show the results of Event B where the ESS and A1 are both dispatched to 50 kW, microgrid load is (65 + j30) kVA, and the microgrid transitions from islanded to grid-tied. The transition occurs smoothly. The sources real power output while grid-tied is determined by the grid frequency, in this case 60.00 Hz, so both sources should be supplying approximately their dispatched value of 50 kW. The ESS is supplying 47.77 kW and A1 is supplying 43.48 kW. While there is some loss in the cable from the sources to the metering point and A1 has a 480V/480V, delta-wye transformer, between it and its metering point, the losses seem high. The ESS is additionally being metered by a Yokogawa ScopeCorder located at its inverter. The data from the Yokogawa indicates that the ESS's batteries are supplying an average of 50 kW. The droop characteristics should apply to the A.C. grid terminals of the inverter rather than the battery terminals so there seems to be a problem here that requires further investigation. No additional metering currently exists for A1 and its power output is 13% below the expected value which is significant.

Again, the reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS is supplying 25.62 kVAr while A1 is supplying 5.95 kVAr. This test case is an example where the test bed reactive load of 31.57 kVAr is less than 45 kVAr and results in the 9 Hz oscillations that can been seen in the real and reactive power graphs as well as the RMS voltage and current plots.

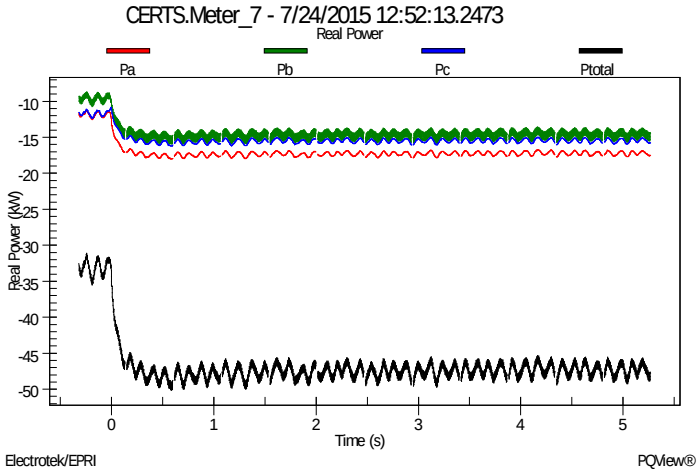

Figure 179: Event B, ESS Real Power

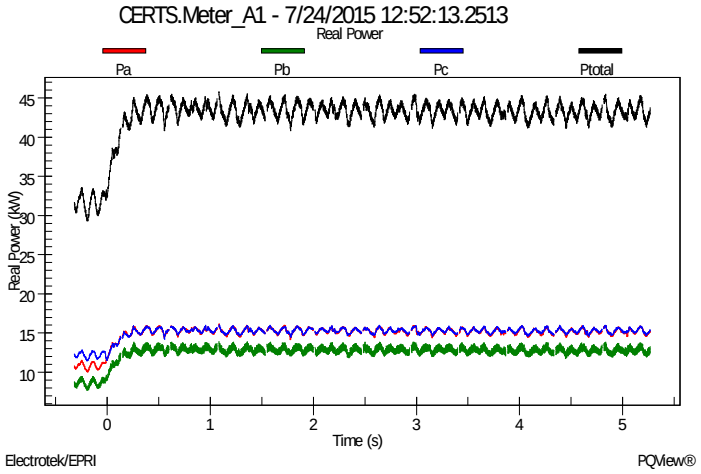

Figure 180: Event B, A1 Real Power

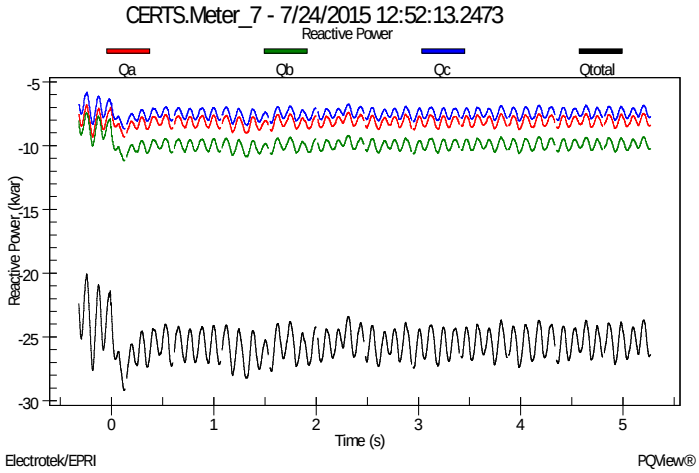

Figure 181: Event B, ESS Reactive Power

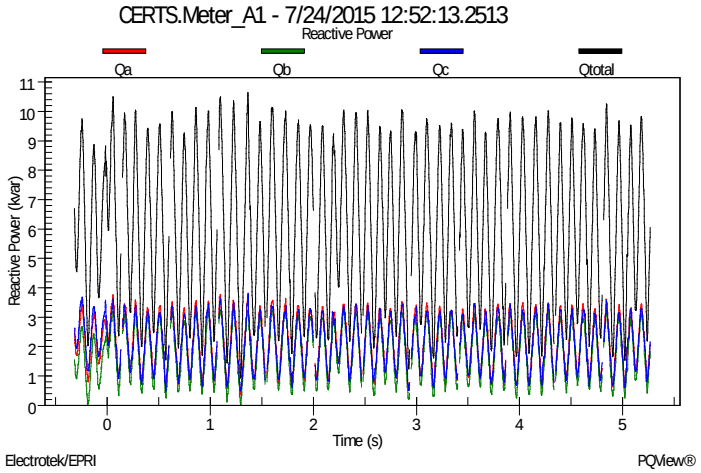

Figure 182: Event B, A1 Reactive Power

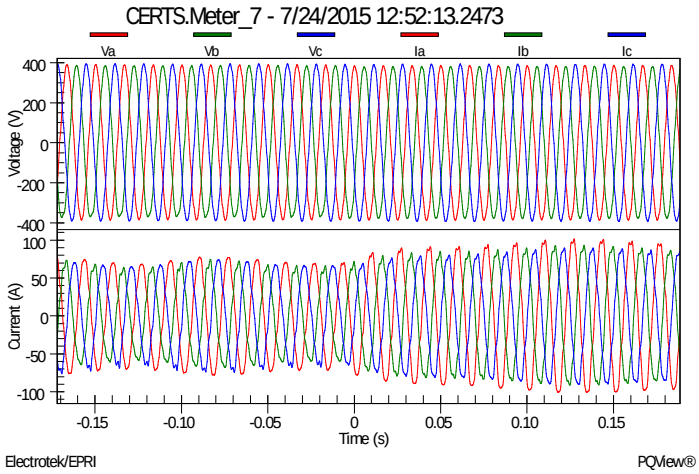

Figure 183: Event B, ESS Voltage & Current Waveform (Zoomed)

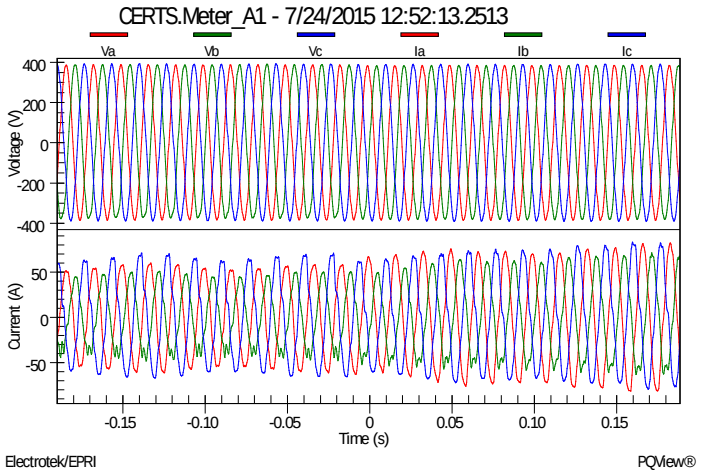

Figure 184: Event B, A1 Voltage & Current Waveform (Zoomed)

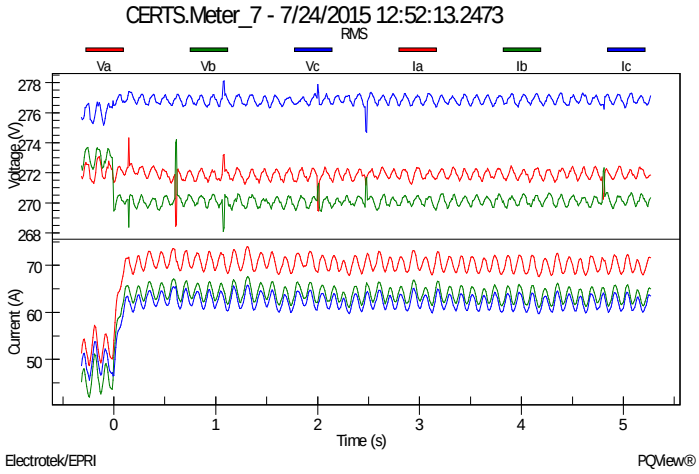

Figure 185: Event B, ESS RMS Voltage & Current

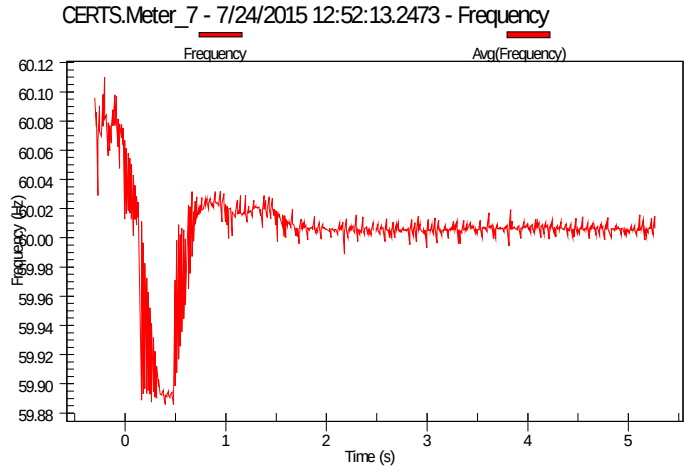

Figure 186: Event B, ESS Frequency

Figure 187 through Figure 194 show the results of Event C where the ESS and A1 are both dispatched to 50 kW, microgrid load is (141 + j68) kVA, and the microgrid transitions from grid-tied to islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 1.99 kW (74.90 kW instead of the expected 72.91 kW). The microgrid frequency achieves an acceptable steady state value of 59.87 Hz which is 0.02 Hz less than the expected 59.89 Hz.

The reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplies 50.58 kVAr while A1 supplies 17.09 kVAr. This test case is an example where the test bed reactive load of 67.67 kVAr is greater than 45 kVAr and does not result in the 9 Hz oscillations in the real and reactive power or the RMS voltage and current plots.

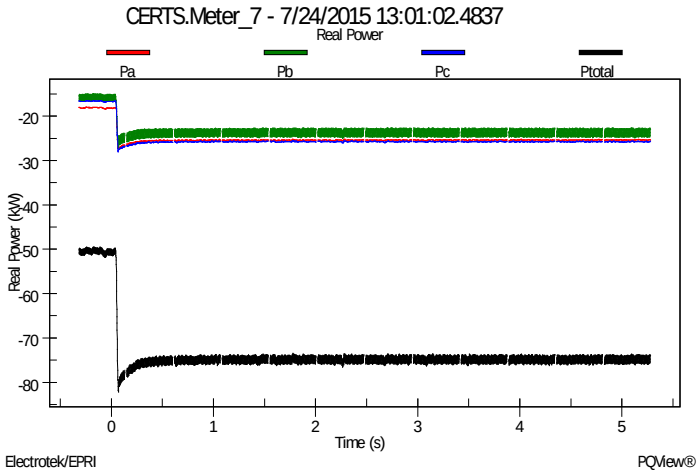

Figure 187: Event C, ESS Real Power

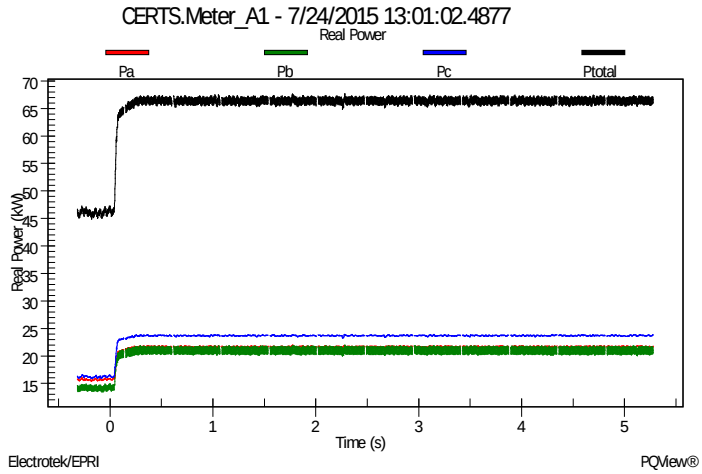

Figure 188: Event C, A1 Real Power

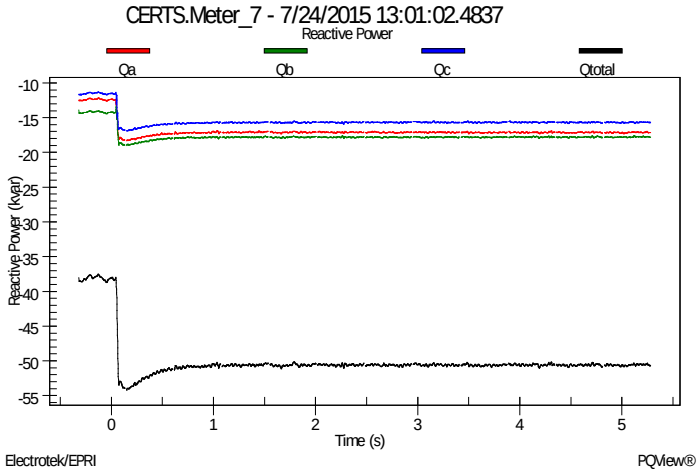

Figure 189: Event C, ESS Reactive Power

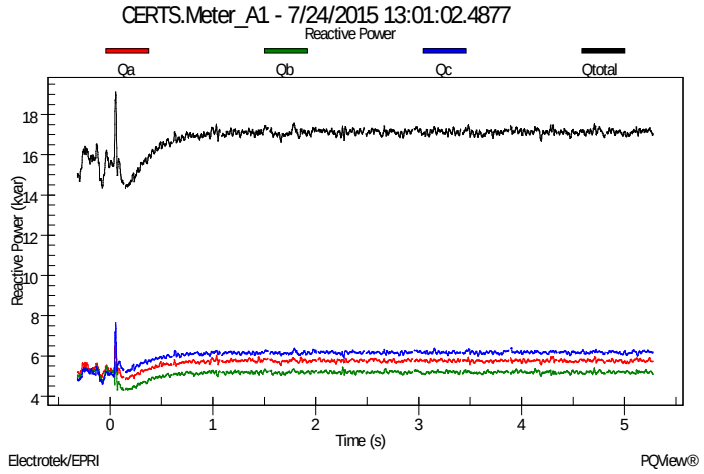

Figure 190: Event C, A1 Reactive Power

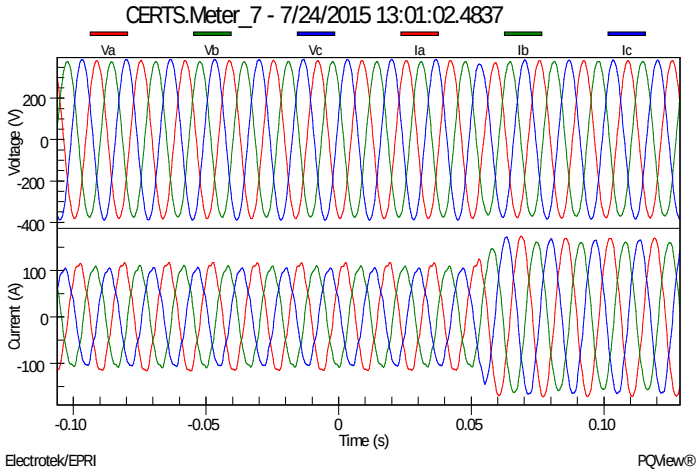

Figure 191: Event C, ESS Voltage & Current Waveform (Zoomed)

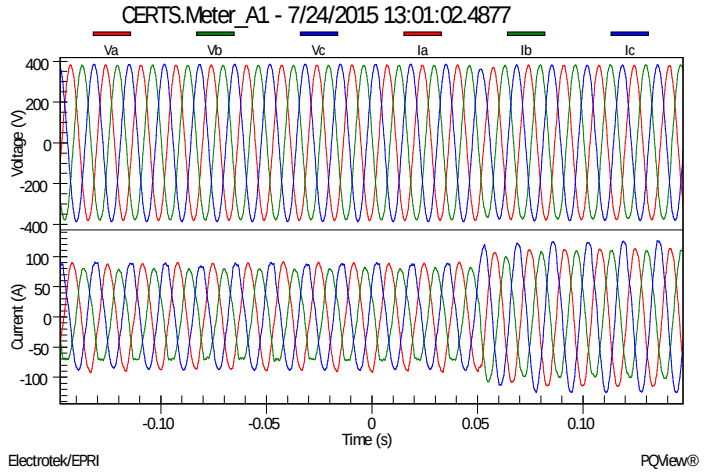

Figure 192: Event C, A1 Voltage & Current Waveform (Zoomed)

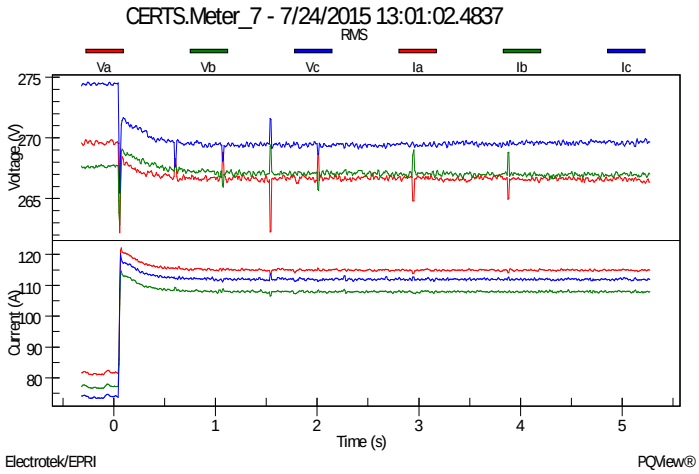

Figure 193: Event C, ESS RMS Voltage & Current

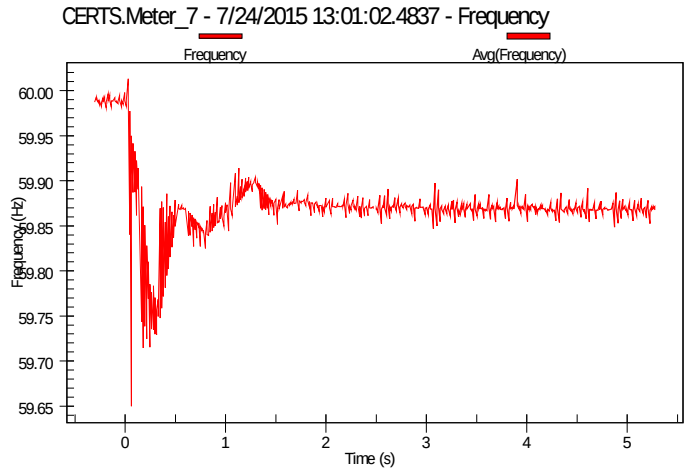

Figure 194: Event C, ESS Frequency

Figure 195 through Figure 202 show the results of Event E where the ESS is dispatched to 30 kW, A1 is dispatched to 80 kW, microgrid load is (140 + j68) kVA, and the microgrid transitions from grid-tied to islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 1.90 kW (48.72 kW instead of the expected 46.82 kW). The microgrid frequency achieves an acceptable steady state value of 59.90 Hz which is 0.02 Hz less than the expected 59.92 Hz.

The reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplies 57.54 kVAr while A1 supplies 10.18 kVAr. This test case is an example where the test bed reactive load of 67.72 kVAr is greater than 45 kVAr and does not result in the 9 Hz oscillations in the real and reactive power or the RMS voltage and current plots.

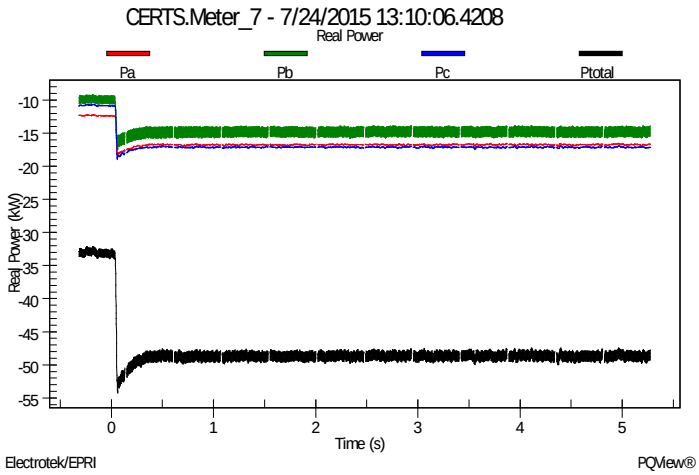

Figure 195: Event E, ESS Real Power

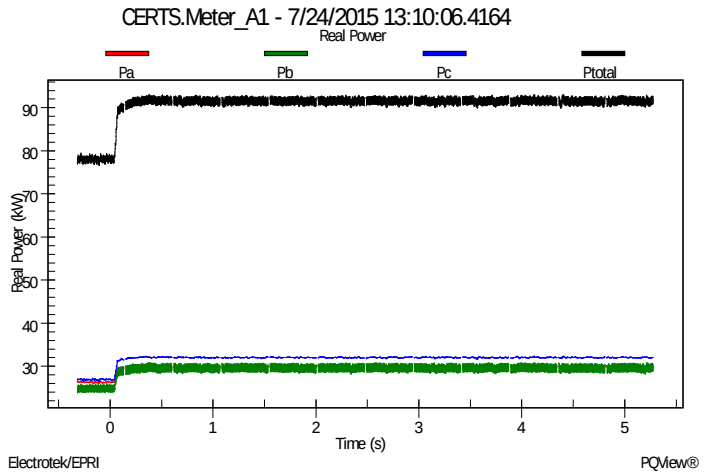

Figure 196: Event E, A1 Real Power

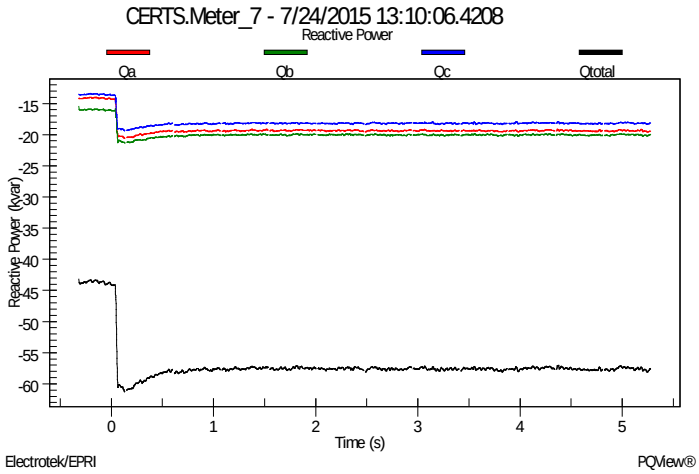

Figure 197: Event E, ESS Reactive Power

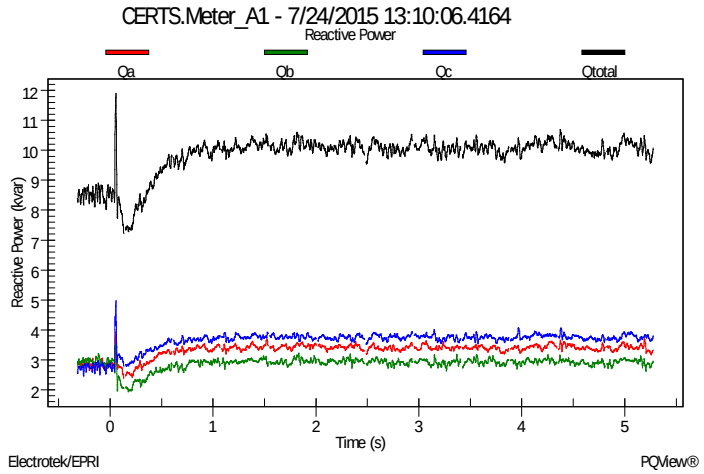

Figure 198: Event E, A1 Reactive Power

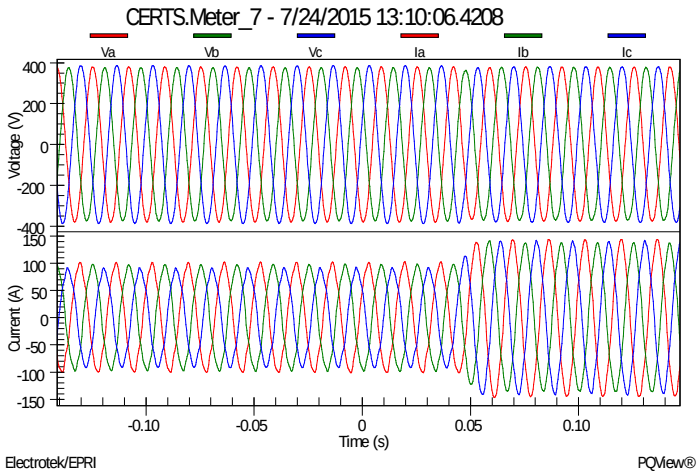

Figure 199: Event E, ESS Voltage & Current Waveform (Zoomed)

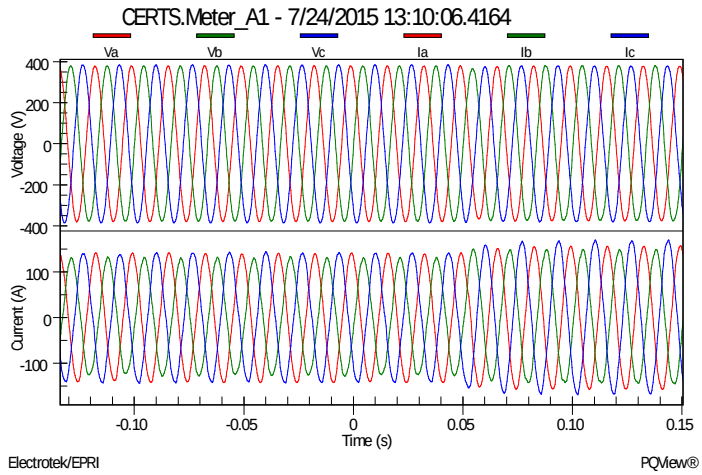

Figure 200: Event E, A1 Voltage & Current Waveform (Zoomed)

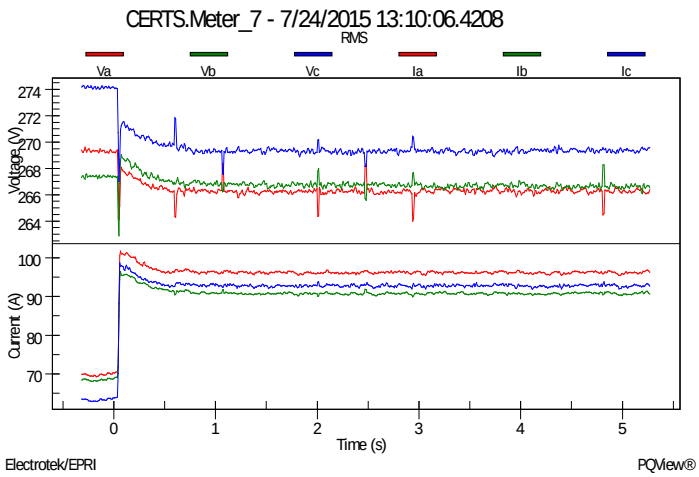

Figure 201: Event E, ESS RMS Voltage & Current

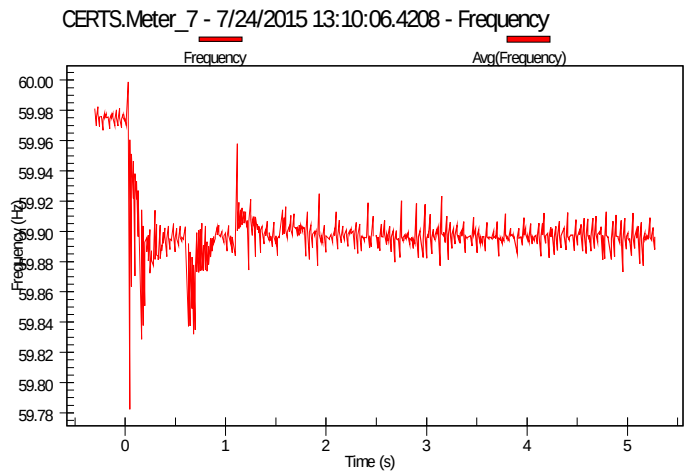

Figure 202: Event E, ESS Frequency

Figure 203 through Figure 210 show the results of Event G where the ESS is dispatched to 30 kW, A1 is dispatched to 80 kW, microgrid load is (81 + j39) kVA, and the microgrid transitions from grid-tied to islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 2.16 kW (16.14 kW instead of the expected 13.98 kW). The microgrid frequency achieves an acceptable steady state value of 60.06 Hz which is 0.02 Hz less than the expected 60.08 Hz.

The reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplied 34.74 kVAr while A1 supplied 4.18 kVAr. This test case is an example where the test bed reactive load of 38.92 kVAr is less than 45 kVAr and results in the 9 Hz oscillations that can been seen in the real and reactive power graphs as well as the RMS voltage and current plots.

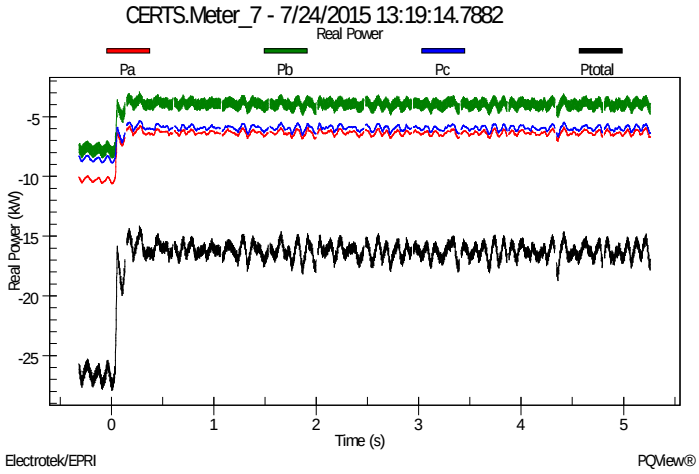

Figure 203: Event G, ESS Real Power

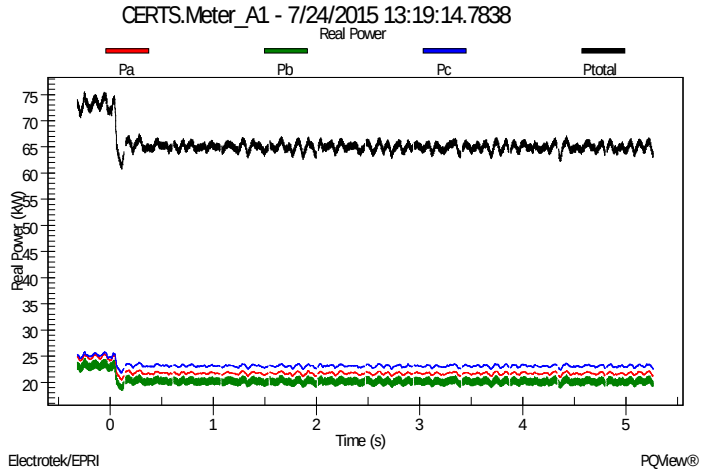

Figure 204: Event G, A1 Real Power

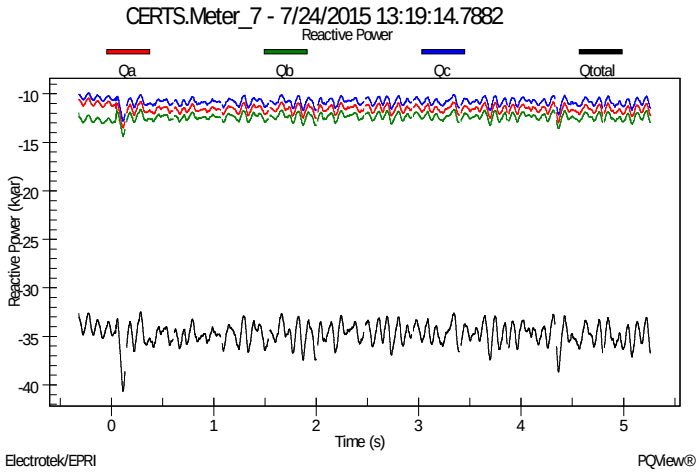

Figure 205: Event G, ESS Reactive Power

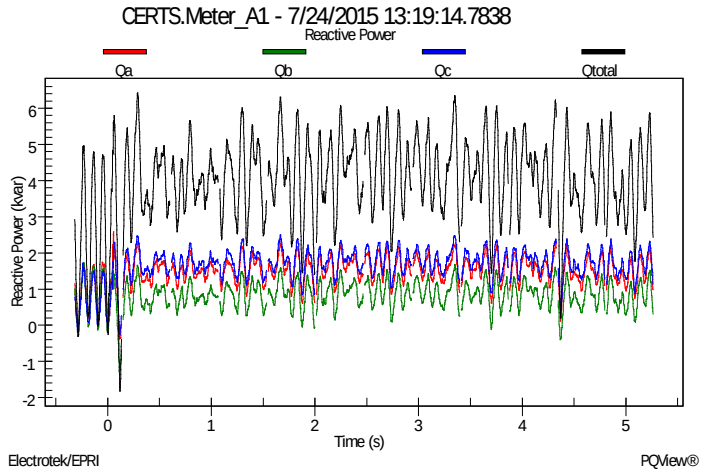

Figure 206: Event G, A1 Reactive Power

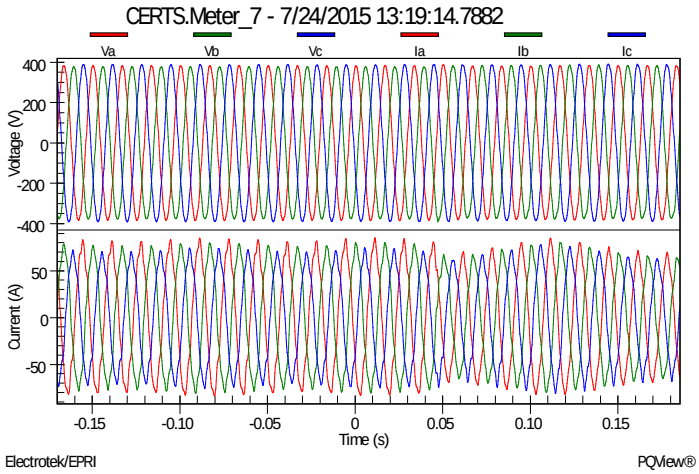

Figure 207: Event G, ESS Voltage & Current Waveform (Zoomed)

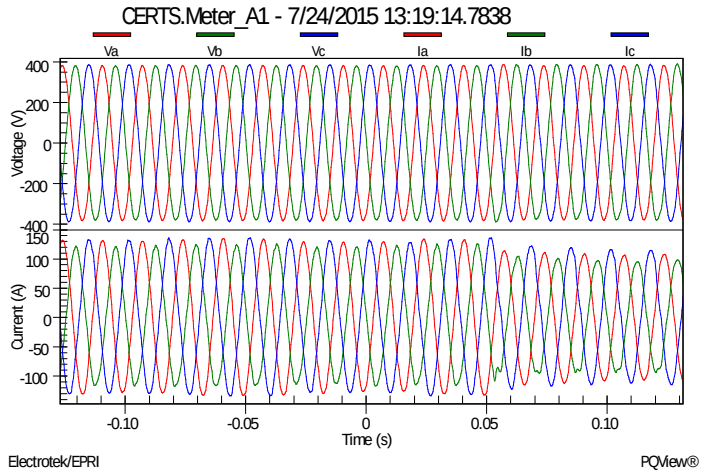

Figure 208: Event G, A1 Voltage & Current Waveform (Zoomed)

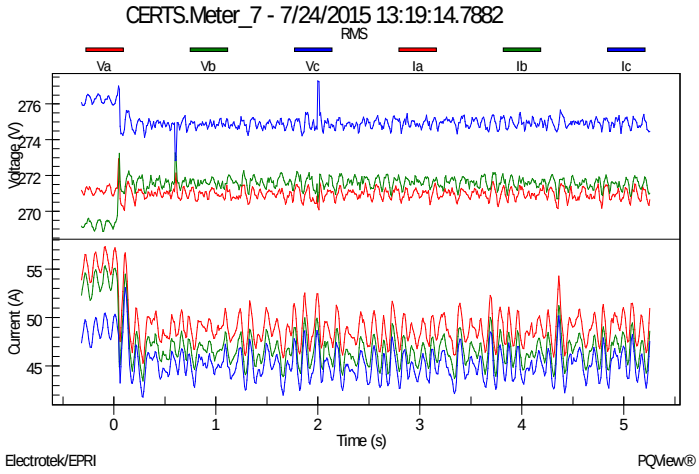

Figure 209: Event G, ESS RMS Voltage & Current

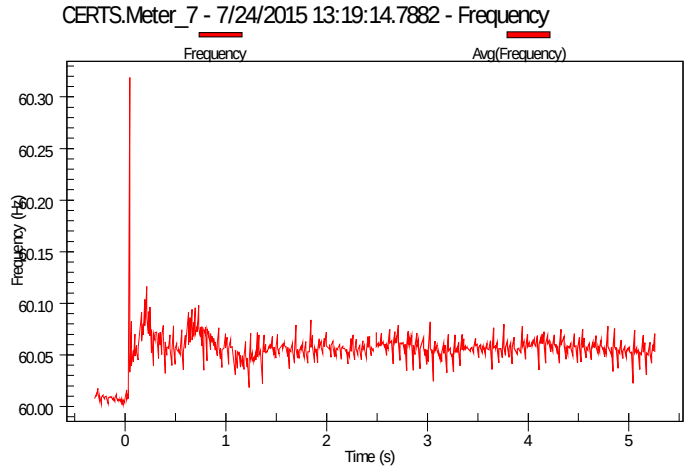

Figure 210: Event G, ESS Frequency

Figure 211 through Figure 218 show the results of Event I where the ESS is dispatched to 80 kW, A1 is dispatched to 30 kW, microgrid load is (59 + j29) kVA, and the microgrid transitions from grid-tied to islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 2.32 kW (54.18 kW instead of the expected 51.86 kW). The microgrid frequency achieves an acceptable steady state value of 60.11 Hz which is 0.03 Hz less than the expected 60.14 Hz.

The reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplied 18.16 kVAr while A1 supplied 11.04 kVAr. This test case is an example where the test bed reactive load of 29.20 kVAr is less than 45 kVAr and results in an 11 Hz oscillation that can been seen in the real and reactive power graphs as well as the RMS voltage and current plots. This 11 Hz oscillation is slightly more than the 9 Hz oscillation seen in the previous cases.

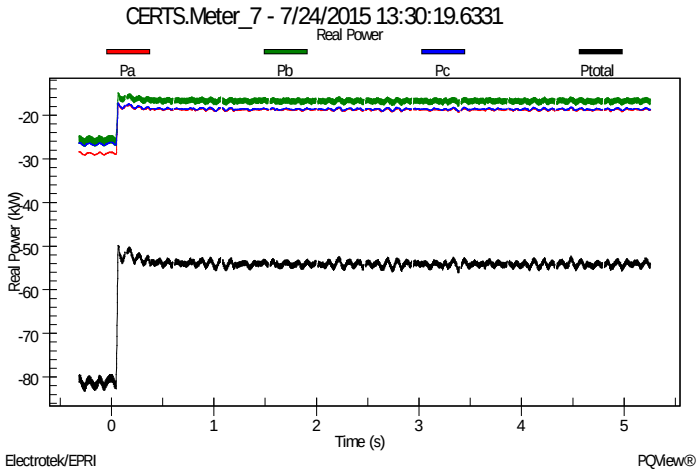

Figure 211: Event I, ESS Real Power

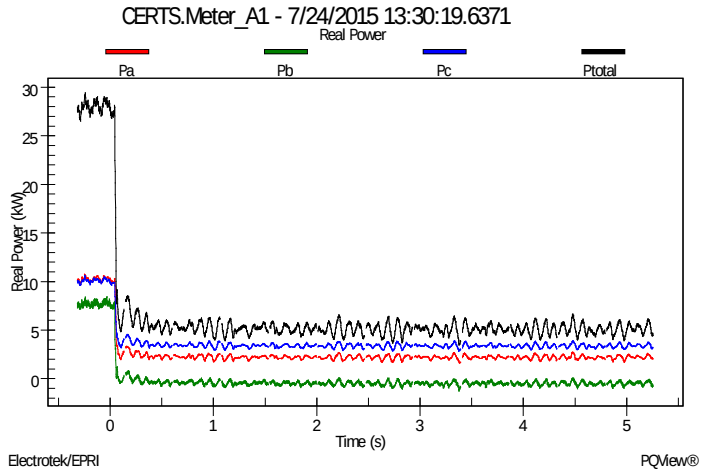

Figure 212: Event I, A1 Real Power

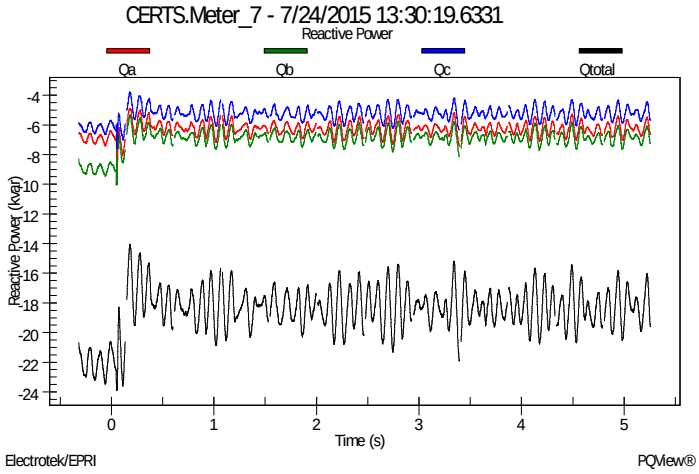

Figure 213: Event I, ESS Reactive Power

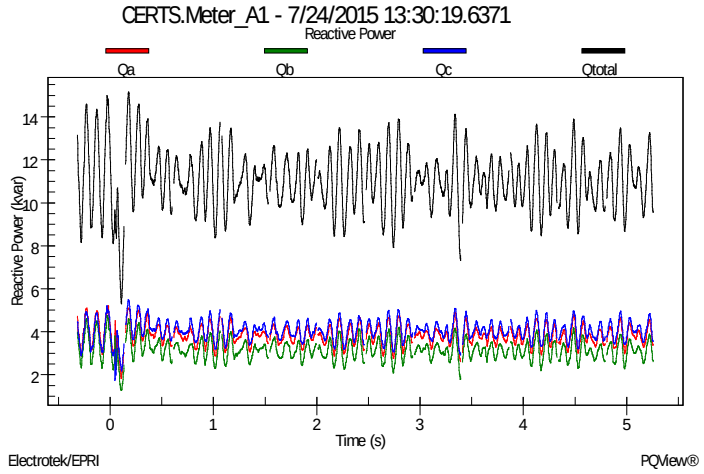

Figure 214: Event I, A1 Reactive Power

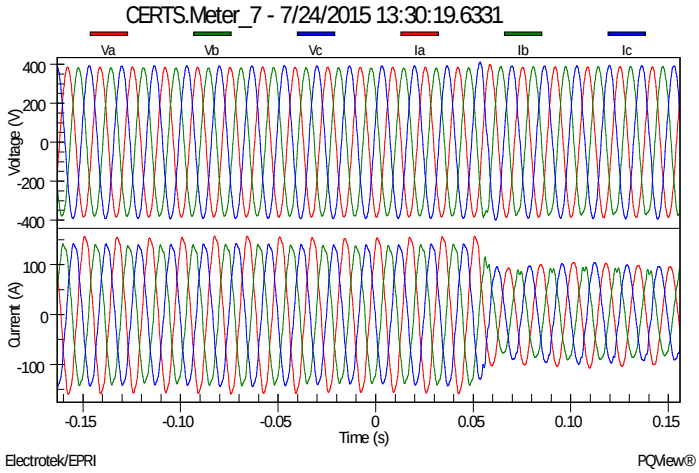

Figure 215: Event I, ESS Voltage & Current Waveform (Zoomed)

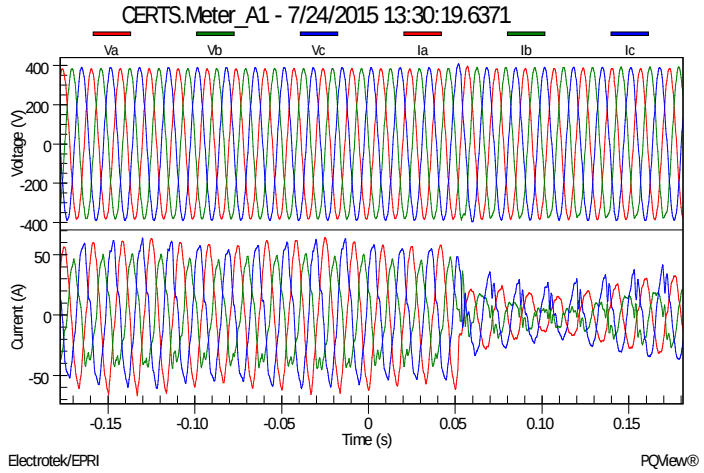

Figure 216: Event I, A1 Voltage & Current Waveform (Zoomed)

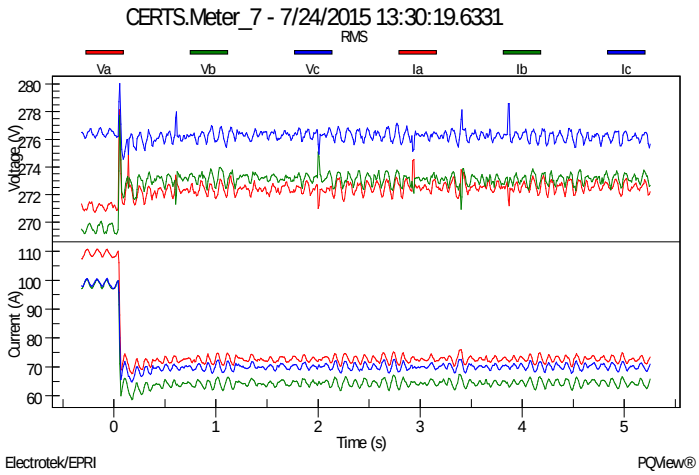

Figure 217: Event I, ESS RMS Voltage & Current

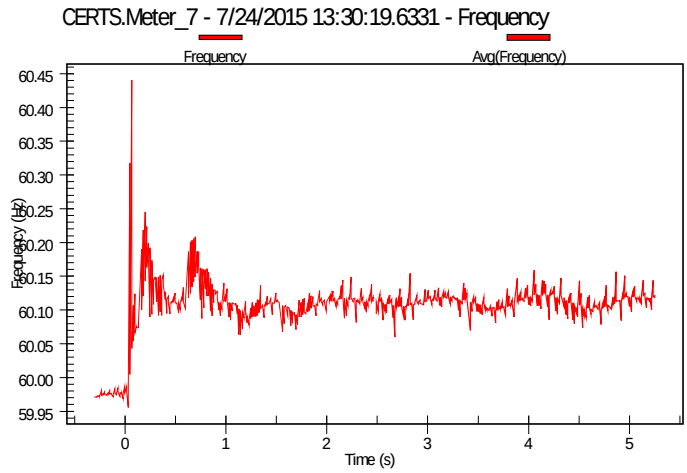

Figure 218: Event I, ESS Frequency

Figure 219 through Figure 226 show the results of Event K where the ESS is dispatched to 80 kW, A1 is dispatched to 30 kW, microgrid load is (131 + j58) kVA, and the microgrid transitions from grid-tied to islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 1.80 kW (93.41 kW instead of the expected 91.61 kW). The microgrid frequency achieves an acceptable steady state value of 59.92 Hz which is 0.02 Hz less than the expected 59.94 Hz.

The reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplies 37.49 kVAr while A1 supplies 20.06 kVAr. This test case is an example where the test bed reactive load of 57.55 kVAr is greater than 45 kVAr and does not result in the 9 Hz oscillations in the real and reactive power or the RMS voltage and current plots.

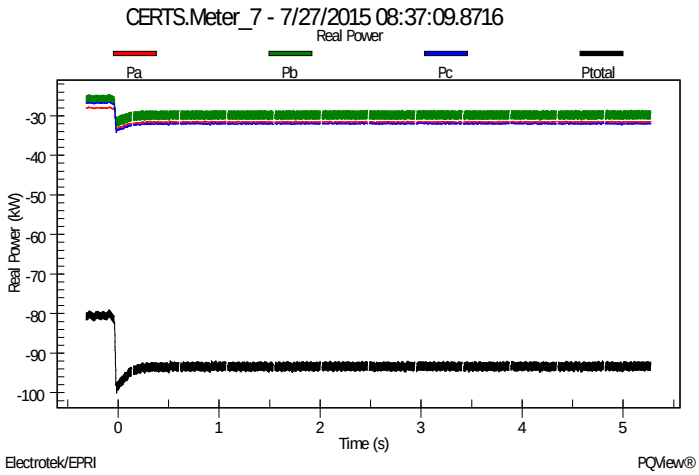

Figure 219: Event K, ESS Real Power

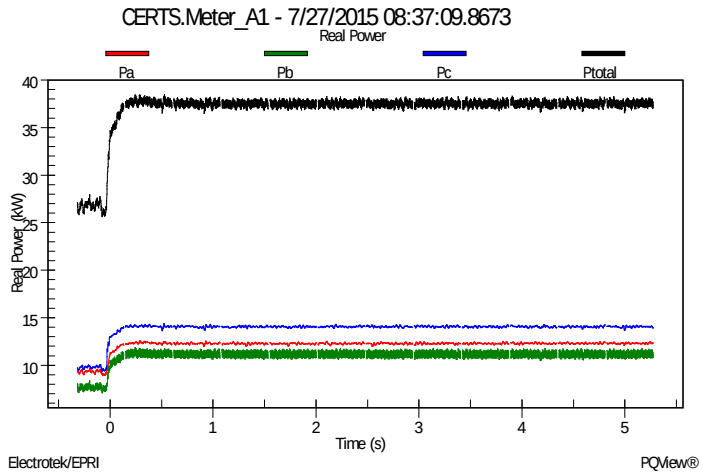

Figure 220: Event K, A1 Real Power

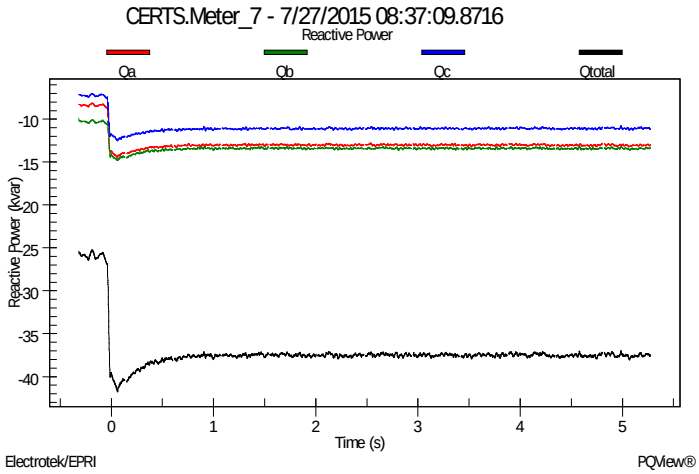

Figure 221: Event K, ESS Reactive Power

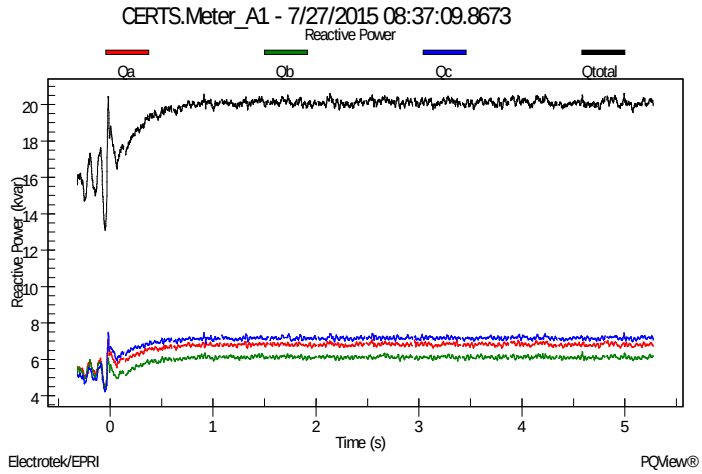

Figure 222: Event K, A1 Reactive Power

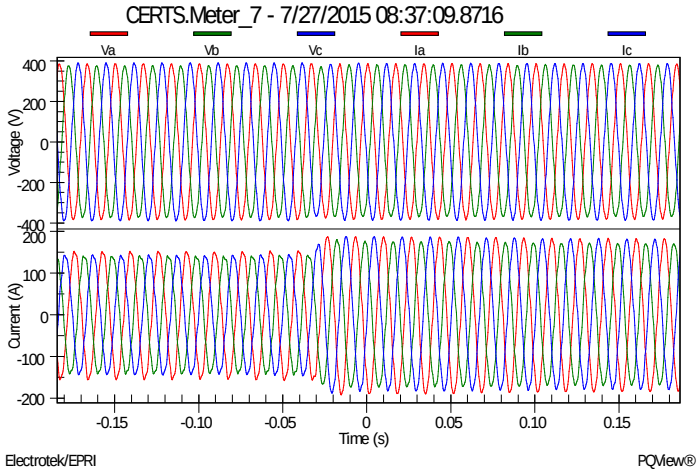

Figure 223: Event K, ESS Voltage & Current Waveform (Zoomed)

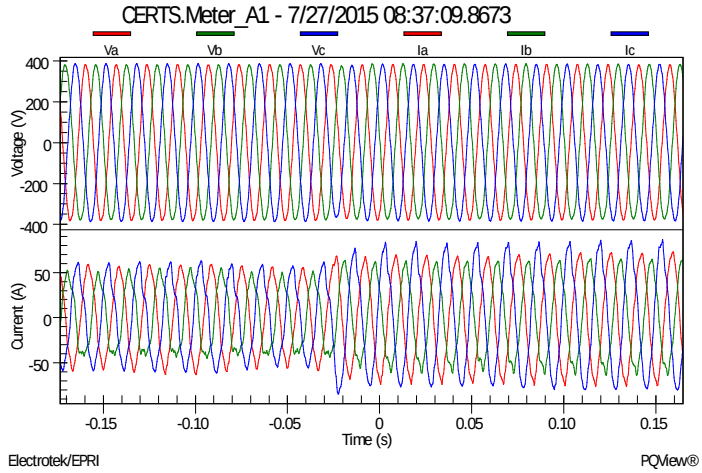

Figure 224: Event K, A1 Voltage & Current Waveform (Zoomed)

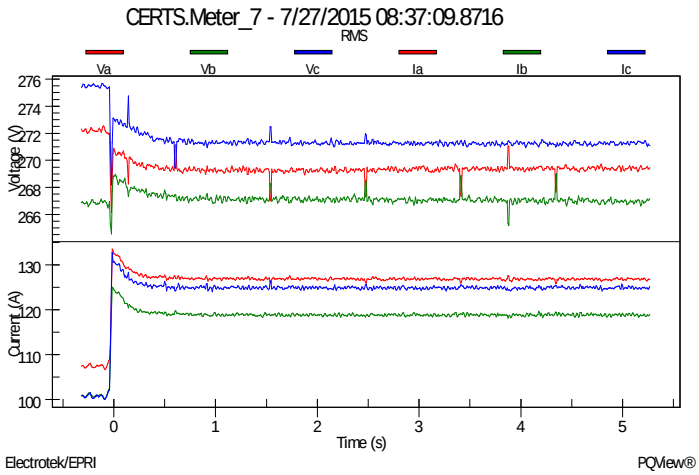

Figure 225: Event K, ESS RMS Voltage & Current

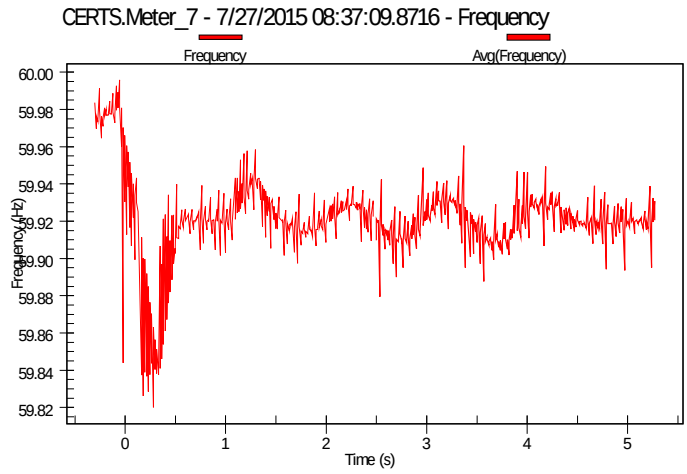

Figure 226: Event K, ESS Frequency

Figure 227 through Figure 234 show the results of Event M where the ESS is dispatched to -10 kW, A1 is dispatched to 50 kW, microgrid load is (130 + j58) kVA, and the microgrid transitions from grid-tied to islanded. This test case begins with the ESS charging while grid-tied and transitions to discharging when islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 2.67 kW (42.39 kW instead of the expected 39.72 kW). The microgrid frequency achieves an acceptable steady state value of 59.75 Hz which is 0.01 Hz less than the expected 59.76 Hz.

The reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplies 49.30 kVAr while A1 supplies 8.56 kVAr. This test case is an example where the test bed reactive load of 57.86 kVAr is greater than 45 kVAr and does not result in the 9 Hz oscillations in the real and reactive power or the RMS voltage and current plots.

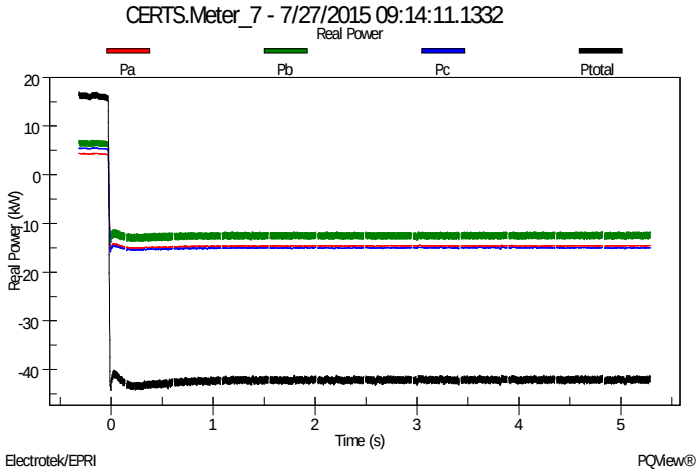

Figure 227: Event M, ESS Real Power

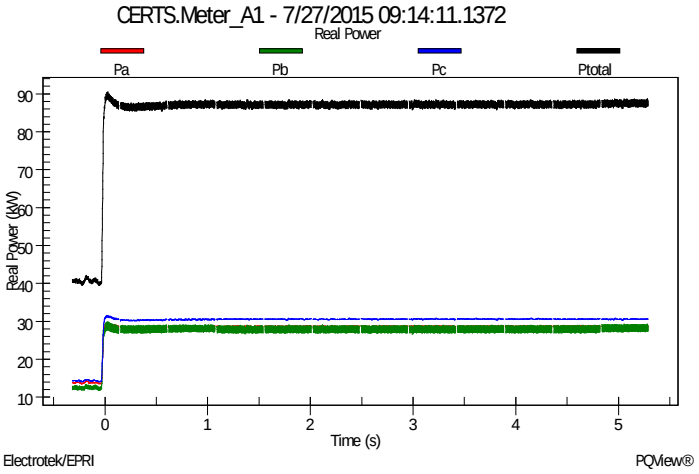

Figure 228: Event M, A1 Real Power

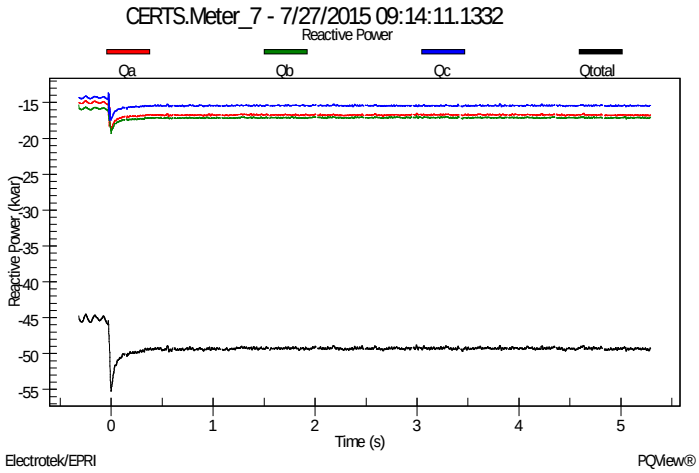

Figure 229: Event M, ESS Reactive Power

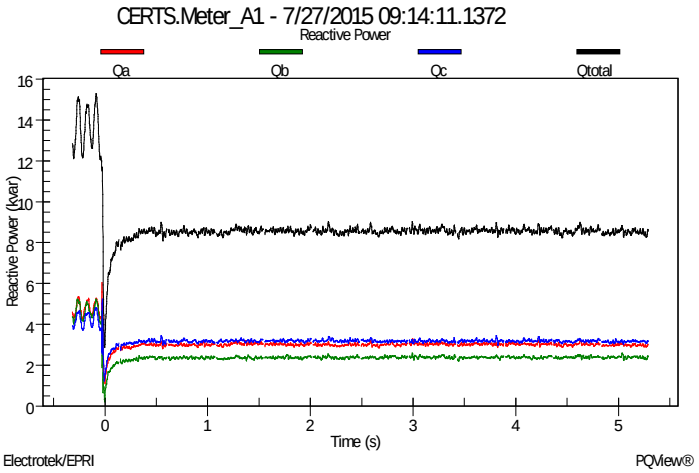

Figure 230: Event M, A1 Reactive Power

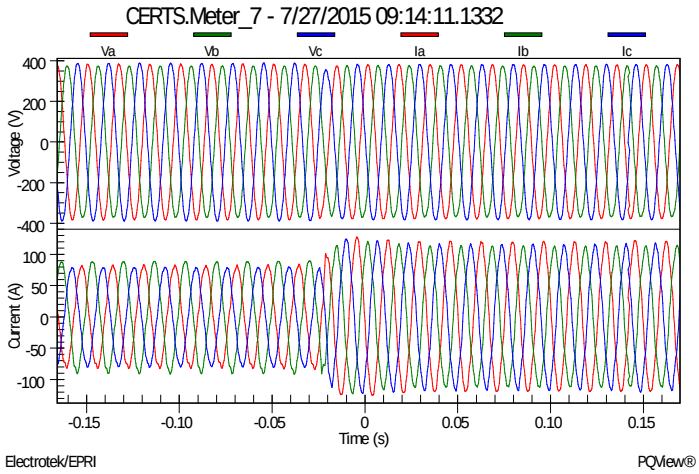

Figure 231: Event M, ESS Voltage & Current Waveform (Zoomed)

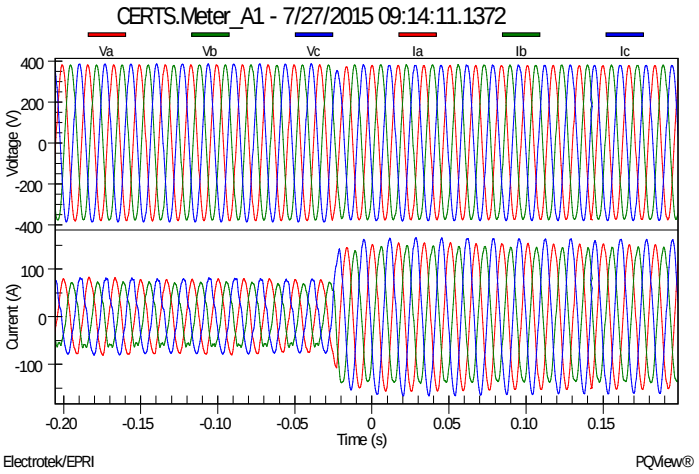

Figure 232: Event M, A1 Voltage & Current Waveform (Zoomed)

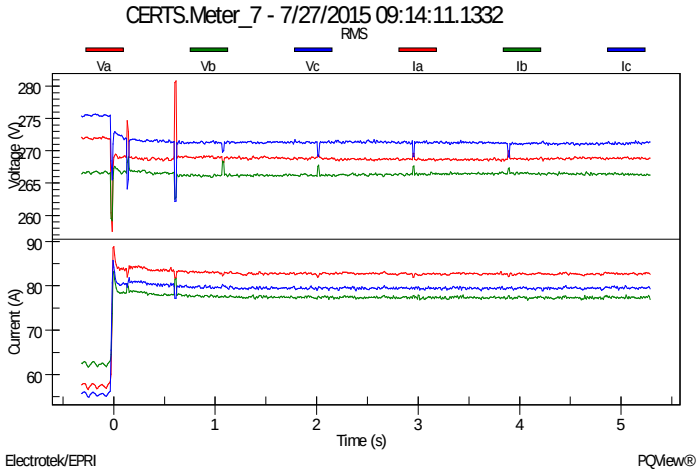

Figure 233: Event M, ESS RMS Voltage & Current

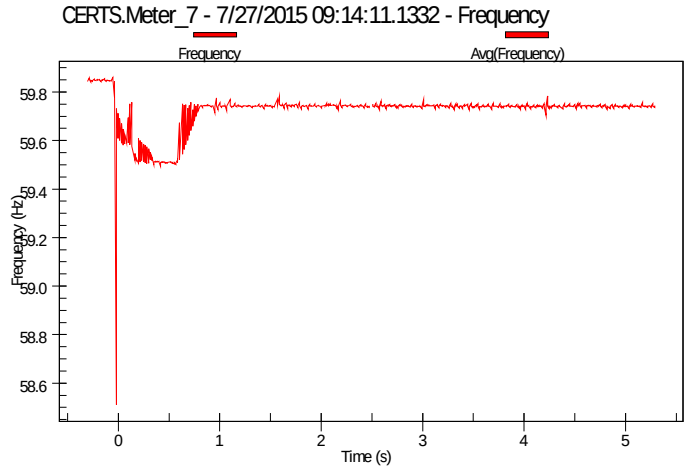

Figure 234: Event M, ESS Frequency

Figure 235 through Figure 242 show the results of Event O where the ESS is dispatched to 10 kW, A1 is dispatched to 65 kW, microgrid load is (30 + j10) kVA, and the microgrid transitions from grid-tied to islanded. This test case begins with the ESS discharging while grid-tied and transitions to charging when islanded. The transition occurs smoothly and the sources share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS charging at a lower real power than expected by 2.56 kW (-12.33 kW instead of the expected -14.89 kW). The microgrid frequency achieves an acceptable steady state value of 60.10 Hz which is 0.02 Hz less than the expected 60.12 Hz.

The reactive power is not shared as expected, approximately equally, between the two sources. In this case the ESS supplied 16.46 kVAr while A1 absorbed 6.20 kVAr. This test case is an example where the test bed reactive load of 10.26 kVAr is less than 45 kVAr and results in the 9 Hz oscillations that can been seen in the real and reactive power graphs as well as the RMS voltage and current plots.

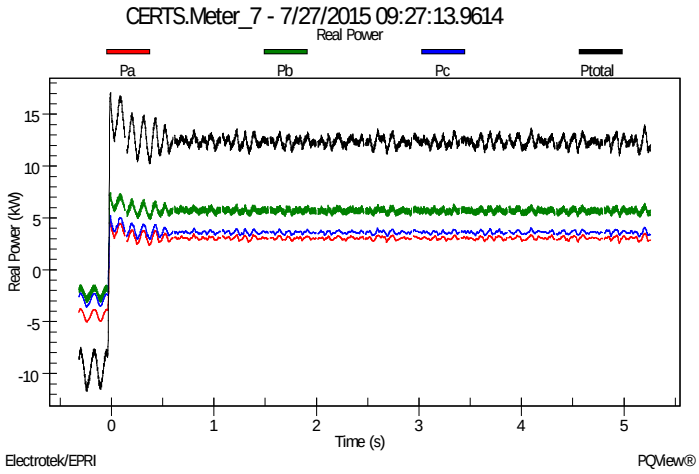

Figure 235: Event O, ESS Real Power

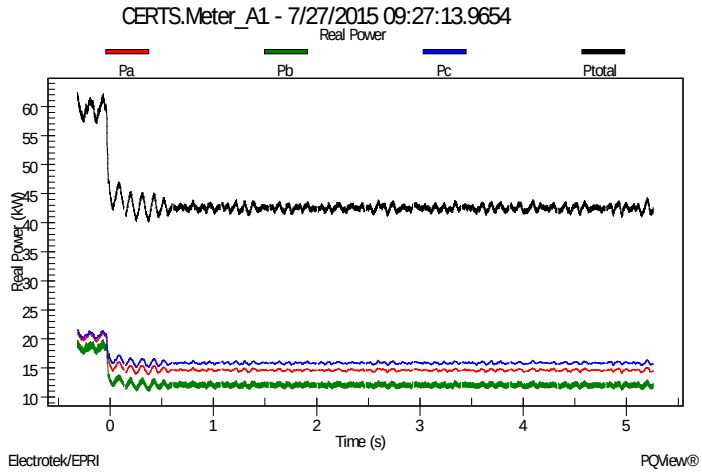

Figure 236: Event O, A1 Real Power

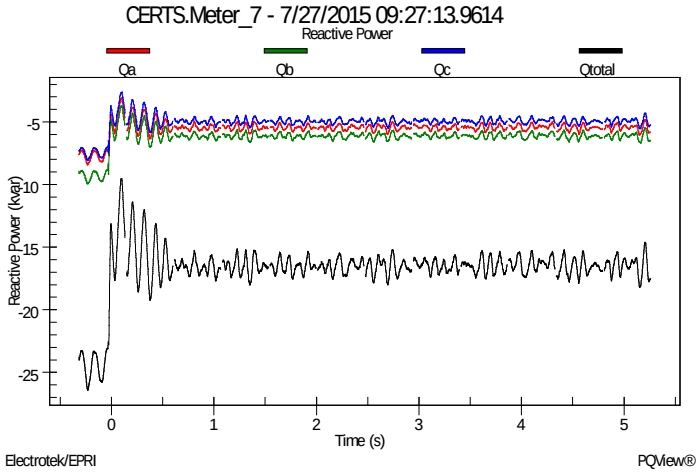

Figure 237: Event O, ESS Reactive Power

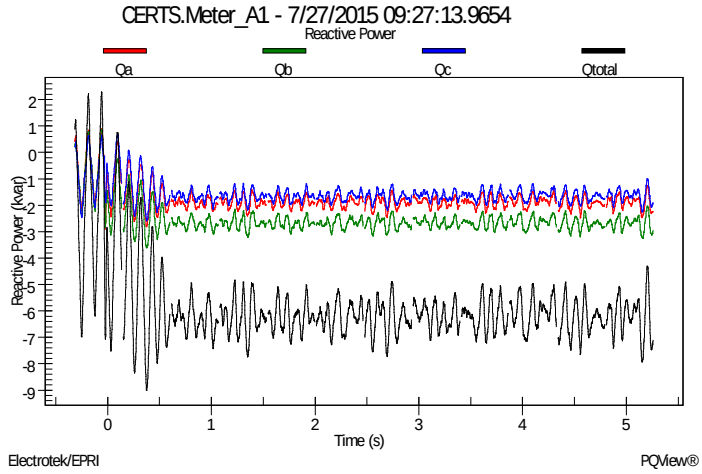

Figure 238: Event O, A1 Reactive Power

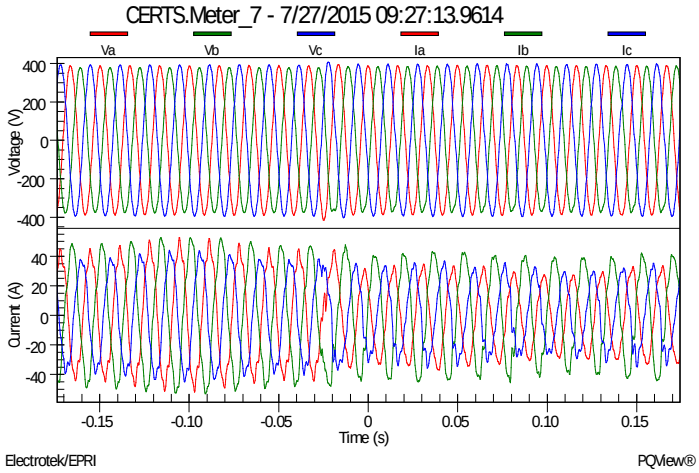

Figure 239: Event O, ESS Voltage & Current Waveform (Zoomed)

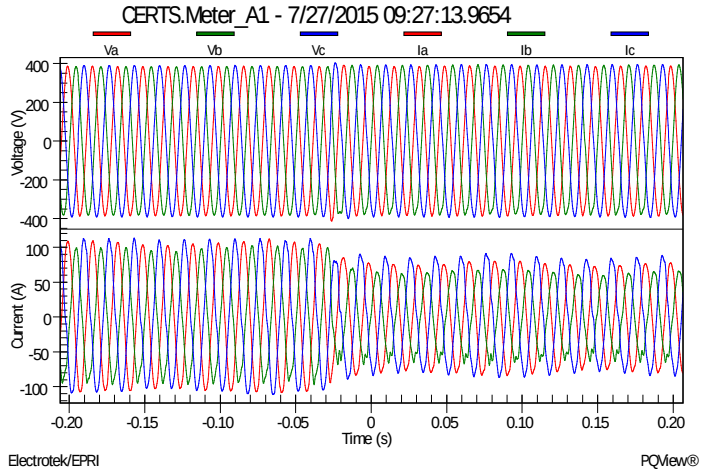

Figure 240: Event O, A1 Voltage & Current Waveform (Zoomed)

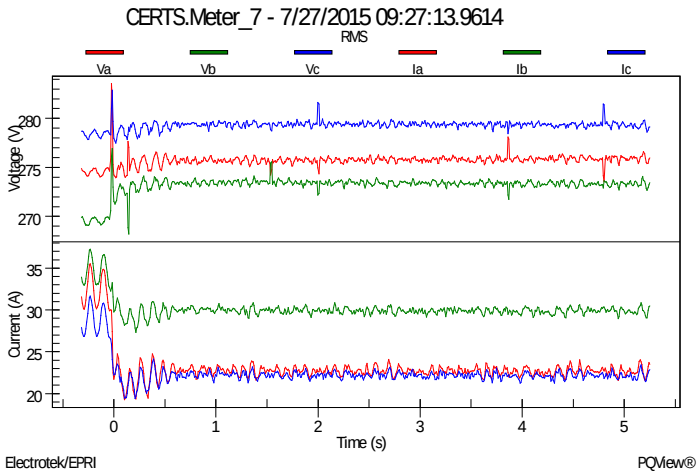

Figure 241: Event O, ESS RMS Voltage & Current

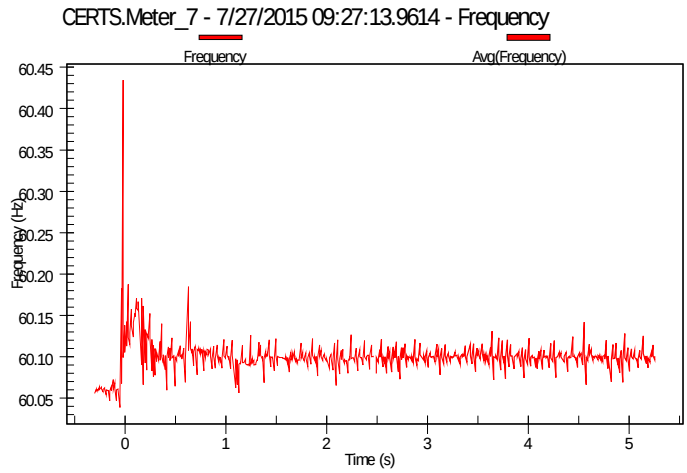

Figure 242: Event O, ESS Frequency

Figure 243 through Figure 250 show the results of Event Q where the ESS and B1 are both dispatched to 50 kW, microgrid load is (60 + j30) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 4 kW (31 kW instead of the expected 27 kW) although the actual difference may be slightly less as it appears the units have not quite reached steady state for real power.

The microgrid frequency achieves an acceptable steady state value of 60.08 Hz which is 0.03 Hz less than the expected 60.11 Hz.

Reactive power is shared as expected with B1 supplying more reactive power than the ESS. It can be seen in Figure 245 and Figure 246 that the reactive power has not reached steady state however it is estimated that B1 would supply approximately 20 kVAr and the ESS about 10 kVAr.

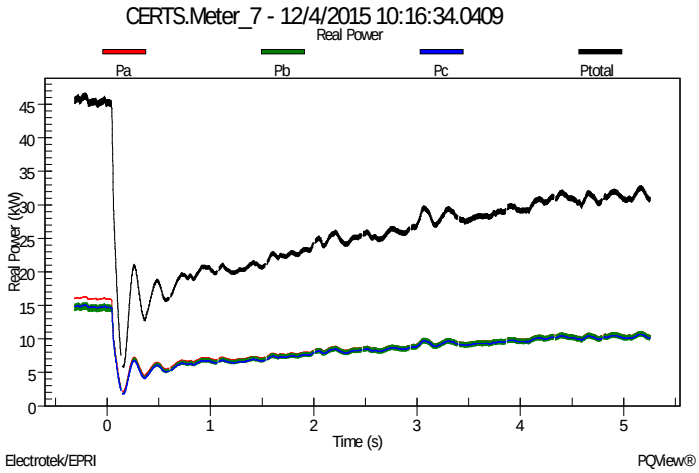

Figure 243: Event Q, ESS Real Power

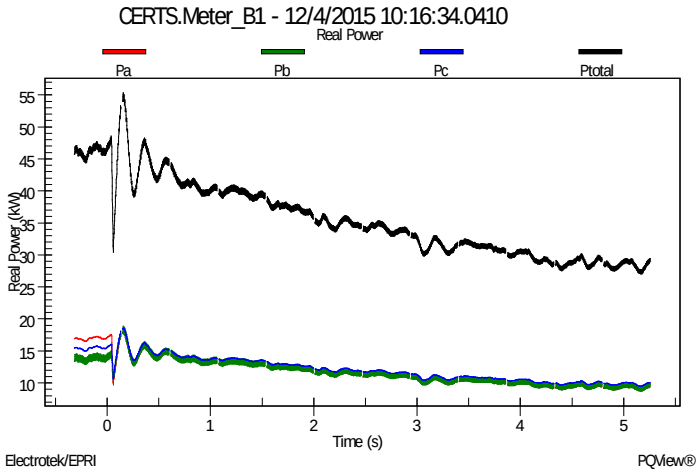

Figure 244: Event Q, B1 Real Power

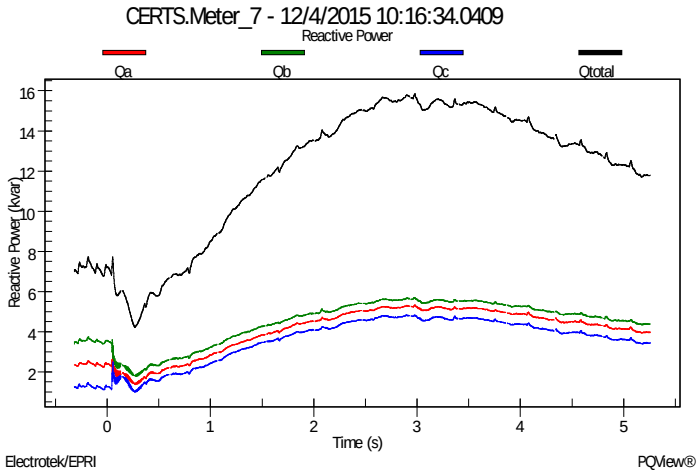

Figure 245: Event Q, ESS Reactive Power

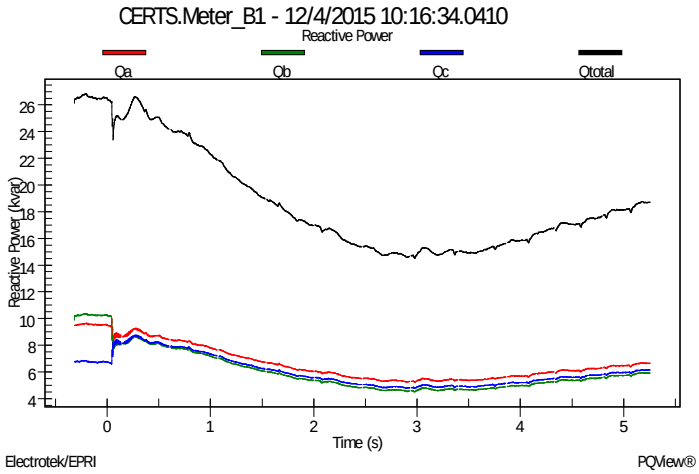

Figure 246: Event Q, B1 Reactive Power

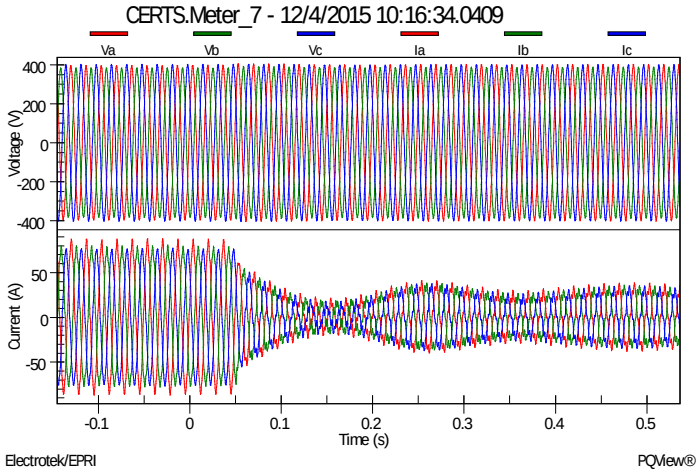

Figure 247: Event Q, ESS Voltage & Current Waveform (Zoomed)

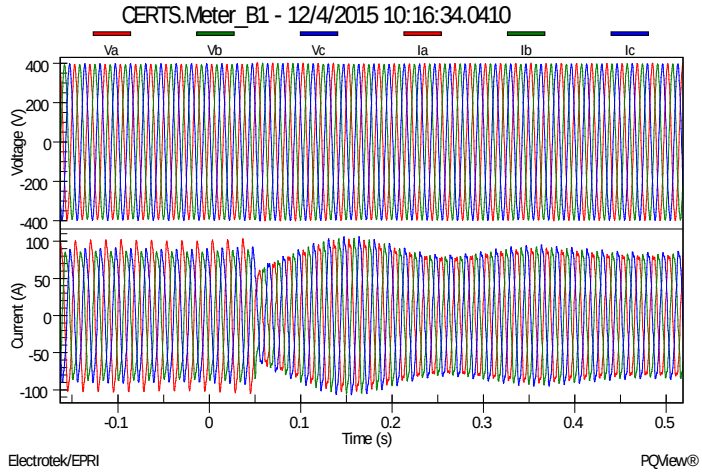

Figure 248: Event Q, B1 Voltage & Current Waveform (Zoomed)

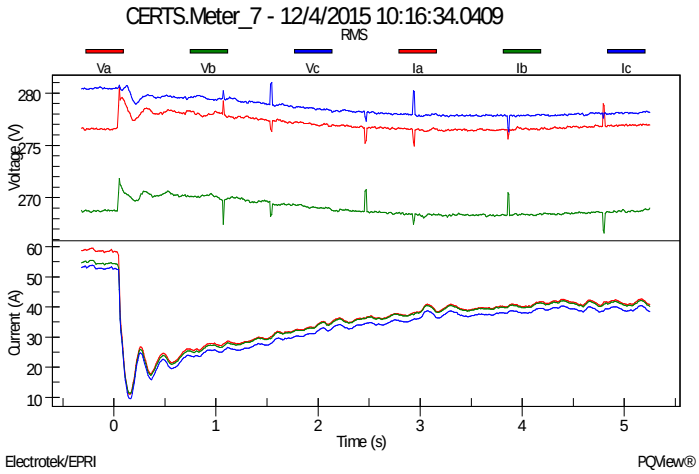

Figure 249: Event Q, ESS RMS Voltage & Current

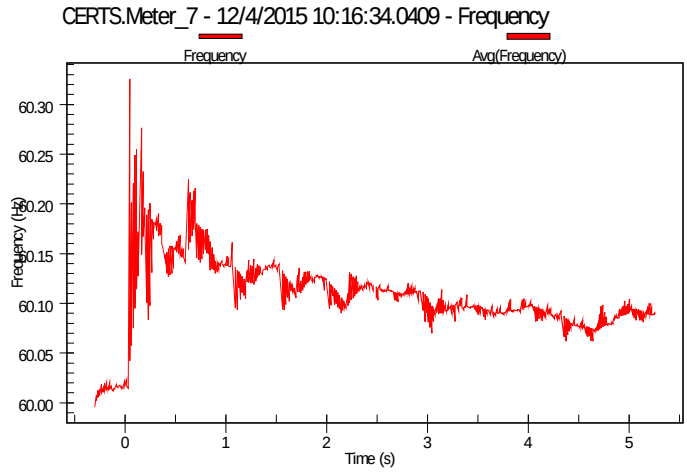

Figure 250: Event Q, ESS Frequency

Figure 251 through Figure 258 show the results of Event R where the ESS and B1 are both dispatched to 50 kW, microgrid load is (60 + j30) kVA, and the microgrid transitions from islanded to grid-tied. The transition occurs smoothly.

The difference in the speed of the real power response can be seen in Figure 251, ESS real power, and Figure 252, B1 real power. The ESS transitions to steady state in approximately 260 ms while B1 takes about 5.1 seconds.

The sources real power output while grid-tied is determined by the grid frequency, in this case 60.00 Hz (as determined by the Yokogawa ScopeCorder in Table 27), so both sources should be supplying approximately their dispatched value of 50 kW. The ESS is supplying 44.9 kW and B1 is supplying 50.0 kW.

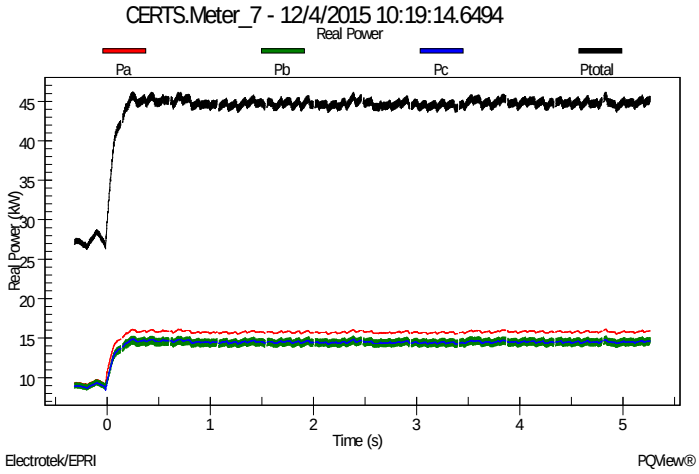

Figure 251: Event R, ESS Real Power

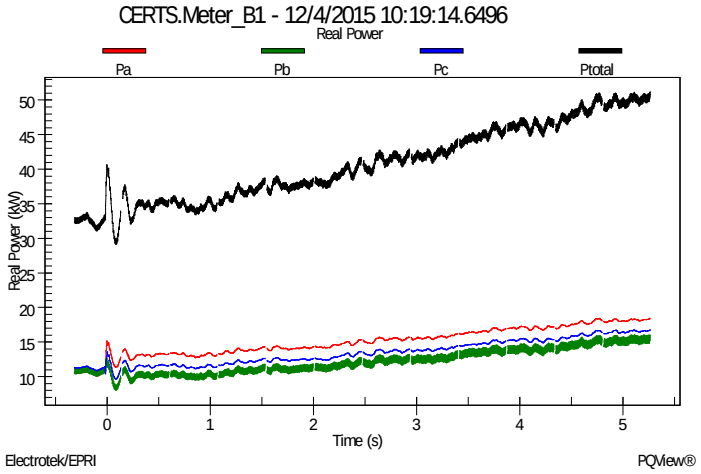

Figure 252: Event R, B1 Real Power

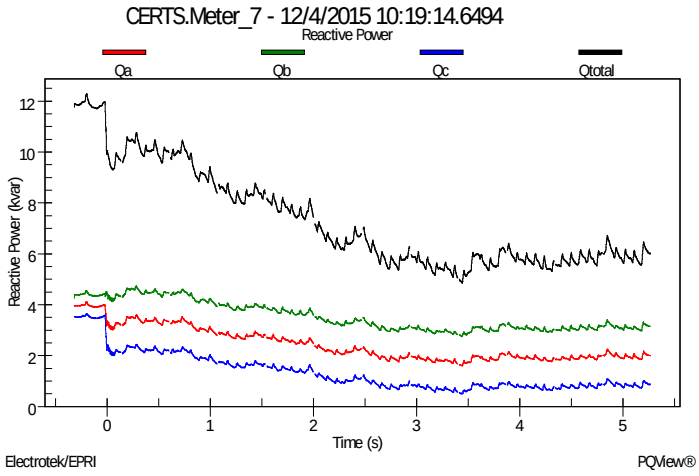

Figure 253: Event R, ESS Reactive Power

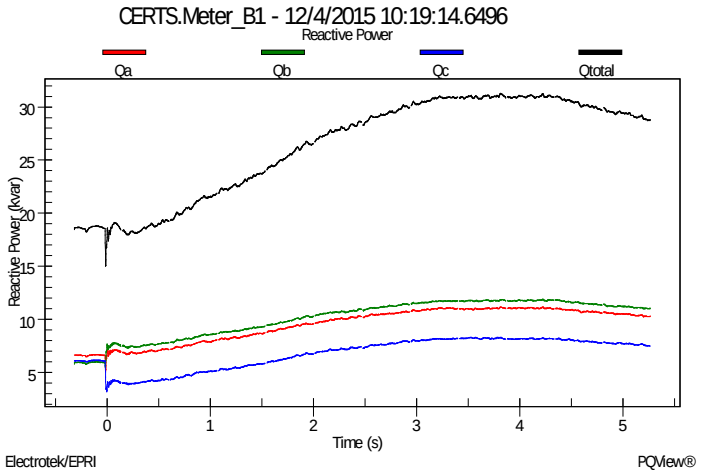

Figure 254: Event R, B1 Reactive Power

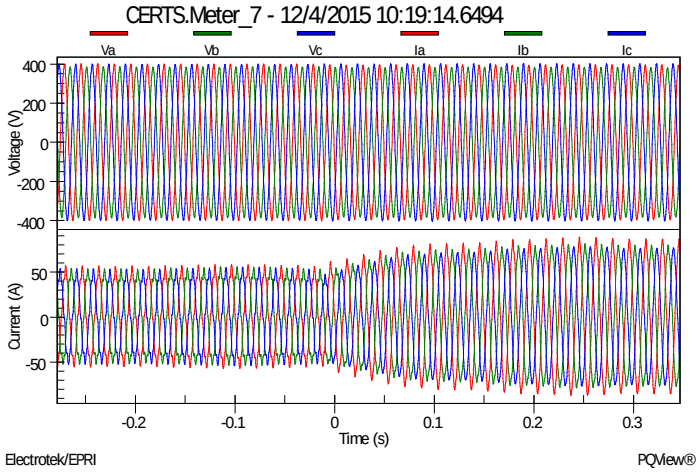

Figure 255: Event R, ESS Voltage & Current Waveform (Zoomed)

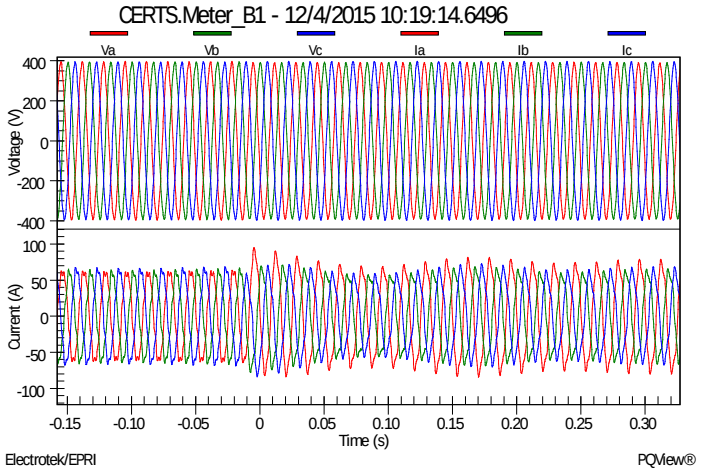

Figure 256: Event R, B1 Voltage & Current Waveform (Zoomed)

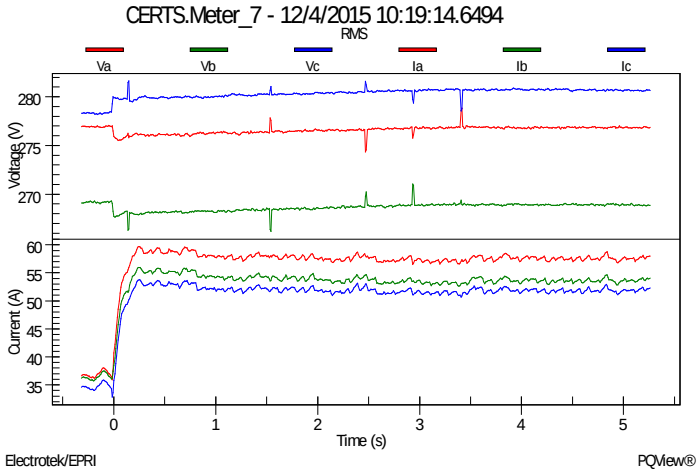

Figure 257: Event R, ESS RMS Voltage & Current

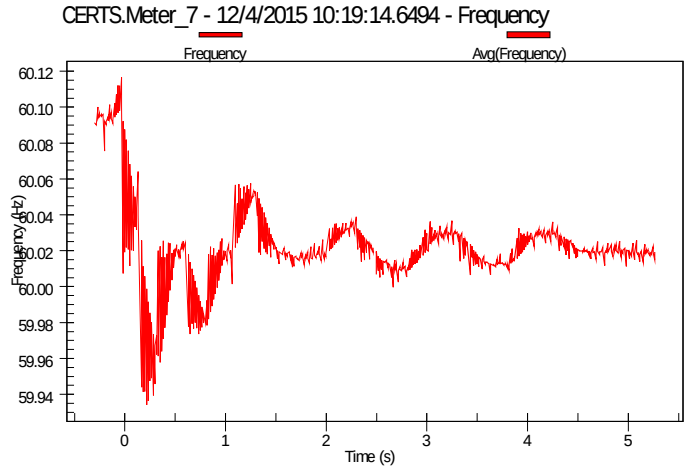

Figure 258: Event R, ESS Frequency

Figure 259 through Figure 266 show the results of Event S where the ESS and B1 are both dispatched to 50 kW, microgrid load is (143 + j73) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward B1 supplying more real power than expected by 7.7 kW (75.9 kW instead of the expected 68.2 kW). In this event the ESS's P_{max} is briefly activated at the beginning of the event since the ESS supplies the additional real power at the time of transition.

The microgrid frequency achieves an acceptable steady state value of 59.92 Hz which is 0.04 Hz more than the expected 59.88 Hz.

Reactive power is shared as expected with B1 supplying more reactive power than the ESS.

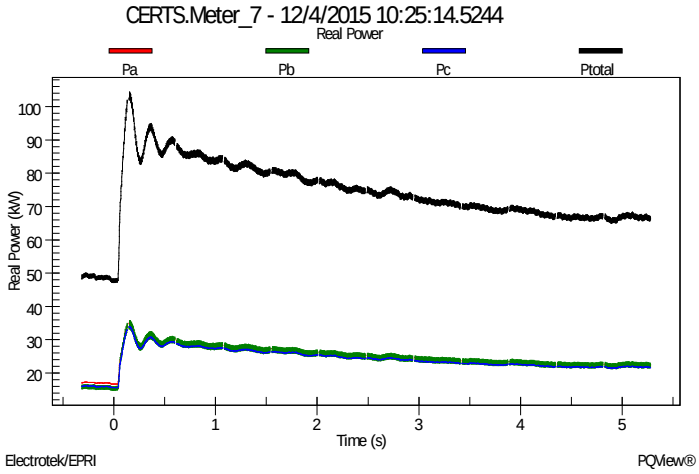

Figure 259: Event S, ESS Real Power

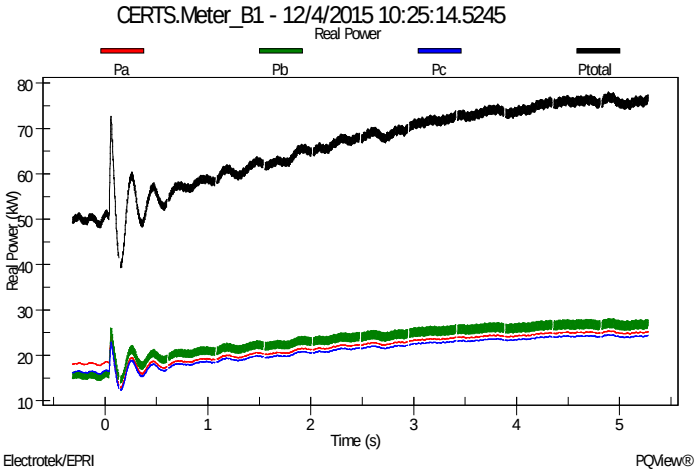

Figure 260: Event S, B1 Real Power

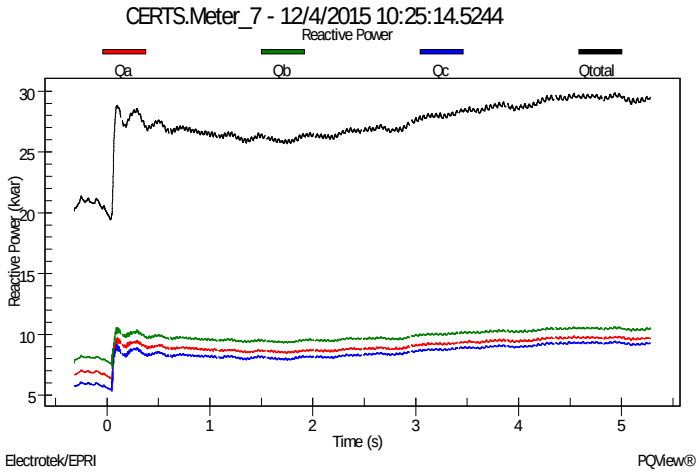

Figure 261: Event S, ESS Reactive Power

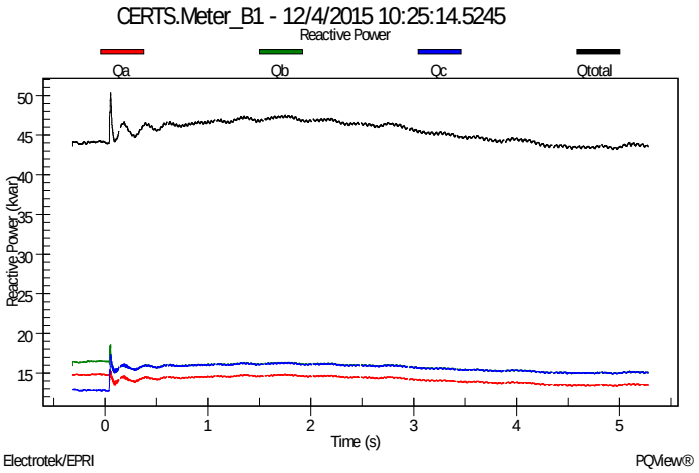

Figure 262: Event S, B1 Reactive Power

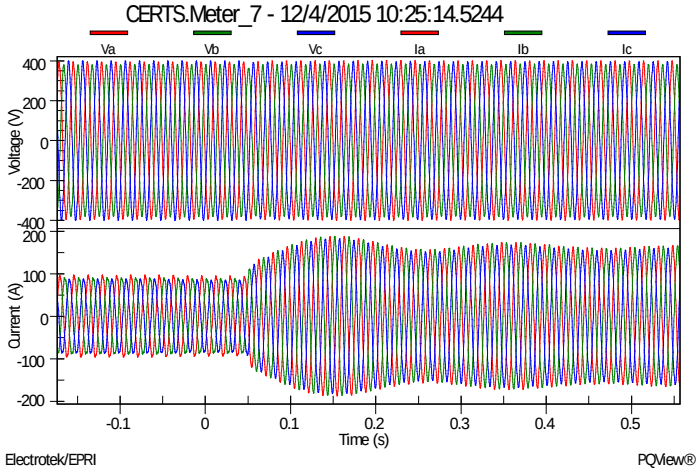

Figure 263: Event S, ESS Voltage & Current Waveform (Zoomed)

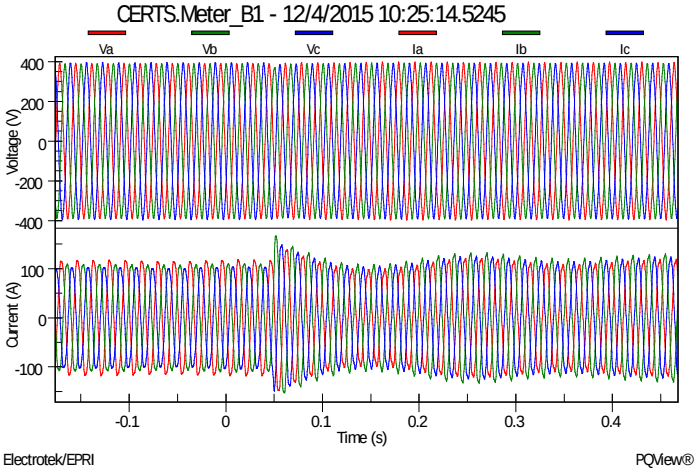

Figure 264: Event S, B1 Voltage & Current Waveform (Zoomed)

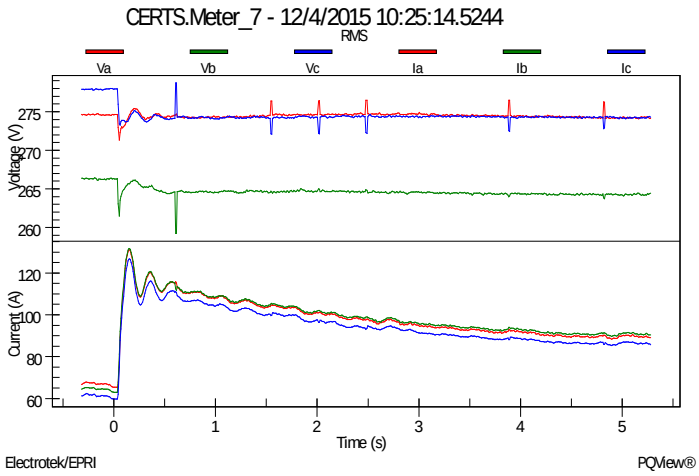

Figure 265: Event S, ESS RMS Voltage & Current

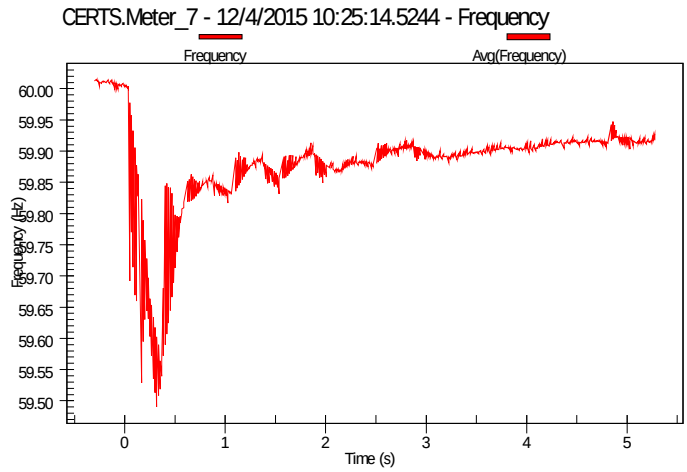

Figure 266: Event S, ESS Frequency

Figure 267 through Figure 276 show the results of Event U where the ESS is dispatched to 30 kW, B1 is dispatched to 80 kW, microgrid load is (135 + j61) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward B1 supplying more real power than expected by 3.2 kW (94.0 kW instead of the expected 90.8 kW).

A disturbance in the system is initiated at 4.25 seconds where the real and reactive power begin an oscillation of approximately (11 + j5) kVA. This extends to the end of the recording period at 5.3 seconds. It is not known what initiates the disturbance or how long it lasts; however, B1 appears to exceed 93 kW at the 3 second mark which would activate is P_{max} functionality. While the test is designed not to activate B1's P_{max} it is intended to bring it close at about 89 kW. B1 then wanders in and out of P_{max} territory through the end of the recorded event. The oscillations are not present 4 minutes later when Event V is triggered. No changes in the microgrid occurred between the end of Event U and the beginning of Event V.

The microgrid frequency achieves an acceptable steady state value of 59.92 Hz which is 0.01 Hz less than the expected 59.93 Hz.

Reactive power is shared as expected with B1 supplying more reactive power than the ESS.

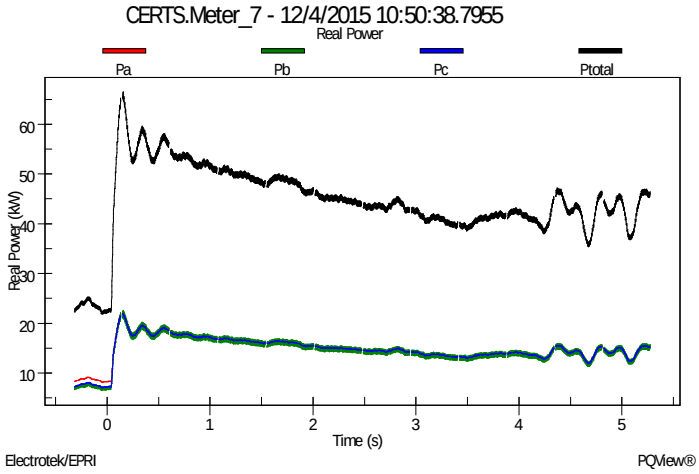

Figure 267: Event U, ESS Real Power

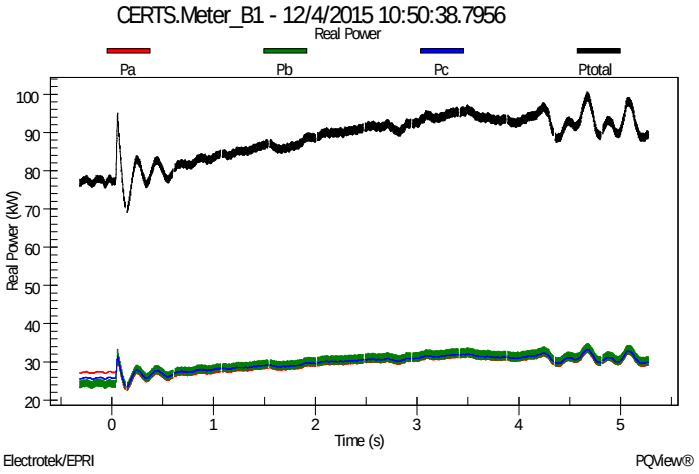

Figure 268: Event U, B1 Real Power

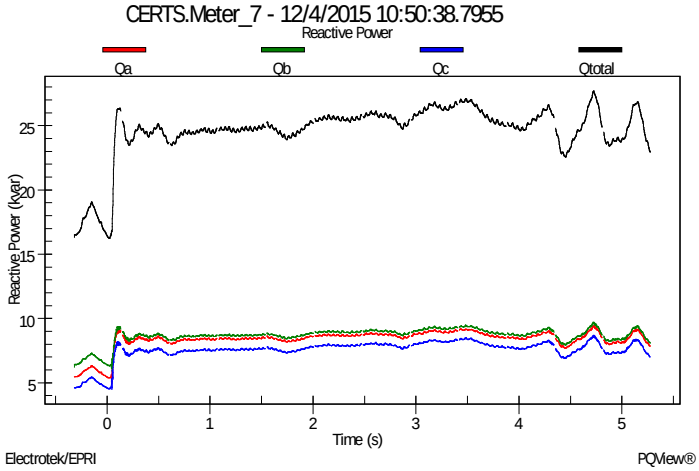

Figure 269: Event U, ESS Reactive Power

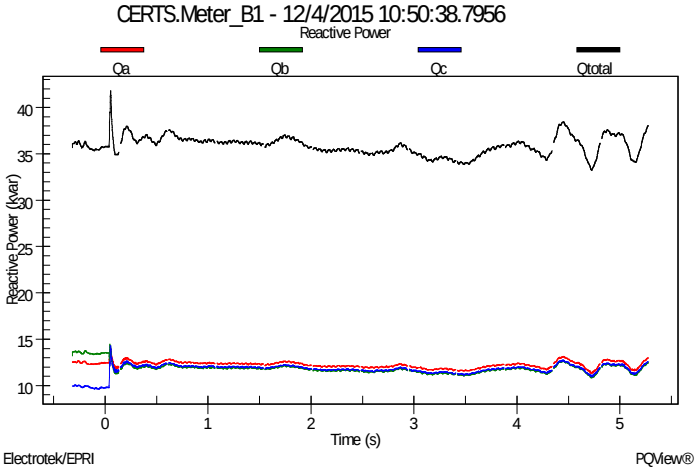

Figure 270: Event U, B1 Reactive Power

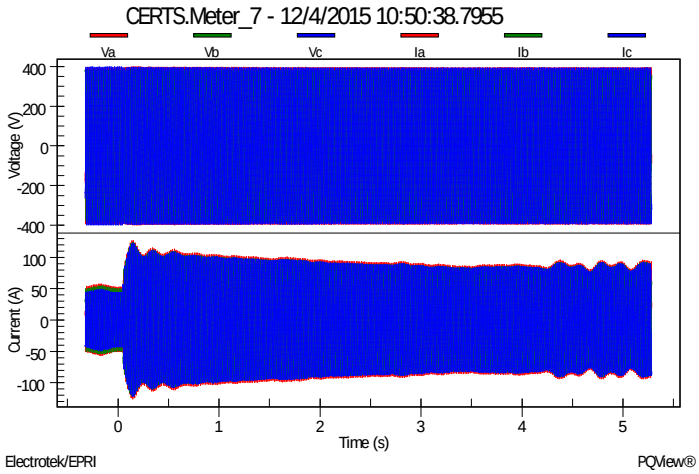

Figure 271: Event U, ESS Voltage & Current Waveform

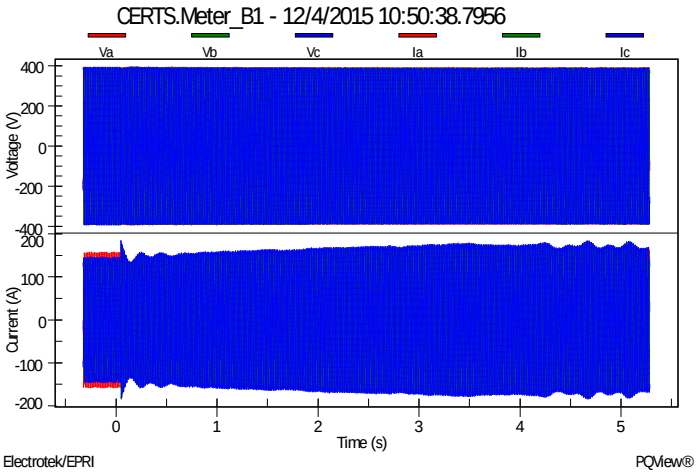

Figure 272: Event U, B1 Voltage & Current Waveform

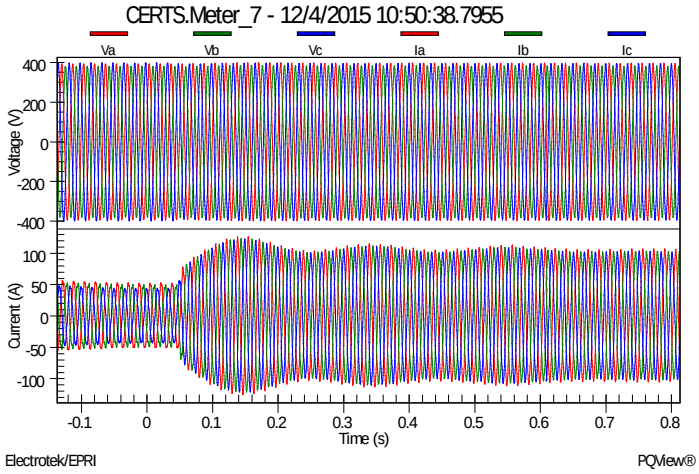

Figure 273: Event U, ESS Voltage & Current Waveform (Zoomed)

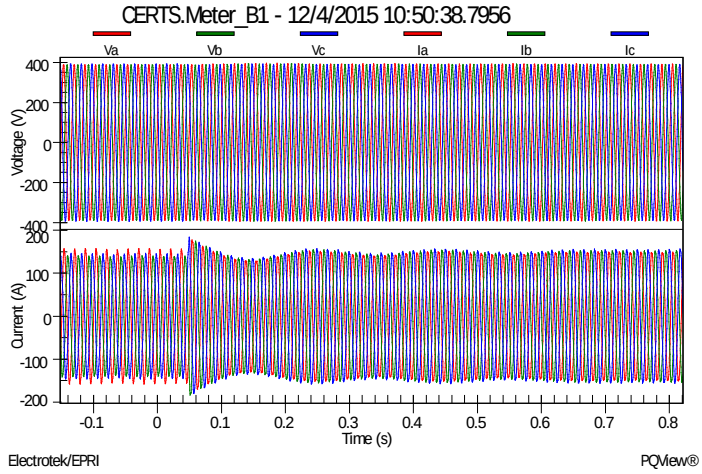

Figure 274: Event U, B1 Voltage & Current Waveform (Zoomed)

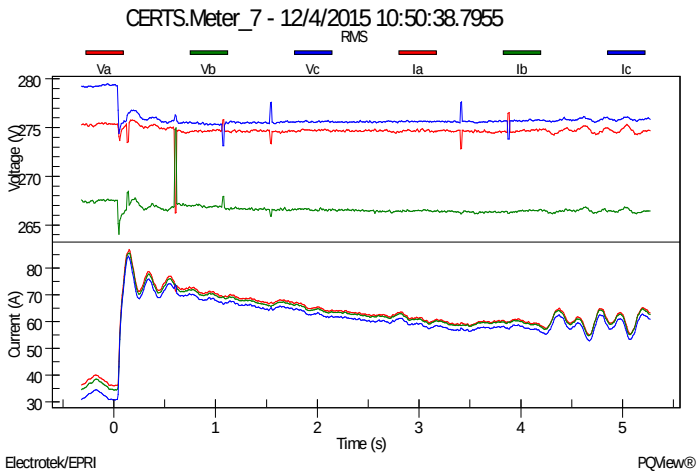

Figure 275: Event U, ESS RMS Voltage & Current

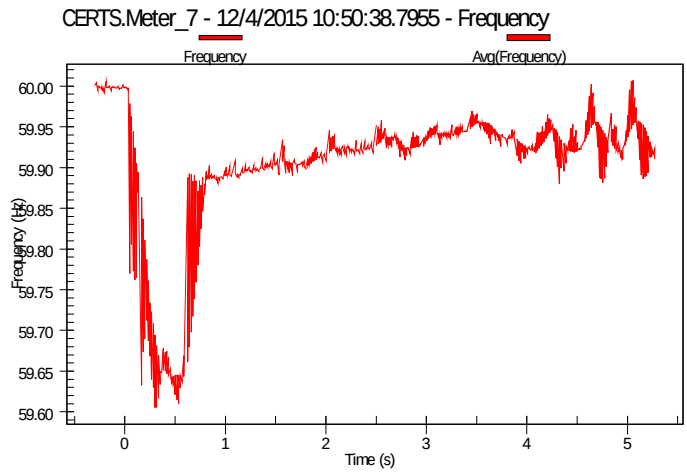

Figure 276: Event U, ESS Frequency

Figure 277 through Figure 284 show the results of Event W where the ESS is dispatched to 30 kW, B1 is dispatched to 80 kW, microgrid load is (84 + j40) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 1.5 kW (16.4 kW instead of the expected 14.9 kW).

The microgrid frequency achieves an acceptable steady state value of 60.08 Hz which is 0.01 Hz more than the expected 60.07 Hz.

Reactive power is shared as expected with B1 supplying more reactive power than the ESS. It can be seen in Figure 279 and Figure 280 that the reactive power has not reached steady state however it is estimated that B1 would supply approximately 25 kVAr and the ESS about 15 kVAr.

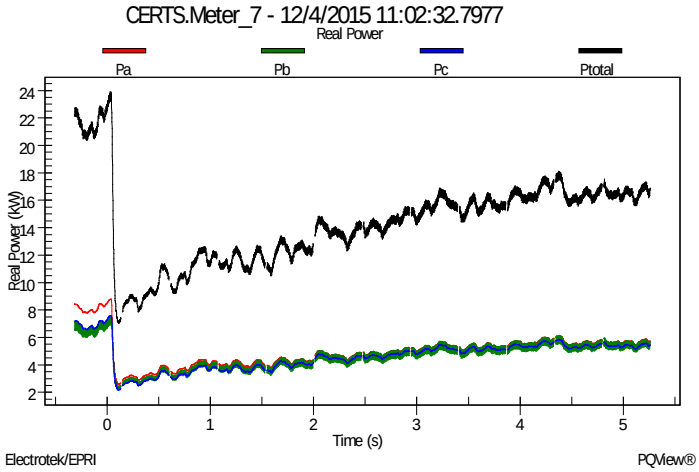

Figure 277: Event W, ESS Real Power

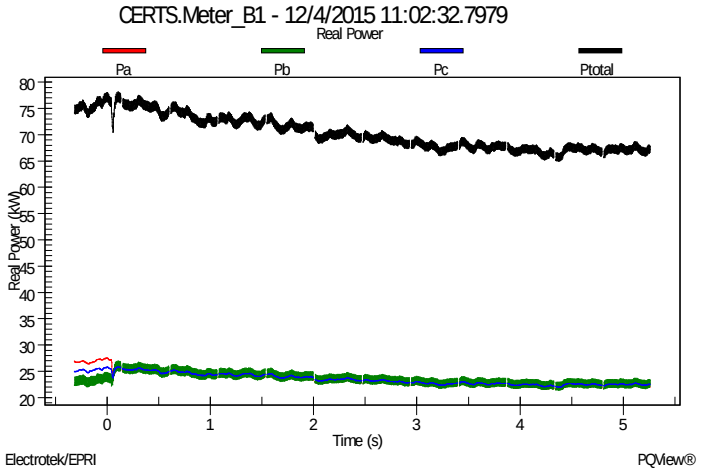

Figure 278: Event W, B1 Real Power

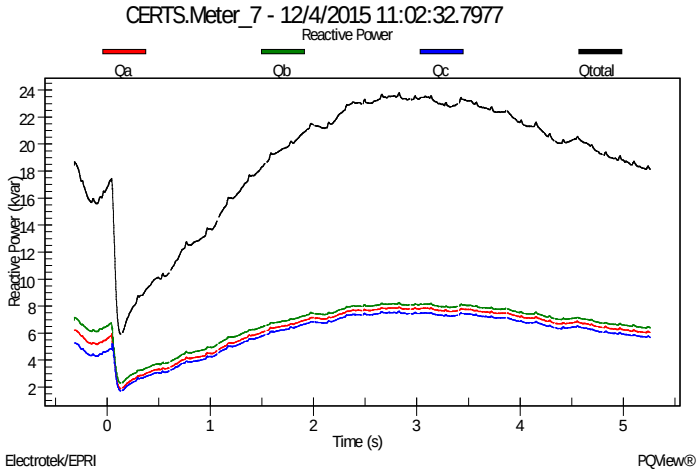

Figure 279: Event W, ESS Reactive Power

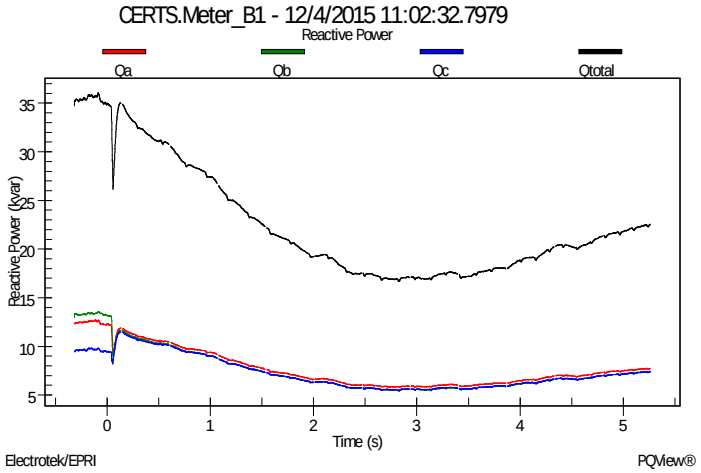

Figure 280: Event W, B1 Reactive Power

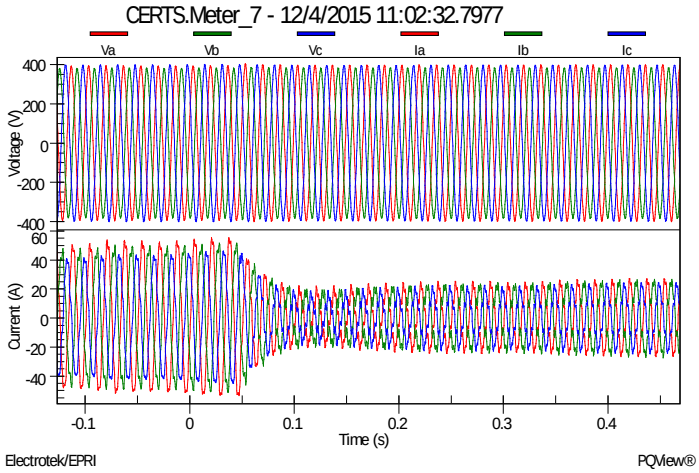

Figure 281: Event W, ESS Voltage & Current Waveform (Zoomed)

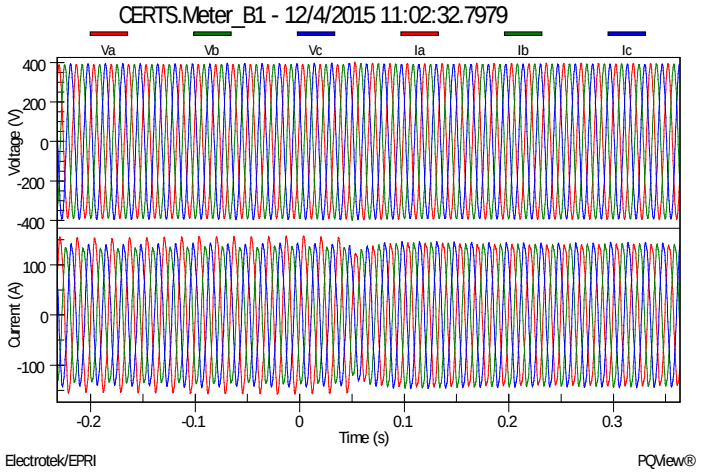

Figure 282: Event W, B1 Voltage & Current Waveform (Zoomed)

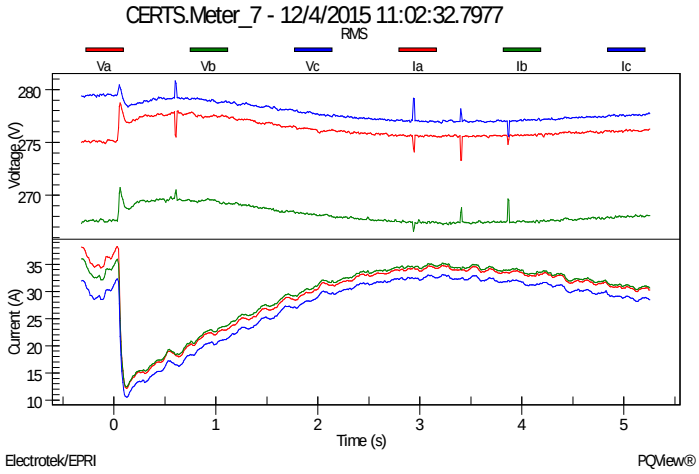

Figure 283: Event W, ESS RMS Voltage & Current

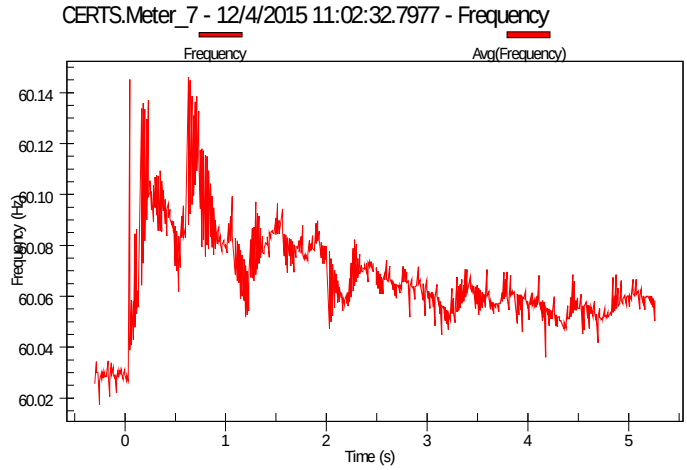

Figure 284: Event W, ESS Frequency

Figure 285 through Figure 292 show the results of Event Y where the ESS is dispatched to 80 kW, B1 is dispatched to 30 kW, microgrid load is (65 + j30) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS supplying more real power than expected by 7.5 kW (61.6 kW instead of the expected 54.1 kW) although the actual difference may be slightly less as it appears the units have not quite reached steady state for real power.

The microgrid frequency achieves an acceptable steady state value of 60.08 Hz which is 0.04 Hz less than the expected 60.12 Hz.

Reactive power is shared as expected with B1 supplying more reactive power than the ESS. It can be seen in Figure 287 and Figure 288 that the reactive power has not reached steady state however it is estimated that B1 would supply approximately 24 kVAr and the ESS about 6 kVAr.

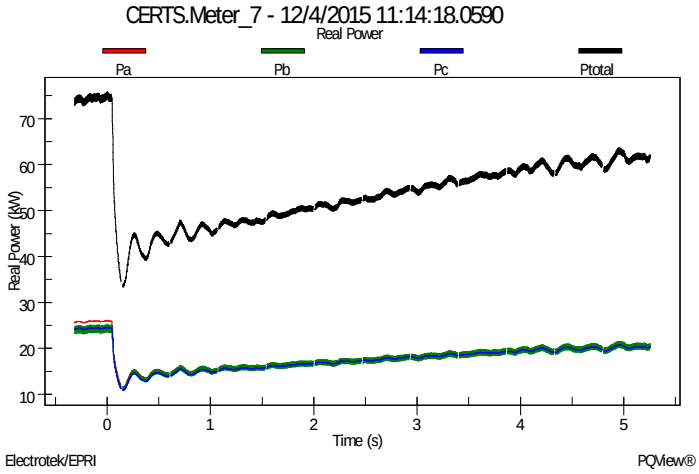

Figure 285: Event Y, ESS Real Power

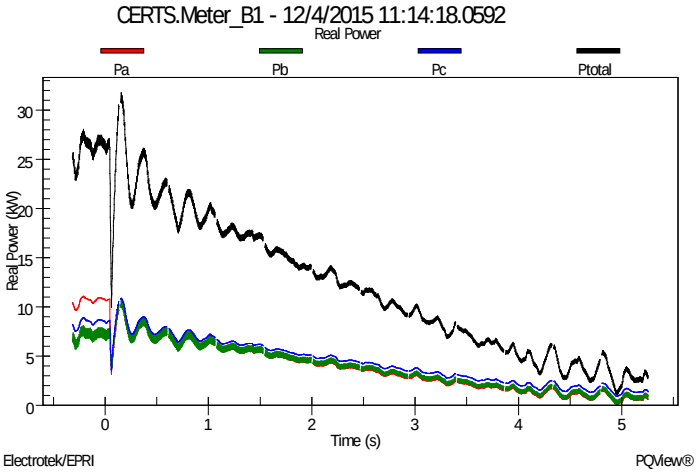

Figure 286: Event Y, B1 Real Power

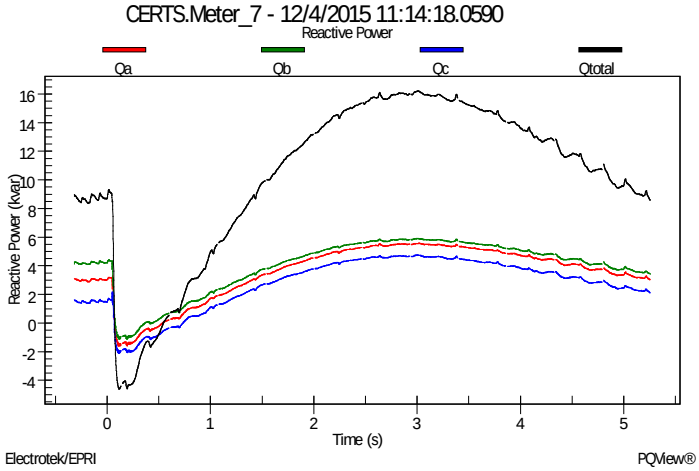

Figure 287: Event Y, ESS Reactive Power

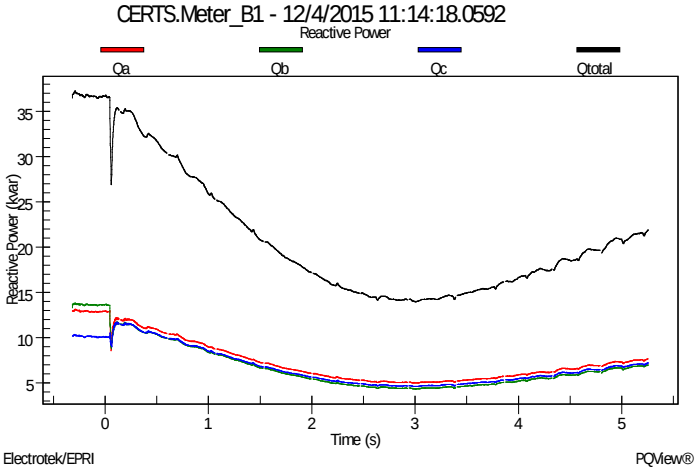

Figure 288: Event Y, B1 Reactive Power

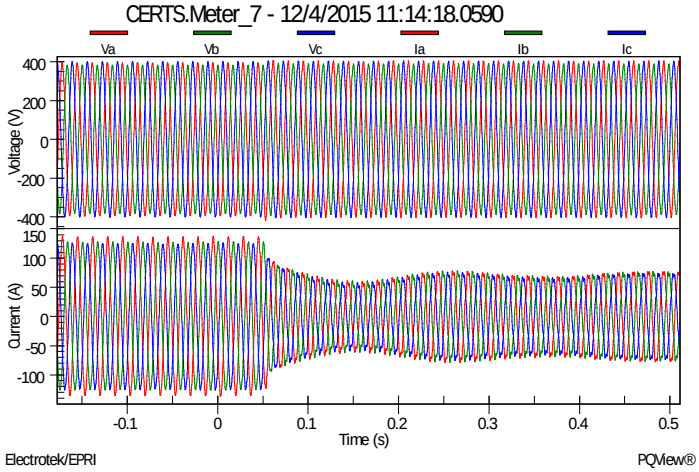

Figure 289: Event Y, ESS Voltage & Current Waveform (Zoomed)

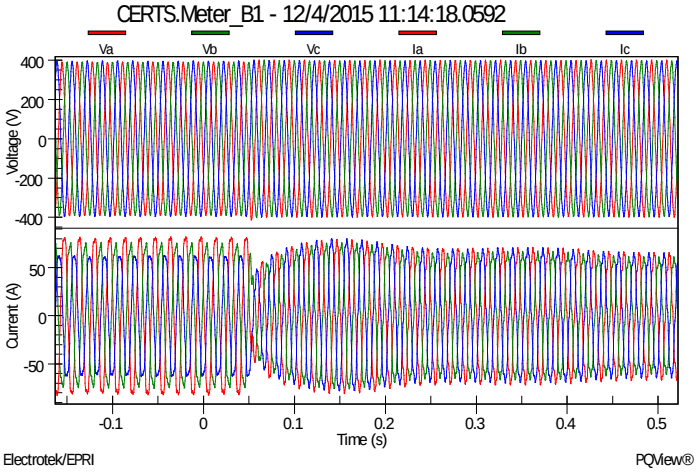

Figure 290: Event Y, B1 Voltage & Current Waveform (Zoomed)

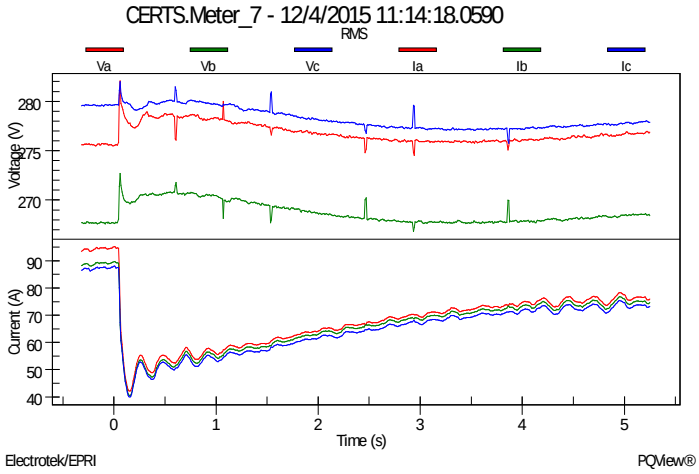

Figure 291: Event Y, ESS RMS Voltage & Current

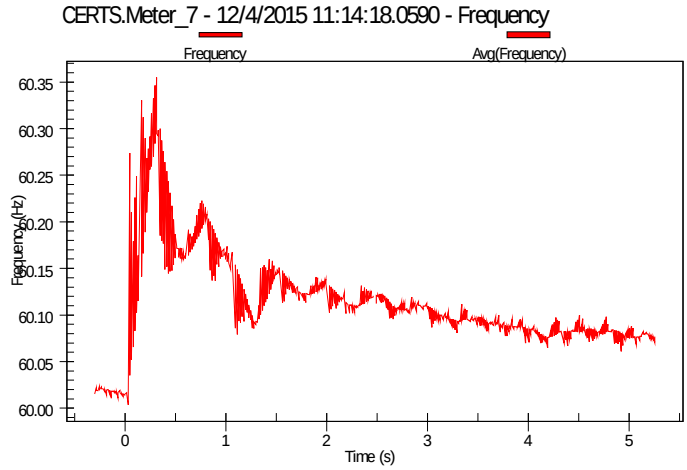

Figure 292: Event Y, ESS Frequency

Figure 293 through Figure 300 show the results of Event AA where the ESS is dispatched to 80 kW, B1 is dispatched to 30 kW, microgrid load is (133 + j61) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward B1 supplying more real power than expected by 3.1 kW (42.7 kW instead of the expected 39.6 kW). In this event the ESS's P_{max} is briefly activated at the beginning of the event since the ESS supplied the additional real power at the time of transition.

The microgrid frequency achieves an acceptable steady state value of 59.92 Hz which is 0.02 Hz less than the expected 59.94 Hz.

Reactive power is shared as expected with B1 supplying more reactive power than the ESS.

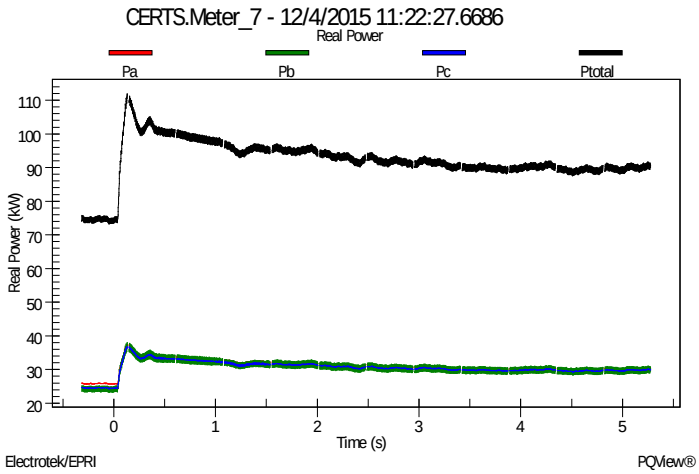

Figure 293: Event AA, ESS Real Power

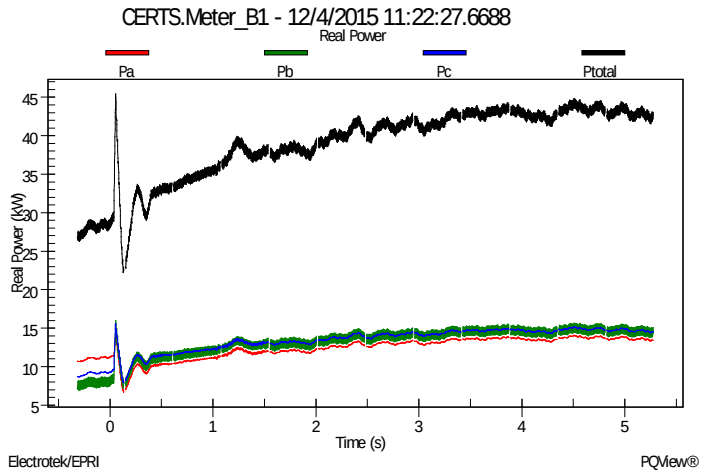

Figure 294: Event AA, B1 Real Power

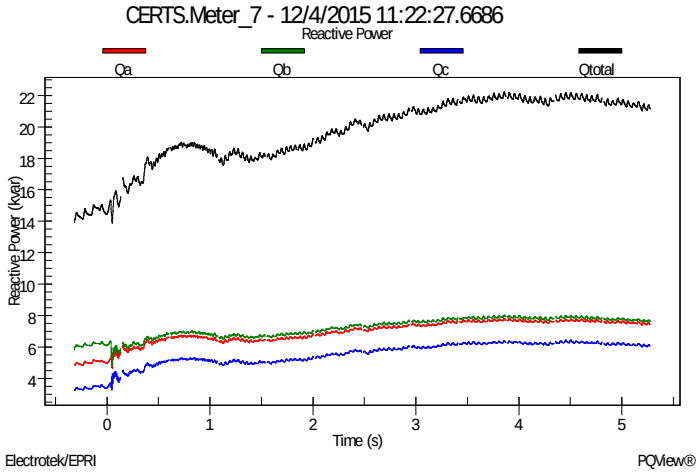

Figure 295: Event AA, ESS Reactive Power

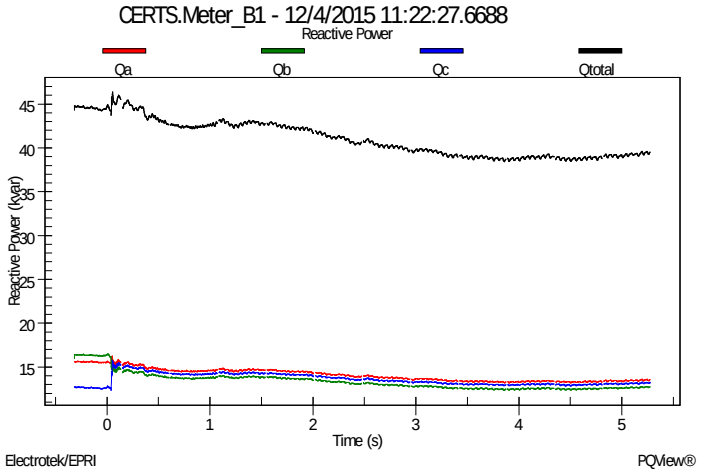

Figure 296: Event AA, B1 Reactive Power

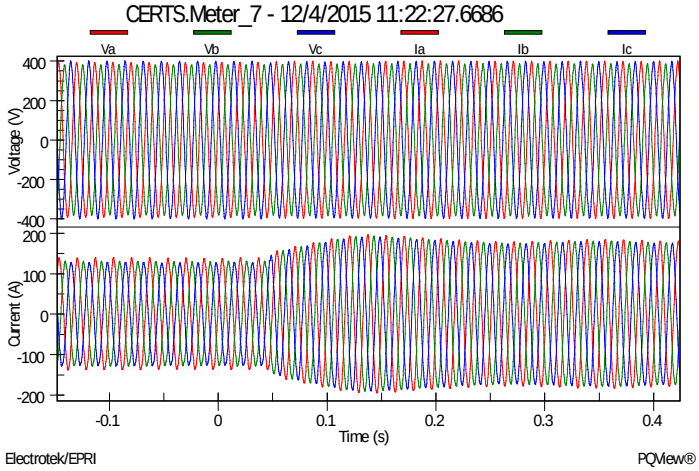

Figure 297: Event AA, ESS Voltage & Current Waveform (Zoomed)

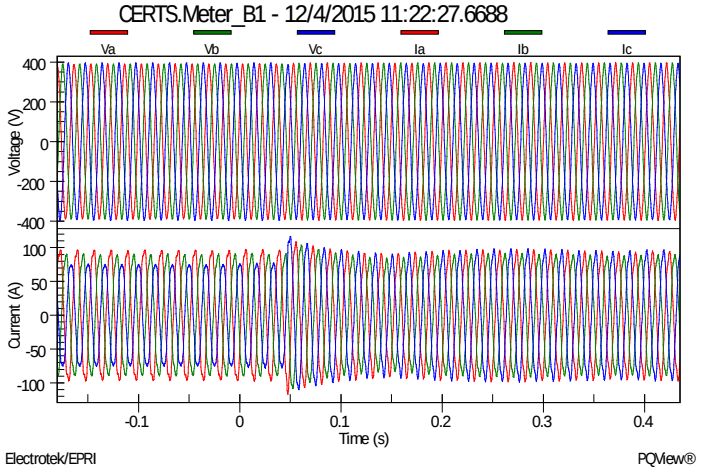

Figure 298: Event AA, B1 Voltage & Current Waveform (Zoomed)

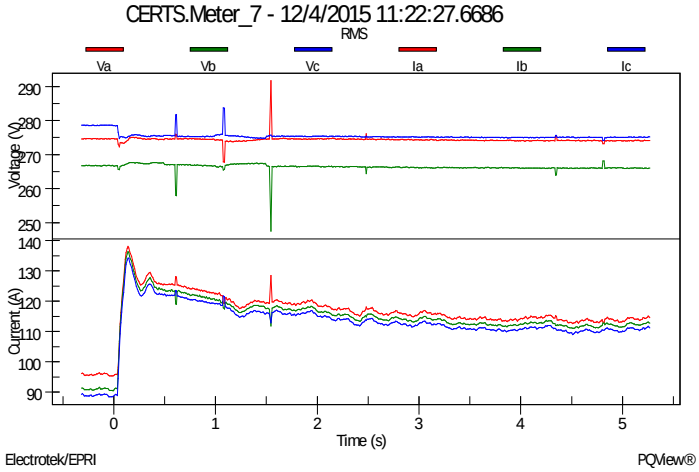

Figure 299: Event AA, ESS RMS Voltage & Current

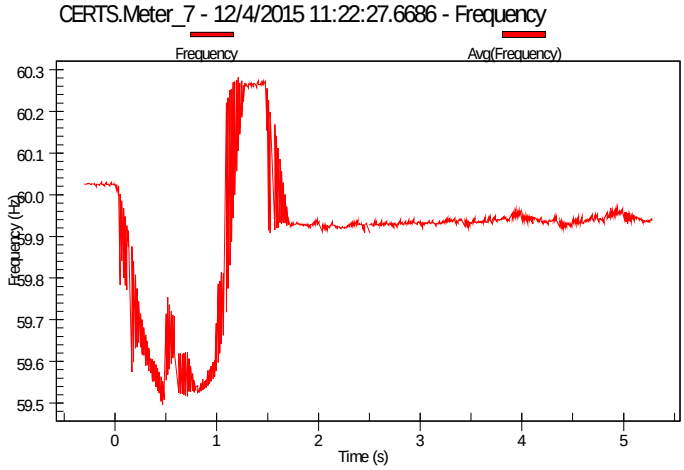

Figure 300: Event AA, ESS Frequency

Figure 301 through Figure 308 show the results of Event CC where the ESS is dispatched to -10 kW, B1 is dispatched to 50 kW, microgrid load is (135 + j61) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward B1 supplying more real power than expected by 3.5 kW (94.1 kW instead of the expected 90.6 kW). In this event the ESS's P_{max} is briefly activated at the beginning of the event since the ESS supplies the additional real power at the time of transition. This event also demonstrates a transition for the ESS from charging at 11 kW to a peak discharge of 116 kW at the initiation of the event.

A disturbance in the system is initiated at 3.7 seconds where the real and reactive power begin an oscillation of approximately (8 + j2) kVA. This extends to the end of the recording period at 5.3 seconds. It is not known what initiated the disturbance or how long it lasted; however, B1 appears to exceed 93 kW at the 2.8 second mark which would activate is P_{max} functionality. While the test is designed not to activate B1's P_{max} it is intended to bring it close at about 88 kW. B1 then wanders in and out of P_{max} territory through the end of the recorded event. The oscillations are not present 4 minutes later when Event DD is triggered. No changes in the microgrid occurred between the end of Event CC and the beginning of Event DD.

The microgrid frequency achieves an acceptable steady state value of 59.76 Hz which is 0.02 Hz more than the expected 59.74 Hz.

Reactive power is shared as expected with B1 supplying more reactive power than the ESS. It can be seen in Figure 303 and Figure 304 that the reactive power has not reached steady state however it is estimated that B1 would supply approximately 39 kVAr and the ESS about 22 kVAr.

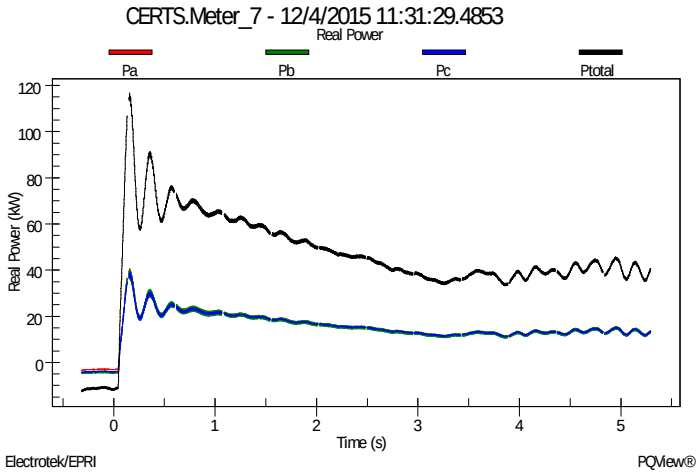

Figure 301: Event CC, ESS Real Power

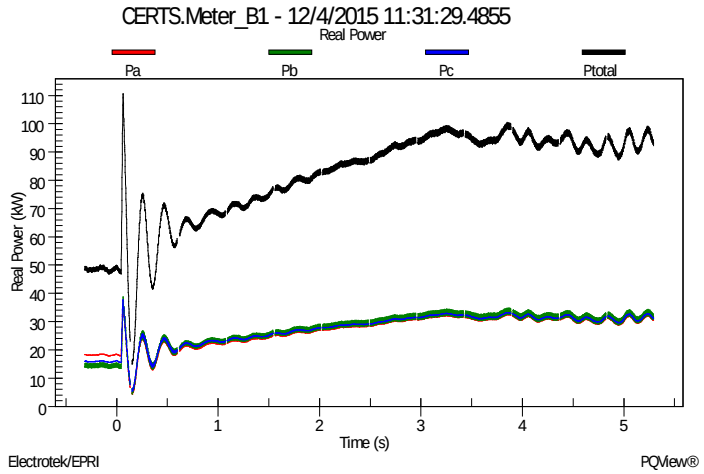

Figure 302: Event CC, B1 Real Power

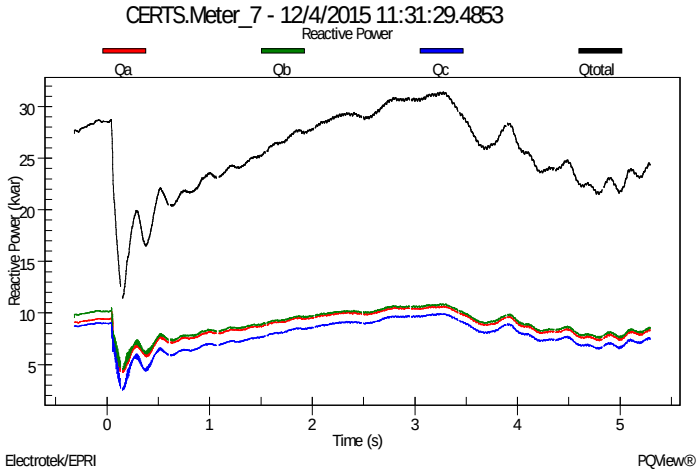

Figure 303: Event CC, ESS Reactive Power

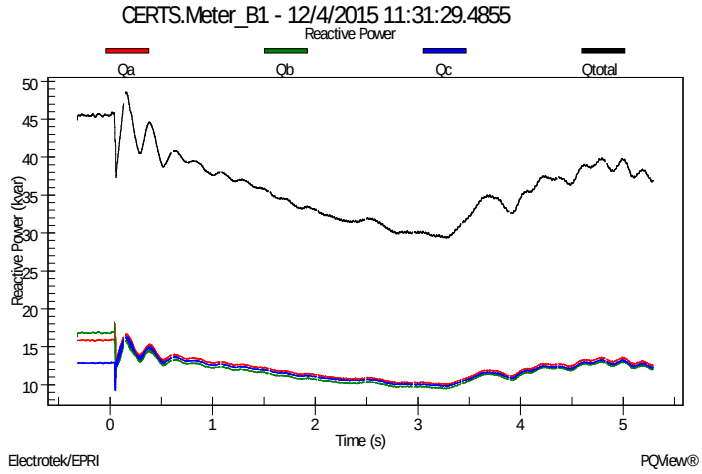

Figure 304: Event CC, B1 Reactive Power

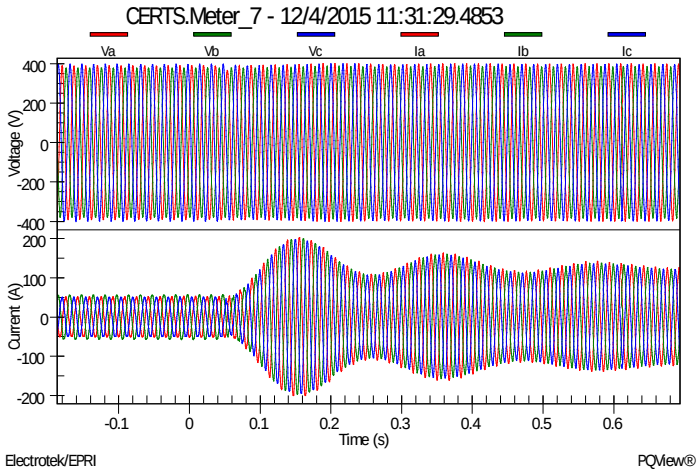

Figure 305: Event CC, ESS Voltage & Current Waveform (Zoomed)

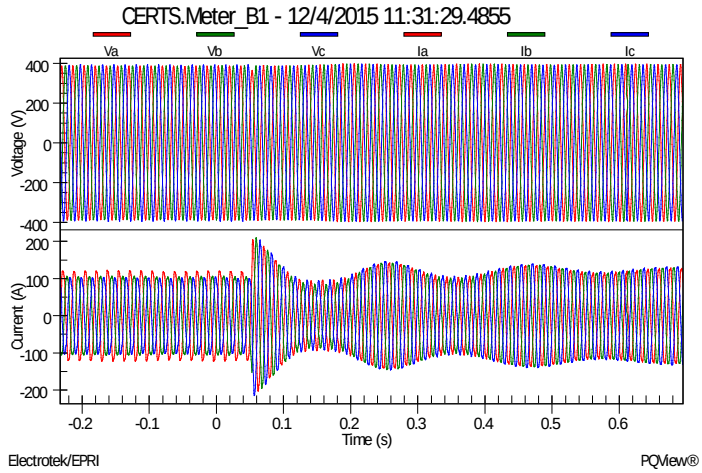

Figure 306: Event CC, B1 Voltage & Current Waveform (Zoomed)

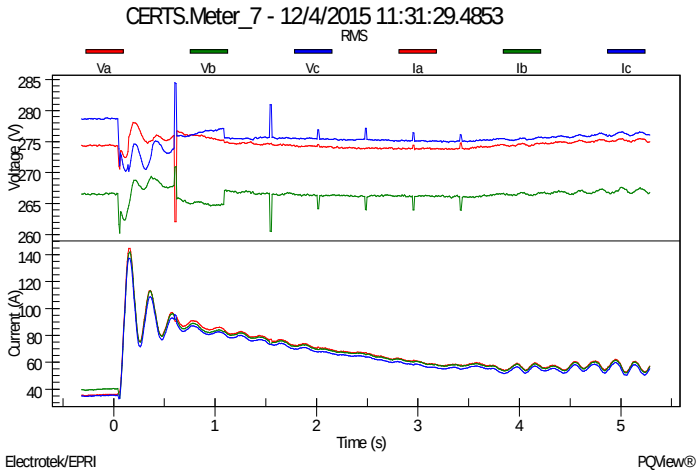

Figure 307: Event CC, ESS RMS Voltage & Current

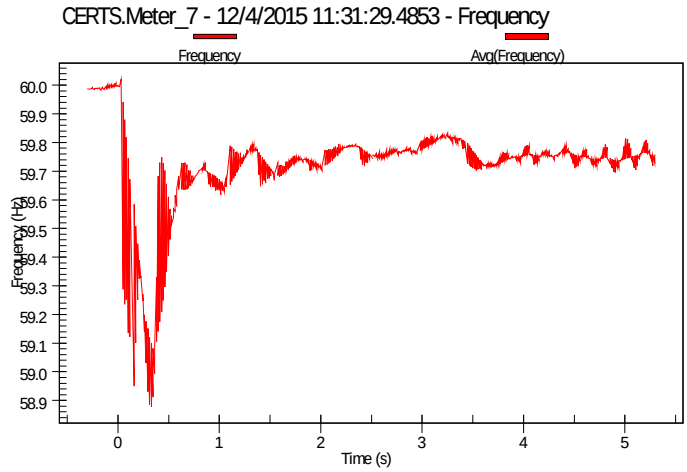

Figure 308: Event CC, ESS Frequency

Figure 309 through Figure 316 show the results of Event EE where the ESS is dispatched to 10 kW, B1 is dispatched to 65 kW, microgrid load is (29 + j10) kVA, and the microgrid transitions from grid-tied to islanded.

The transition occurs with the ESS initially adjusting its real power output and then the units smoothly transitioning to share the load appropriately according to their real power droop characteristics with a slight bias toward the ESS charging at a lower rate than expected by 4.1 kW (-12.3 kW instead of the expected -16.4 kW) although the actual difference may be slightly less as it appears the units have not quite reached steady state for real power.

The microgrid frequency achieves an acceptable steady state value of 60.09 Hz which is 0.04 Hz less than the expected 60.13 Hz.

Reactive power is shared as expected with ESS supplying more reactive power than the B1 since the ESS is in charge mode. It can be seen in Figure 311 and Figure 312 that the reactive power has not reached steady state however it is estimated that B1 would supply approximately 4 kVAr and the ESS about 6 kVAr.

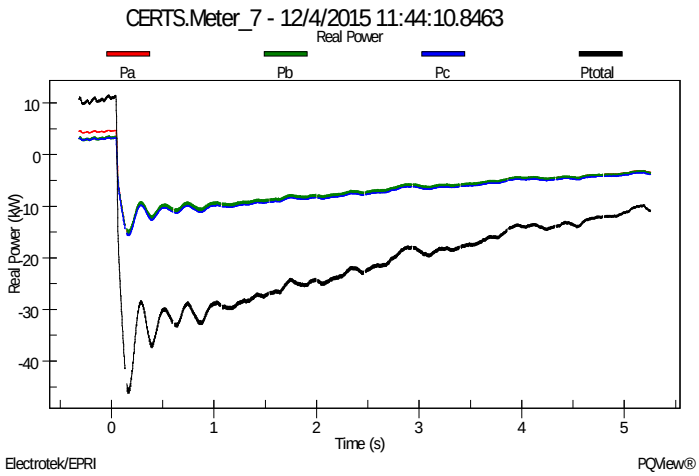

Figure 309: Event EE, ESS Real Power

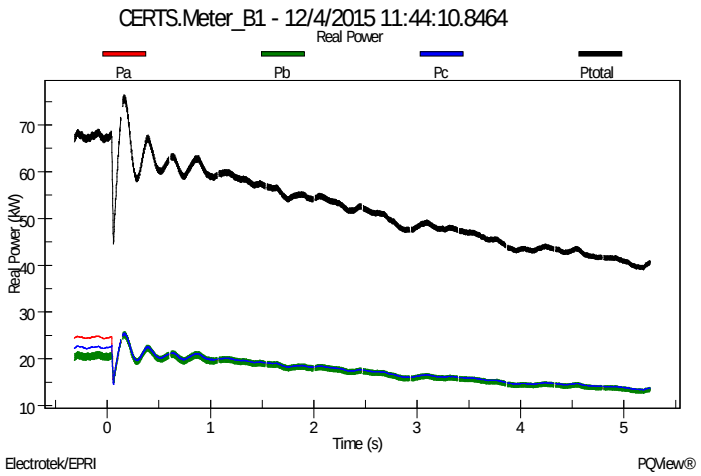

Figure 310: Event EE, B1 Real Power

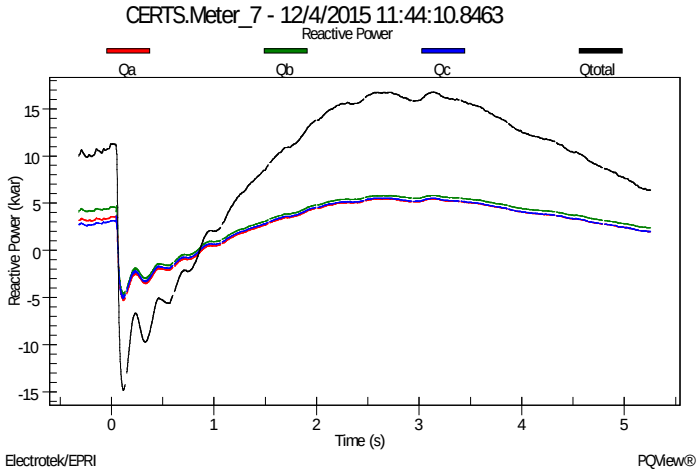

Figure 311: Event EE, ESS Reactive Power

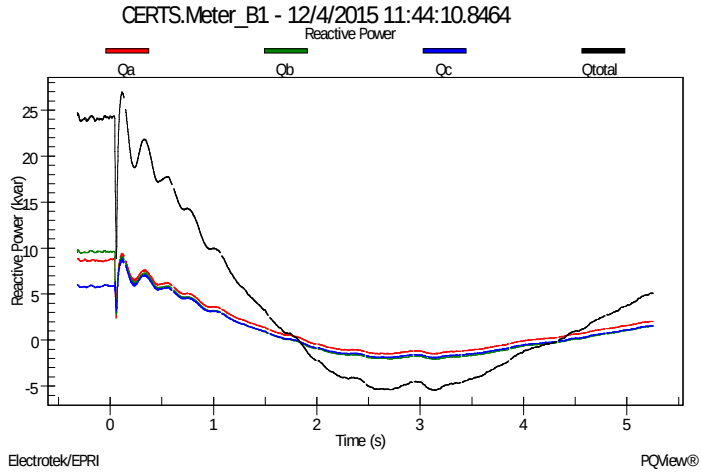

Figure 312: Event EE, B1 Reactive Power

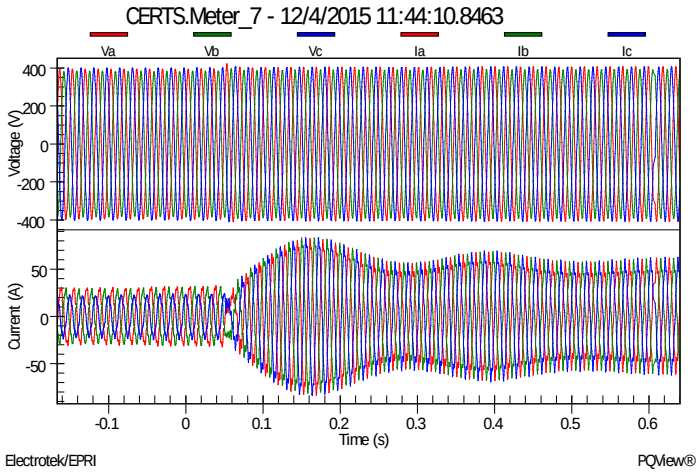

Figure 313: Event EE, ESS Voltage & Current Waveform (Zoomed)

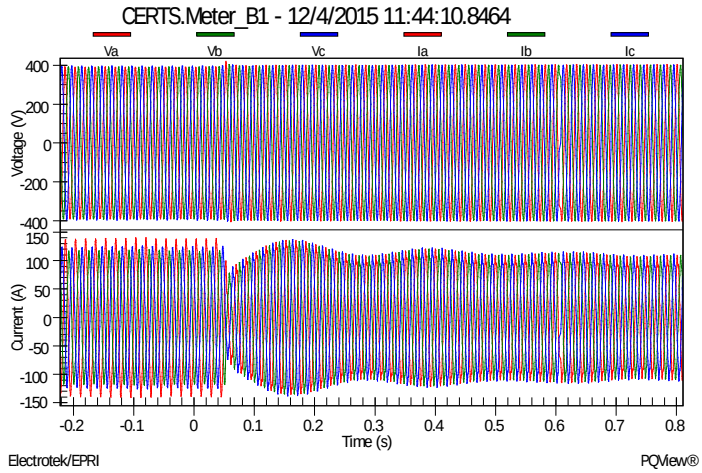

Figure 314: Event EE, B1 Voltage & Current Waveform (Zoomed)

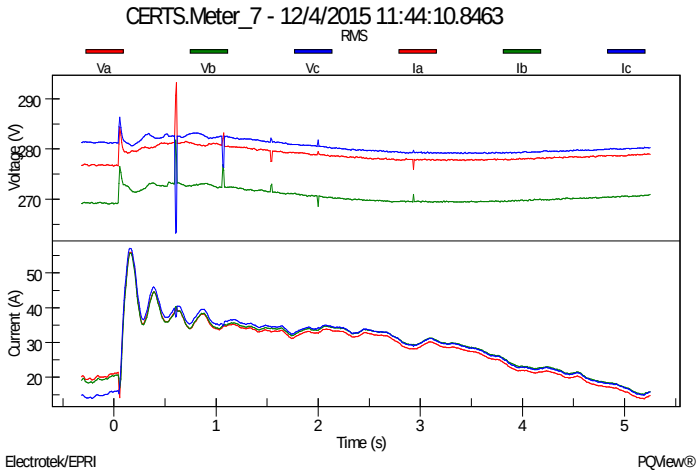

Figure 315: Event EE, ESS RMS Voltage & Current

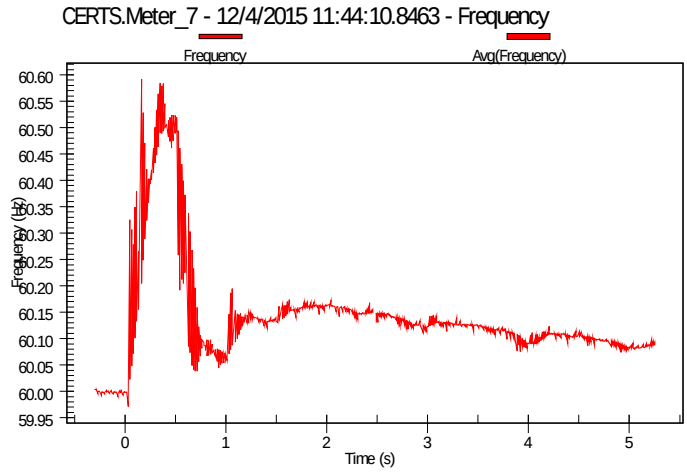

Figure 316: Event EE, ESS Frequency

5.14 Pmax Control – Multiple Sources, Islanded

Performance Goal

The intent of this testing is to ensure proper implementation of the CERTS P_{max} function when a pair of DERs are operating in the islanded microgrid. The P_{max} function is activated when the DER is operating at its maximum limit of real power capability. This function responds to an overload condition by driving the output frequency down to allow other CERTS DERs in the microgrid the opportunity to pick up additional load and relieve the overloaded unit(s). The DER should demonstrate a predictable adjustment in frequency when the real power it is producing exceeds its P_{max} setting.

These tests will examine how the sources share load when P_{max} is activated on one source, either the ESS or the accompanying gen-set. These tests are performed with the ESS and A1 to see how load sharing works with another inverter-connected source and then with the ESS and the synchronous generator, B1.

Description of Procedure

The pair of DERs will initially be grid-connected. One unit will have its $P_{dispatch}$ set rather high and the other will be set low. A load is applied in the microgrid so that when islanded it will be sufficient to drive the unit with the higher $P_{dispatch}$ setting into overload but not both units. The microgrid is then disconnected from the utility. This should result in the unit whose $P_{dispatch}$ is set high to have its P_{max} activated thus driving the system frequency down. The result should be that the other unit will increase its output and limit the overloaded unit to its P_{max} setting.

The units are dispatched to various real power settings. Otherwise, all units are dispatched to 1% Frequency Droop, 480 V_{LL}, 5% Voltage Droop.

Test Settings

For these tests the following parameter settings are made:

<u>ESS</u>

Pdispatch = Varies

Frequency Droop = 1%

Real Power-Frequency Droop = -.0048 Hz/kW

P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)

P_{min} = -25 kW (P_{min} = Battery Power Limit Min parameter on inverter)

Voltage Set Point = 480 V_{LL} (Inverter Voltage Reference = 102.2)

Voltage Droop = -0.24 V_{LL}/kVAr (5%)

Voltage Regulation P-gain = 0.4

Voltage Regulation I-gain = 16

<u>A1 (Inverde 100)</u>

Pdispatch = Varies

Frequency Droop = 1%
Real Power-Frequency Droop = -.006 Hz/kW
P_{max} = 100 kW
P_{min} = 0 kW
Voltage Set Point = 480 V_{LL}
Voltage Droop = -0.14 V_{LN}/kVAr (5%)

<u>B1 (Sync Gen)</u>
Pdispatch = Varies
Frequency Droop = 1%
Real Power-Frequency Droop = -.006452 Hz/kW
P_{max} = 93 kW
P_{min} = 0 kW
Voltage Set Point = 480 V_{LL}
Voltage Droop = -0.24 V_{LL}/kVAr (5%)

During each sequence of tests in Table 28, a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers "Closed"; load banks are set as close as possible to the prescribed values; reactive load is set to achieve a power factor of approximately 0.9 lagging inside the microgrid (excludes load bank 6 which is outside of the microgrid); and events are triggered based on the transition of the GIS.

Test Events A, B, G, and H are designed to activate P_{max} in the accompanying gen-set A1 or B1. The remaining tests are designed to activate P_{max} on the ESS.

	Dispatch			Pre-Event Loads (pf = 0.9)			Pre-Event Meter Values					Islanded Freq (Hz)	
Test Event	A1 (kW)	ESS (kW)	B1 (kW)	L 3 (kW)	L 4 (kW)	L 6 (kW)	A1 (kW)	Meter 3 (kW)	B1 (kW)	Meter 7 (kW)	SS (kW)		GIS
A	90	20	-	75	75	-	90	60	0	-20	40	59.856	Closed → Open
B	90	20	-	75	75	-	100	50	0	-50	-	59.856	Open → Closed
C	20	90	-	75	75	-	20	130	0	-90	40	59.82	Closed → Open
D	20	90	-	75	75	-	50	100	0	-100	-	59.82	Open → Closed
E	30	70	-	90	90	-	30	150	0	-70	80	59.7	Closed → Open
F	30	70	-	90	90	-	80	100	0	-100	-	59.7	Open → Closed
G	-	20	90	75	75	-	0	150	90	-20	40	59.822	Closed → Open
H	-	20	90	75	75	-	0	150	93	-57	-	59.822	Open → Closed
I	-	90	20	75	75	-	0	150	20	-90	40	59.806	Closed → Open
J	-	90	20	75	75	-	0	150	50	-100	-	59.806	Open → Closed
K	-	70	30	90	90	-	0	180	30	-70	80	59.677	Closed → Open
L	-	70	30	90	90	-	0	180	80	-100	-	59.677	Open → Closed

Table 28: Pmax Control – Multiple Sources, Islanded, Test Settings

Test Results

The test results for the P_{max} control, multiple sources, and islanded test events are shown in the following two tables. Table 29 shows the results for tests performed using the ESS and A1 as sources and Table 30 contains the results for tests using the ESS and B1.

Test Event	Pre-Event				Transient Extremum		Post-Event					Pass/Fail
	A1	ESS	Microgrid Bus		A1	ESS	A1	ESS	Microgrid Bus		Total Real Power (kW)	
	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)		
A	83.2	20.0	269.1	60.00	104.5	54.2	99.1	50.4	264.4	59.85	149.5	Pass
B	99.2	50.2	264.4	59.84	80.8	15.7	83.1	19.3	268.8	60.00	102.4	Pass
C	13.5	87.1	269.5	60.00	54.1	113.2	53.1	96.4	265.1	59.77	149.4	Pass
D	54.6	94.5	264.9	59.76	9.4	63.9	10.5	82.8	269.0	60.02	93.3	Pass
E	20.2	64.3	268.9	60.02	79.8	112.5	78.2	95.9	264.1	59.67	174.1	Pass
F	80.7	93.8	263.2	59.66	23.8	46.8	24.9	70.1	269.0	59.99	95.0	Pass

Table 29: Pmax Control – Multiple Sources, Islanded, Test Results ESS A1

Test Event	Pre-Event				Transient Extremum		Post-Event					Pass/Fail	Notes
	B1	ESS	Microgrid Bus		B1	ESS	B1	ESS	Microgrid Bus		Total Real Power (kW)		
	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)			
G	91.9	24.6	272.4	59.98	109.1	67.5	90.9	59.2	270.4	59.81	150.1	Pass	
H	92.8	57.6	270.0	59.83	70.4	16.5	89.1	18.6	272.2	60.01	107.7	Pass	
I1	18.6	85.6	272.8	60.02	134.9	115.9	-	-	-	-	-	Fail	ESS Trips
I2	26.0	82.8	272.8	59.96	135.8	116.5	-	-	-	-	-	Fail	ESS Trips
I3	42.3	90.5	272.0	59.99	58.7	109.3	54.4	96.1	270.2	59.96	150.4	Pass	
J	54.2	95.7	269.9	59.85	35.5	68.2	34.4	85.3	271.9	60.01	119.7	Pass	
K	25.4	64.9	273.2	60.02	140.0	118.6	9.3	0.0	110.6	23.23	9.3	Fail	ESS Trips
L	-	-	-	-	-	-	-	-	-	-	-	N/A	

Table 30: Pmax Control – Multiple Sources, Islanded, Test Results ESS B1

Analysis

The ESS in combination with A1 successfully passes all P_{max} Control islanding tests conducted. Both units respond quickly to the additional load. The overloaded unit's P_{max} functionality is activated, driving the frequency down in a linear manner. The supporting unit relieves the overloaded unit and the system achieves steady-state conditions in approximately 2 seconds.

The ESS's P_{max} setting is functionally applied by setting a maximum battery power limit according to the inverter's manufacturer. Since this is applied to the D.C. real power, the actual output of the ESS will be larger than the P_{max} setting by the losses in the inverter plus the line losses to the meter. It can be seen in Figure 330 that the actual A.C. real power output by the ESS is approximately 110 kW when its P_{max} is set to 100 kW. However, once the supporting DER(s) relieve the overload condition on the ESS it reaches a steady-state value of approximately 96 kW as seen in the results of Events C, E, and I3.

The reactive power sharing issue with A1 is discussed in Section 5.13, Multiple Unit Load Sharing, and again is demonstrated in these tests that include the ESS and A1. As before, the ESS supplies the majority of reactive power and takes on this burden during the transient that occurs during grid separation. The reactive power settles to steady-state in approximately 1 second.

The ESS in combination with B1 does not pass all P_{max} Control islanding tests conducted. The ESS responds to the real power load increase much more quickly than B1 and as a result picks up the majority of real power load. The ESS's inverter has an output current rating of 142 Amperes which if exceeded can result in the inverter tripping. This occurred on Events I1, I2, and K. In these cases the ESS is dispatched higher than B1 and the additional load is sufficient to exceed the ESS's capability.

In the islanding cases where the ESS's capability is not exceeded, Events G and I3, the ESS responds more quickly to the real power load increase. Then the overloaded unit's P_{max} functionality is activated, driving the frequency down in a linear manner. The supporting unit relieves the overloaded unit and the system achieves steady-state conditions.

There are transient reactive power flow issues between the ESS and B1 during the transition to the islanded condition. The ESS responds more quickly than B1 to supply reactive power. In the events that survive the reactive power transient are damped and settle down after several seconds. In Event I2 the transient is oscillating and increasing until the ESS trips. While the reactive load on the ESS is small compared to the real power load (less than half), it does play a role in holding the current above the ESS's trip threshold resulting in system collapse.

Test Event A's results are shown in Figure 317 through Figure 328 where A1 is dispatched to 90 kW, the ESS to 20 kW, and the load in the microgrid is 149 kW. After grid separation, A1's P_{max} is activated and the units transition smoothly and predictably to the steady-state condition in 1.5 seconds. Figure 317 shows the transition for both units on a composite frequency droop curve.

A1's real power graph, Figure 319, shows its P_{max} is activated, i.e. real power output exceeds 100 kW, until 0.35 seconds. During this time the frequency plot, Figure 328, shows a linear decline in frequency at a rate of 1.2 Hz/s to a minimum frequency of 59.62 Hz. A1's P_{max} is then released and the system reaches a steady-state frequency of 59.85 Hz at 1.5 seconds.

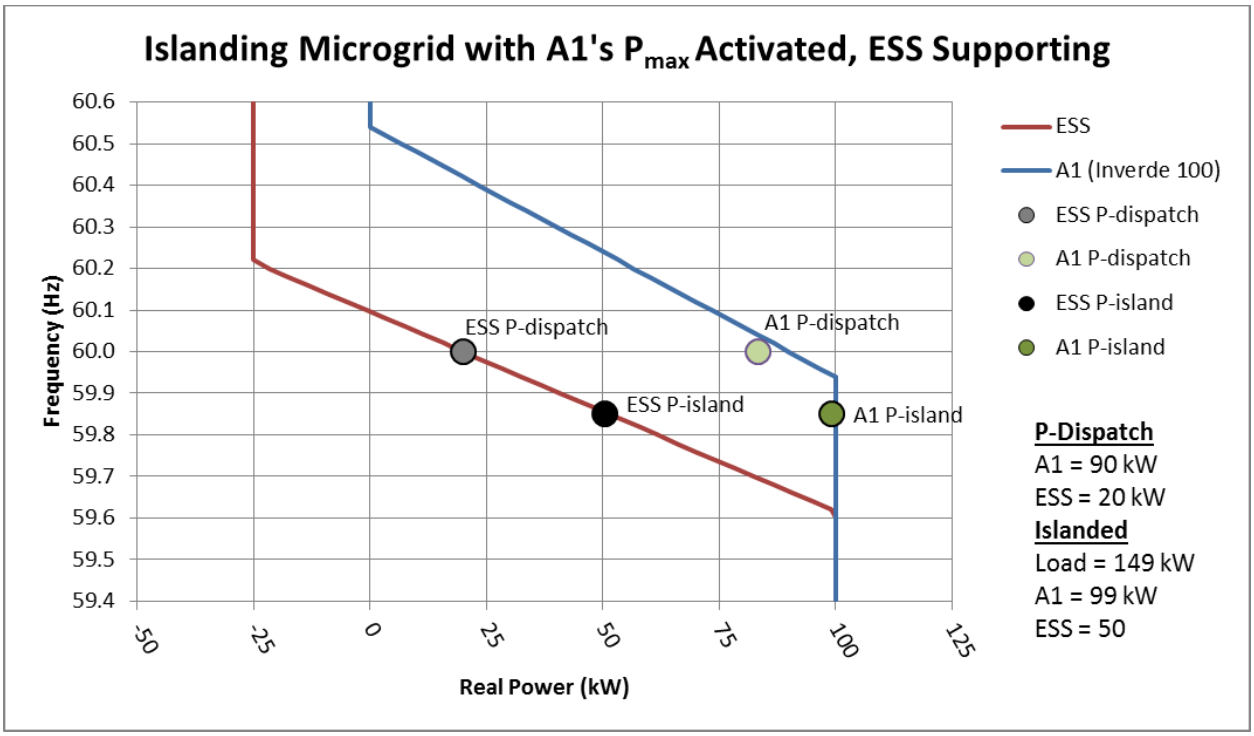

Figure 317: Pmax, Multi-unit, ESS A1, Composite Frequency Droop, Event A

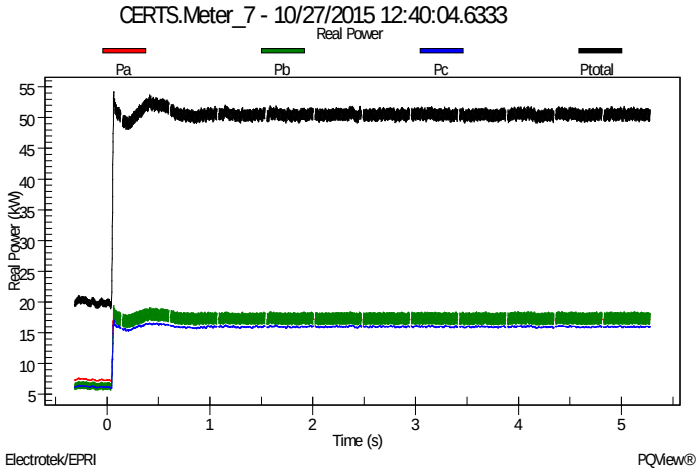

Figure 318: Pmax, Multi-unit, ESS A1, ESS Real Power, Event A

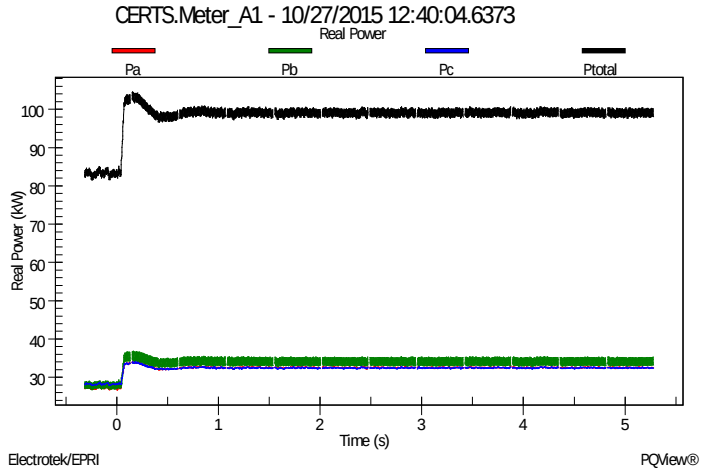

Figure 319: Pmax, Multi-unit, ESS A1, A1 Real Power, Event A

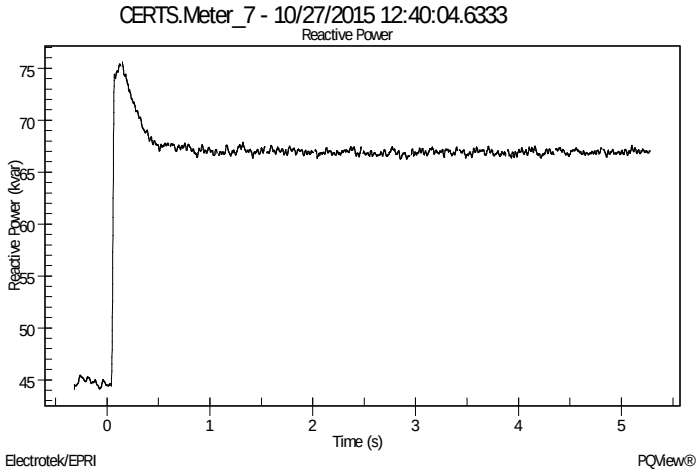

Figure 320: Pmax, Multi-unit, ESS A1, ESS Reactive Power, Event A

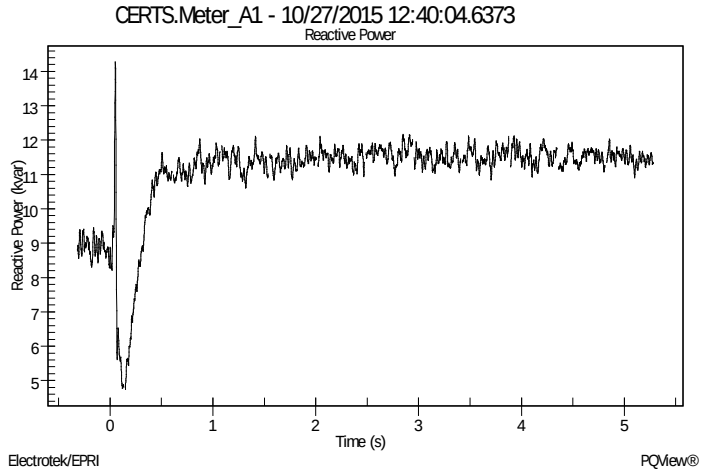

Figure 321: Pmax, Multi-unit, ESS A1, A1 Reactive Power, Event A

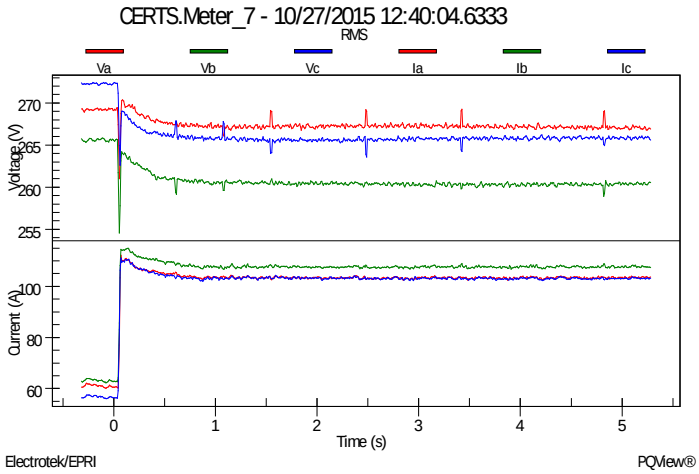

Figure 322: Pmax, Multi-unit, ESS A1, ESS RMS V&I, Event A

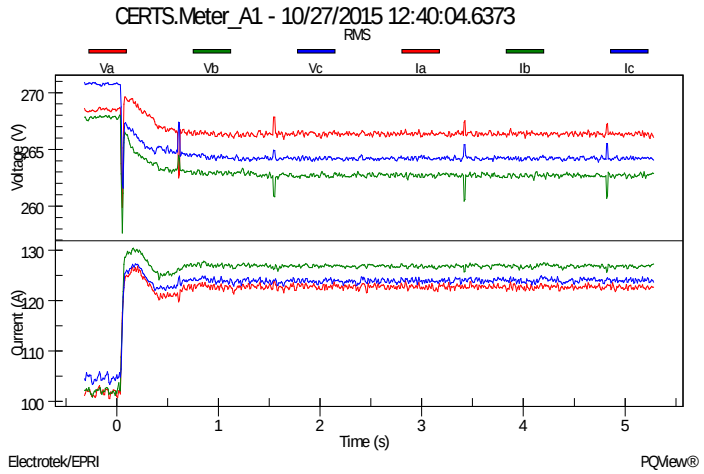

Figure 323: Pmax, Multi-unit, ESS A1, A1 RMS V&I, Event A

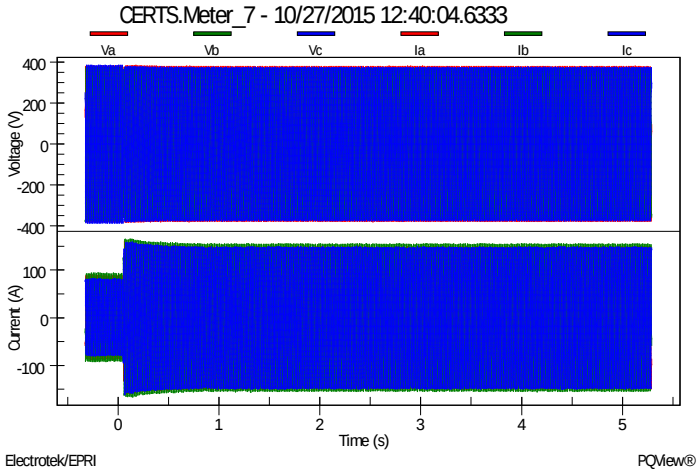

Figure 324: Pmax, Multi-unit, ESS A1, ESS V&I Waveform, Event A

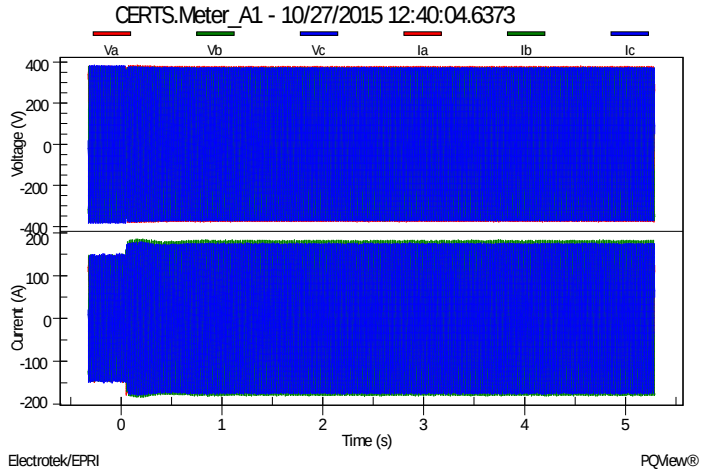

Figure 325: Pmax, Multi-unit, ESS A1, A1 Waveform V&I, Event A

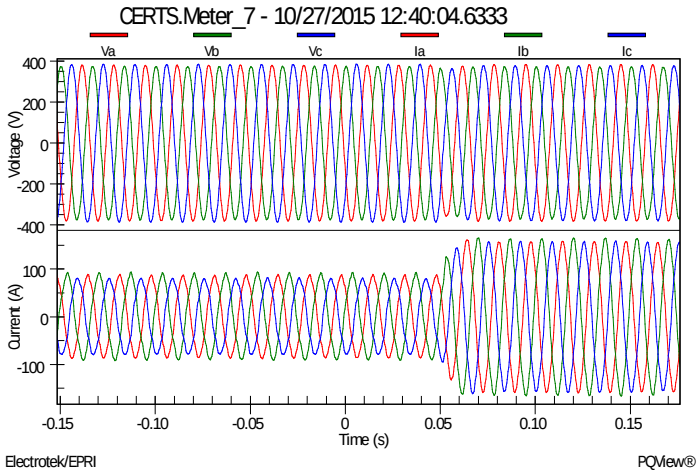

Figure 326: Pmax, Multi-unit, ESS A1, ESS V&I Waveform (Zoomed), Event A

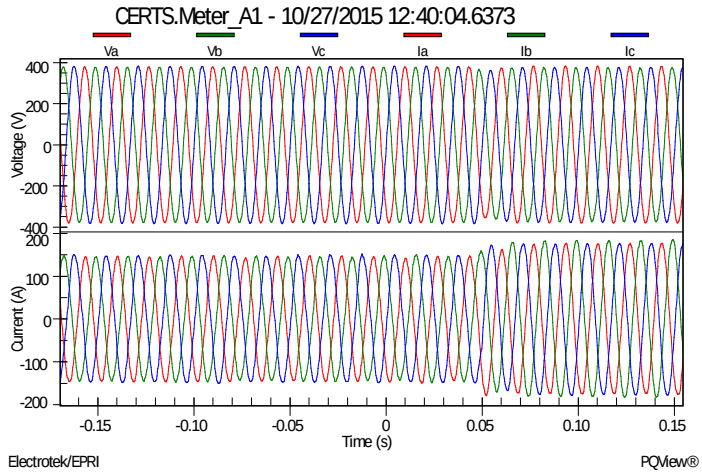

Figure 327: Pmax, Multi-unit, ESS A1, A1 V&I Waveform (Zoomed), Event A

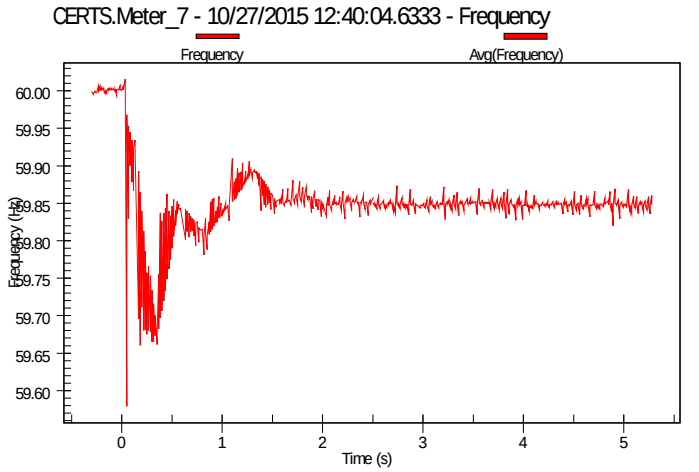

Figure 328: Pmax, Multi-unit, ESS A1, ESS Frequency, Event A

Test Event C's results are shown in Figure 329 through Figure 340 where the ESS is dispatched to 90 kW, A1 to 20 kW, and the load in the microgrid is 149 kW. After grid separation, the ESS's P_{max} is activated and the units transition smoothly and predictably to the steady-state condition in 2.0 seconds. Figure 329 shows the transition for both units on a composite frequency droop curve.

The ESS's real power graph, Figure 330, shows its P_{max} is activated, until about 0.3 seconds. During this time the frequency plot, Figure 328, shows an approximately linear decline in frequency at a rate of 2.0 Hz/s to a minimum frequency of 59.4 Hz. The ESS's P_{max} is then released and the system reaches a steady-state frequency of 59.77 Hz at 1.5 seconds.

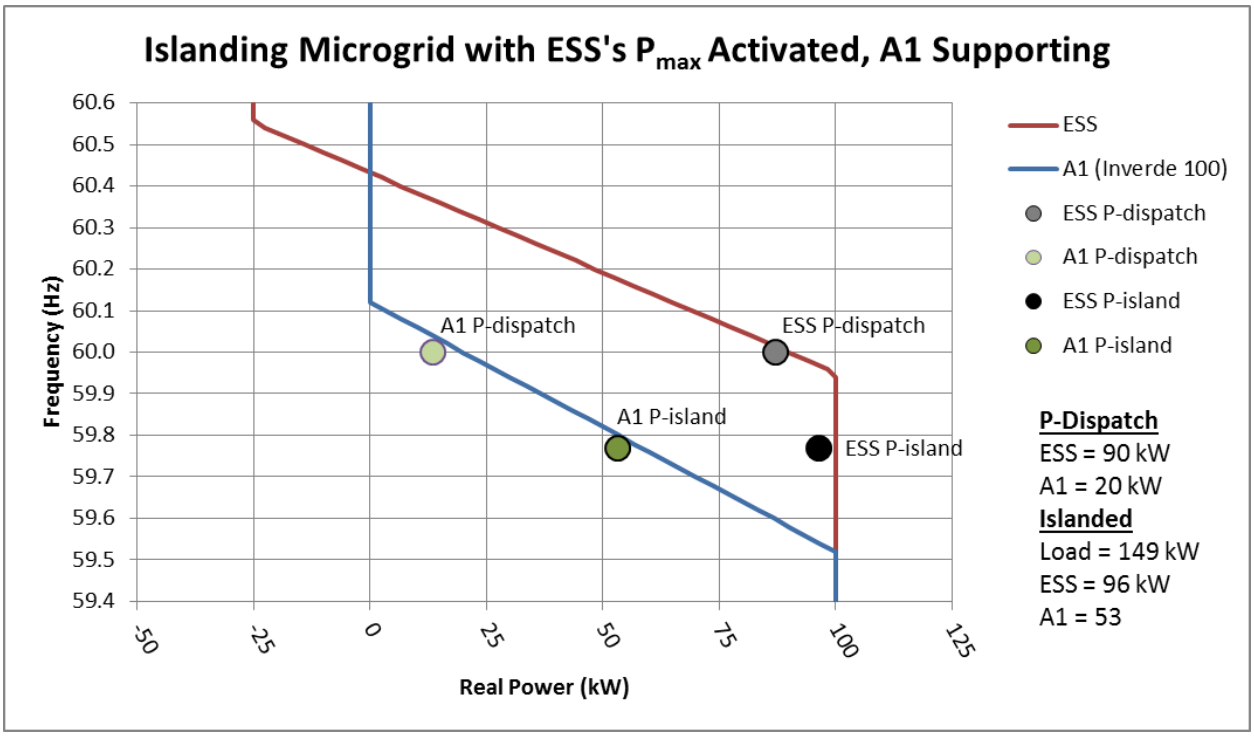

Figure 329: Pmax, Multi-unit, ESS A1, Composite Frequency Droop, Event C

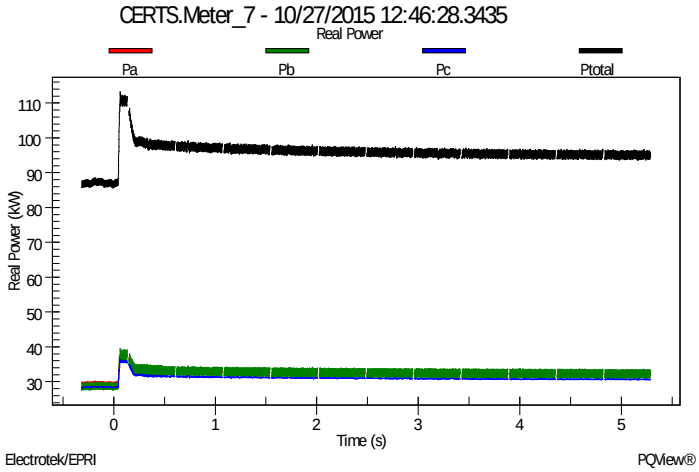

Figure 330: Pmax, Multi-unit, ESS A1, ESS Real Power, Event C

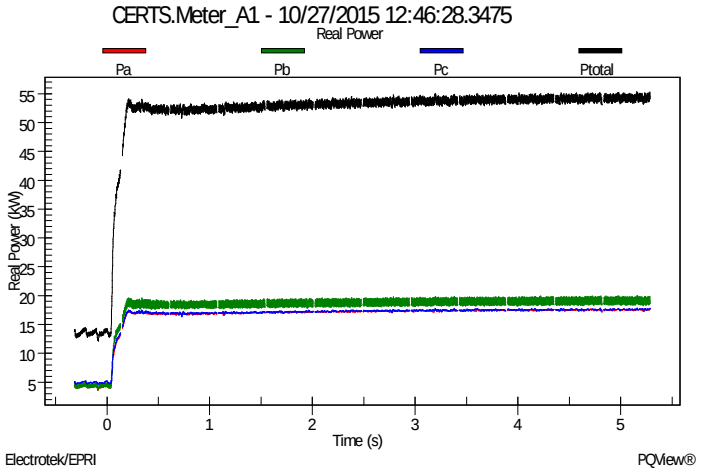

Figure 331: Pmax, Multi-unit, ESS A1, A1 Real Power, Event C

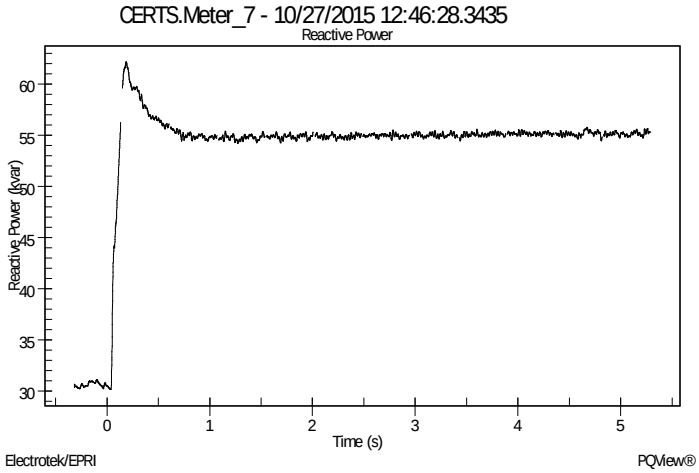

Figure 332: Pmax, Multi-unit, ESS A1, ESS Reactive Power, Event C

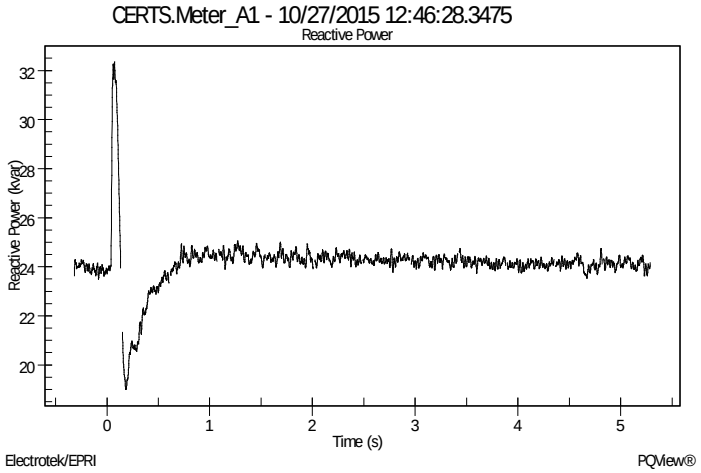

Figure 333: Pmax, Multi-unit, ESS A1, A1 Reactive Power, Event C

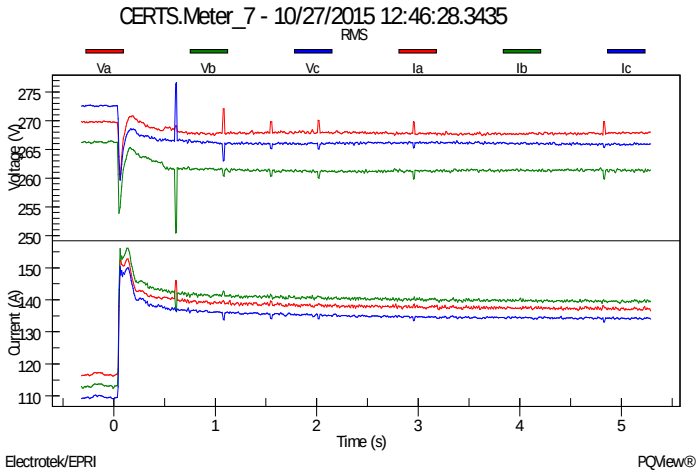

Figure 334: Pmax, Multi-unit, ESS A1, ESS RMS V&I, Event C

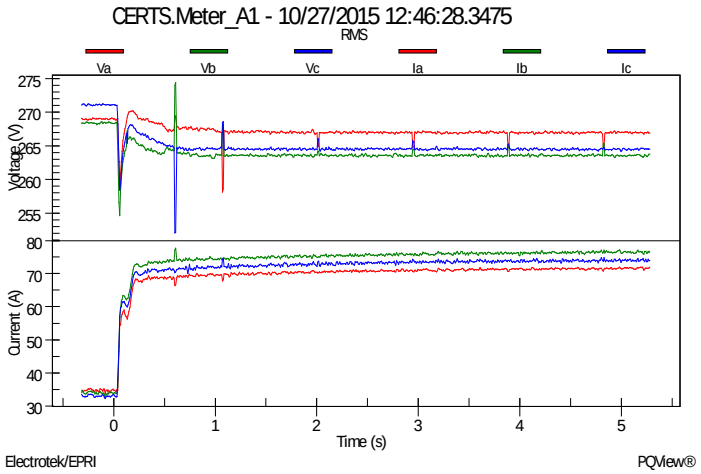

Figure 335: Pmax, Multi-unit, ESS A1, A1 RMS V&I, Event C

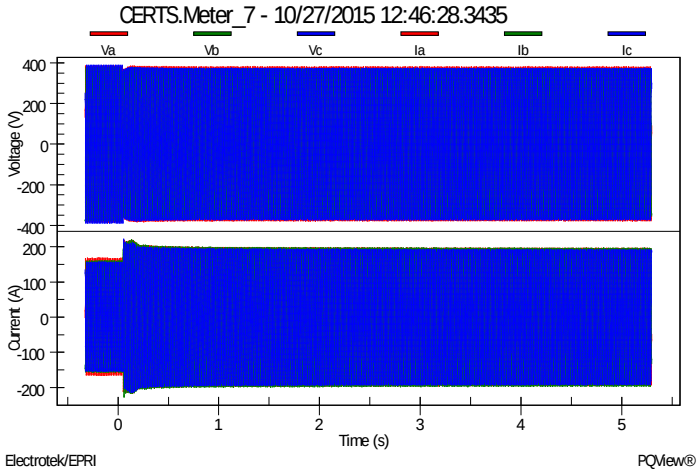

Figure 336: Pmax, Multi-unit, ESS A1, ESS V&I Waveform, Event C

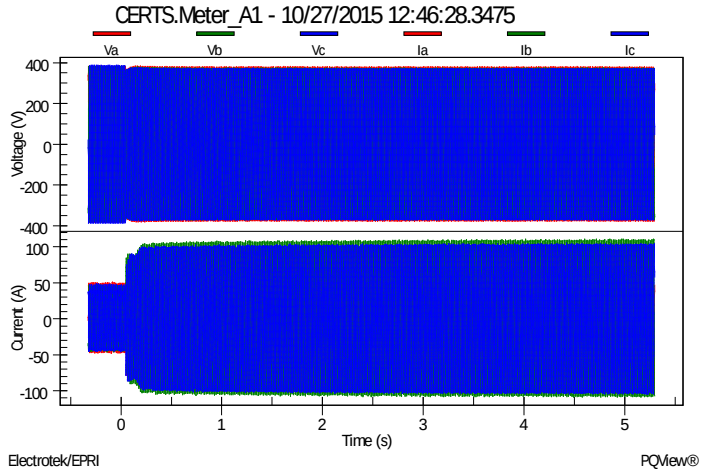

Figure 337: Pmax, Multi-unit, ESS A1, A1 Waveform V&I, Event C

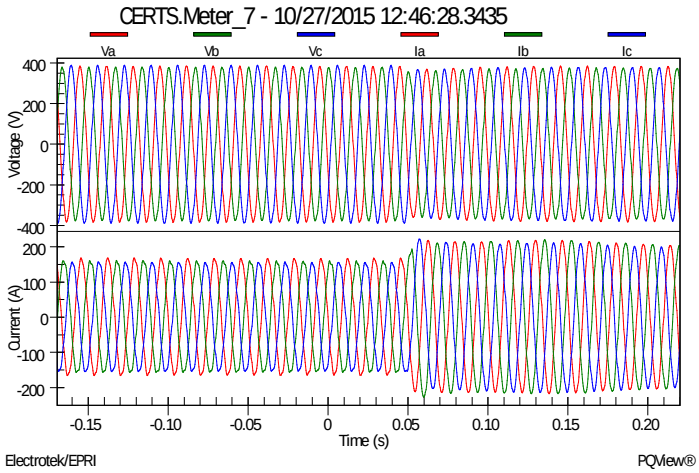

Figure 338: Pmax, Multi-unit, ESS A1, ESS V&I Waveform (Zoomed), Event C

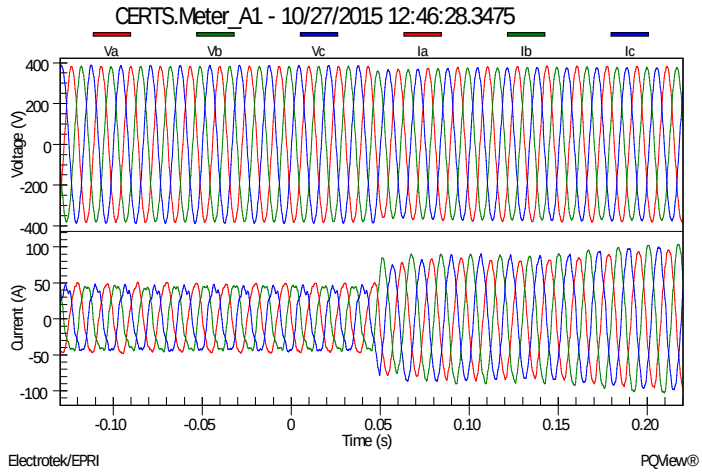

Figure 339: Pmax, Multi-unit, ESS A1, A1 V&I Waveform (Zoomed), Event C

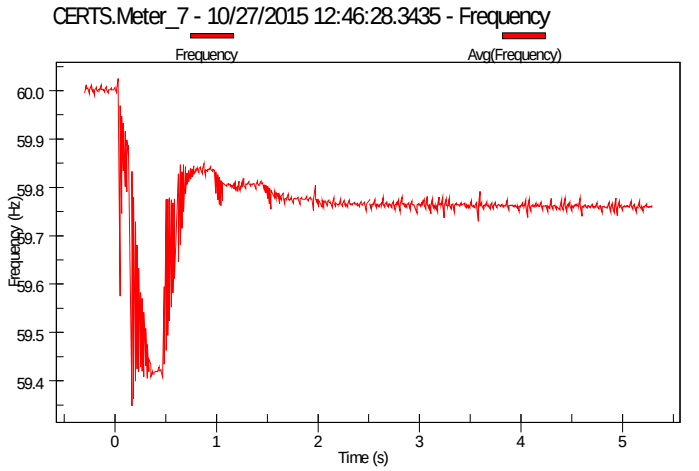

Figure 340: Pmax, Multi-unit, ESS A1, ESS Frequency, Event C

Test Event E's results are shown in Figure 341 through Figure 352 where the ESS is dispatched to 70 kW, A1 to 30 kW, and the load in the microgrid is 174 kW. After grid separation, the ESS's P_{max} is activated and the units transition smoothly and predictably to the steady-state condition in 2.0 seconds. Figure 341 shows the transition for both units on a composite frequency droop curve.

The ESS's real power graph, Figure 342, shows its P_{max} is activated, until about 0.3 seconds. During this time the frequency plot, Figure 352, shows an approximately linear decline in frequency at a rate of 2.9 Hz/s to a minimum frequency of 59.3 Hz. The ESS's P_{max} is then released and the system reaches a steady-state frequency of 59.67 Hz at 2.0 seconds.

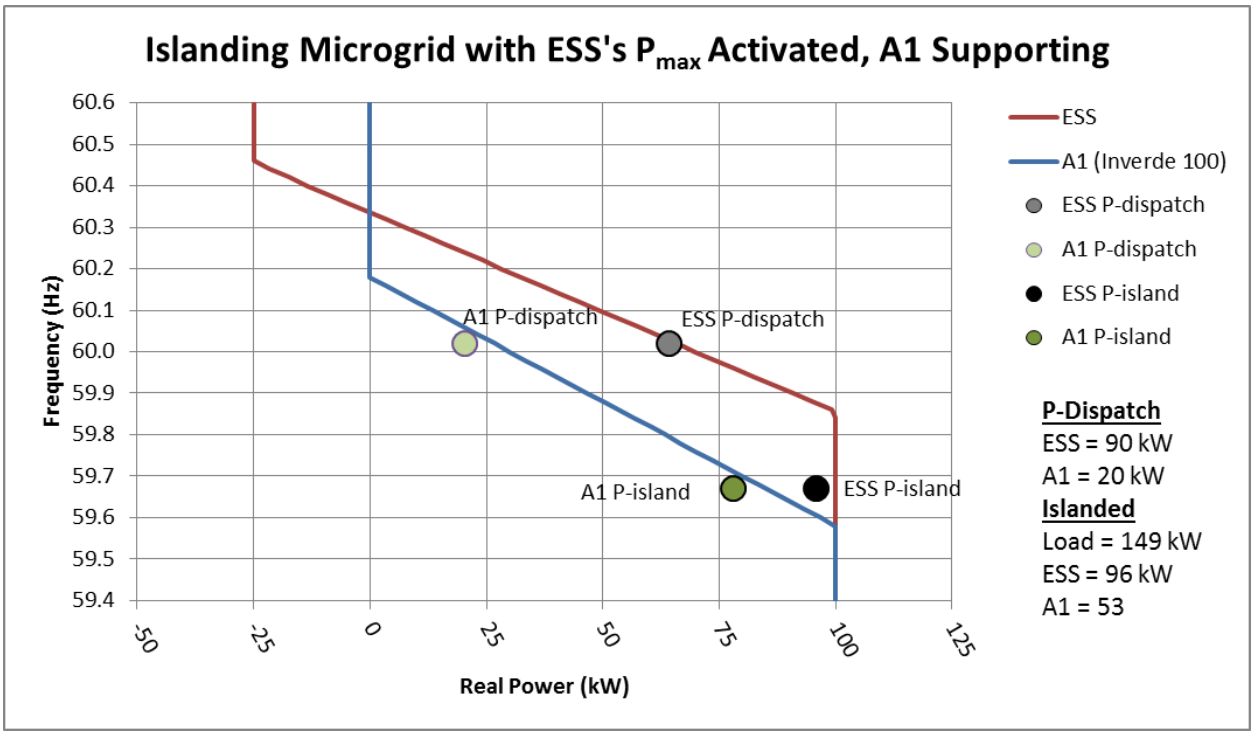

Figure 341: Pmax, Multi-unit, ESS A1, Composite Frequency Droop, Event E

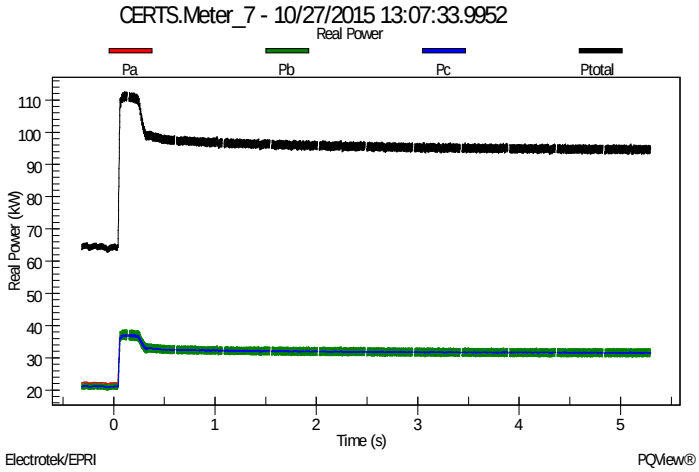

Figure 342: Pmax, Multi-unit, ESS A1, ESS Real Power, Event E

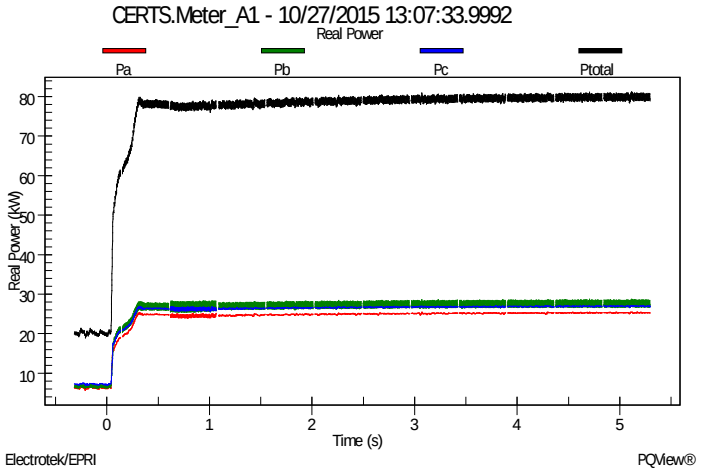

Figure 343: Pmax, Multi-unit, ESS A1, A1 Real Power, Event E

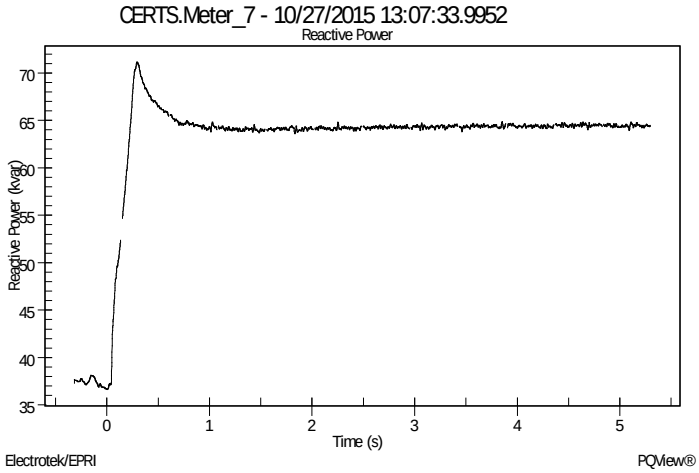

Figure 344: Pmax, Multi-unit, ESS A1, ESS Reactive Power, Event E

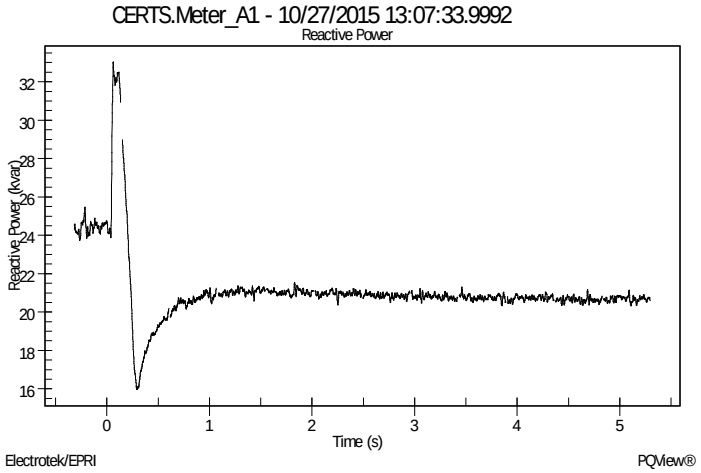

Figure 345: Pmax, Multi-unit, ESS A1, A1 Reactive Power, Event E

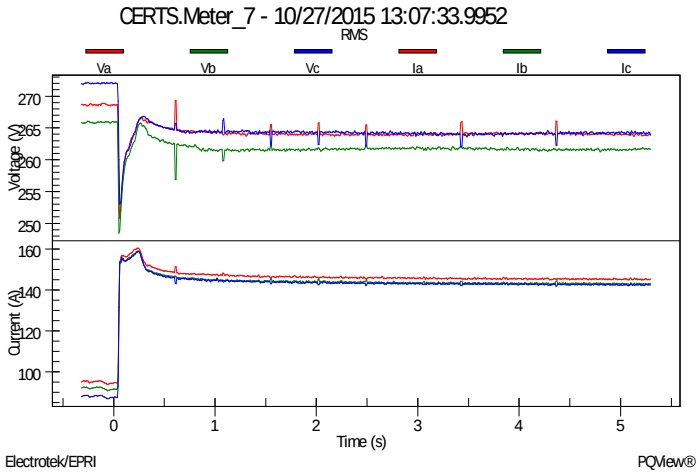

Figure 346: Pmax, Multi-unit, ESS A1, ESS RMS V&I, Event E

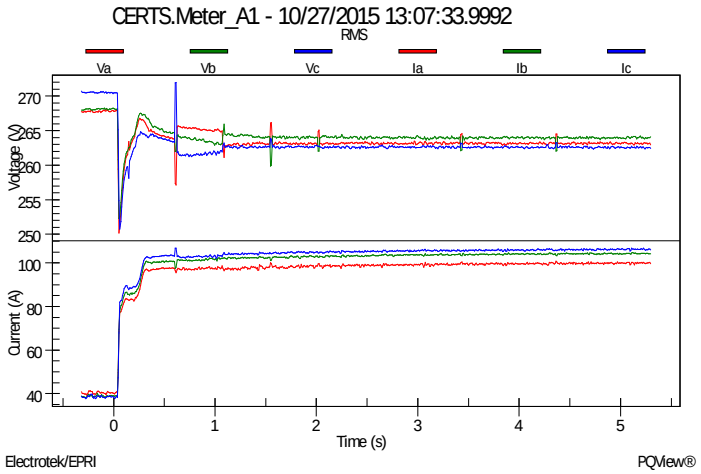

Figure 347: Pmax, Multi-unit, ESS A1, A1 RMS V&I, Event E

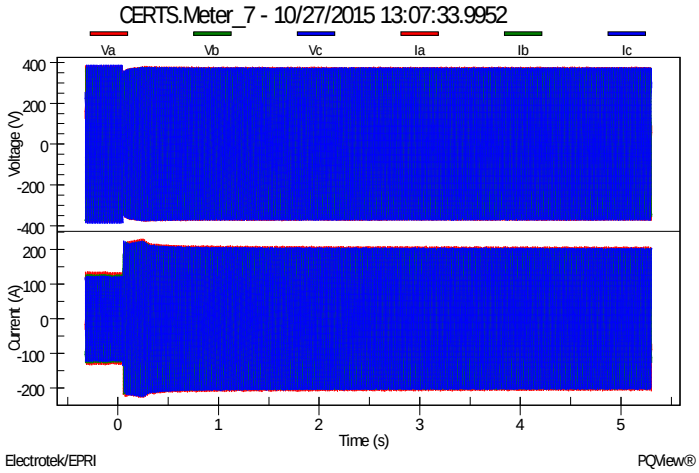

Figure 348: Pmax, Multi-unit, ESS A1, ESS V&I Waveform, Event E

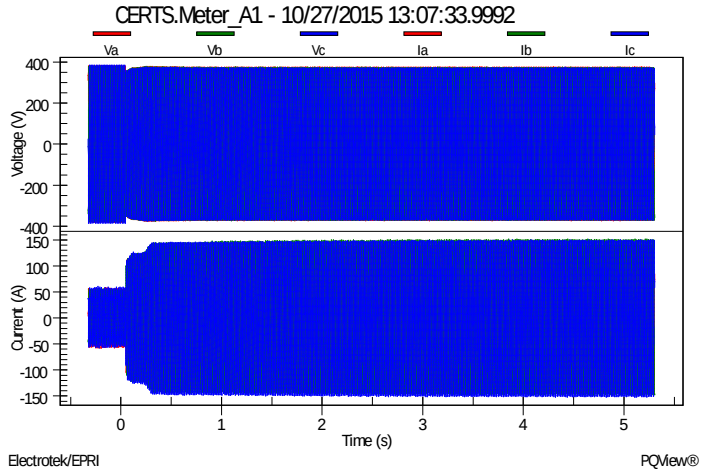

Figure 349: Pmax, Multi-unit, ESS A1, A1 Waveform V&I, Event E

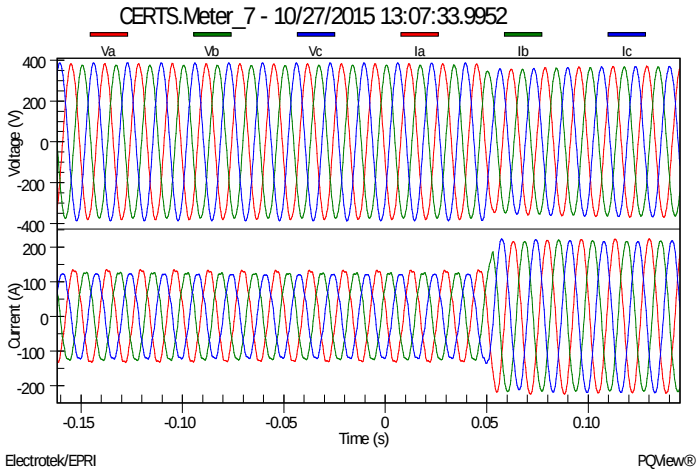

Figure 350: Pmax, Multi-unit, ESS A1, ESS V&I Waveform (Zoomed), Event E

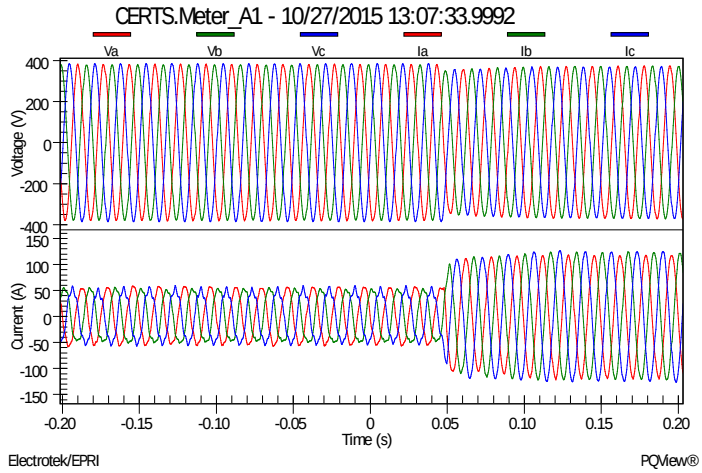

Figure 351: Pmax, Multi-unit, ESS A1, A1 V&I Waveform (Zoomed), Event E

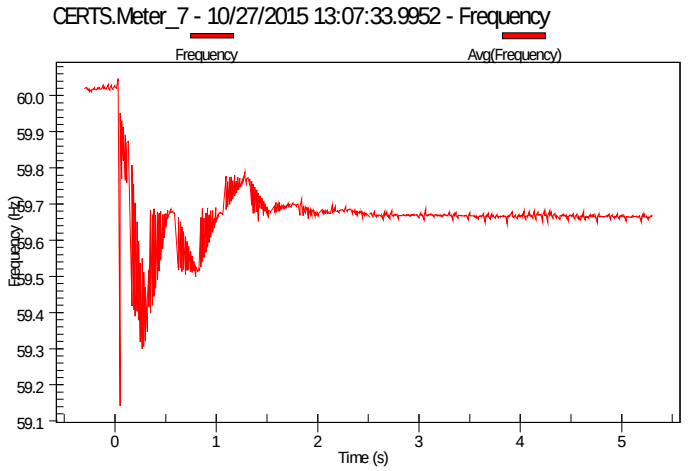

Figure 352: Pmax, Multi-unit, ESS A1, ESS Frequency, Event E

Test Event G's results are shown in Figure 353 through Figure 364 where B1 is dispatched to 90 kW, the ESS to 20 kW, and the load in the microgrid is 150 kW. Figure 353 shows the transition for both units on a composite frequency droop curve where it is shown that the units achieve the expected steady-state conditions.

The frequency response shown in Figure 364 indicates that B1's P_{max} is activated after islanding until 0.35 seconds. During this time a linear decline in frequency at a rate of 1.3 Hz/s to a minimum frequency of 59.55 Hz. It then appears that B1's P_{max} is released and the system reaches a steady-state frequency of 59.82 Hz at 0.7 seconds. B1's P_{max} appears to be activated again from the 1.47 second mark until 1.74 the second mark. The system again achieves a steady-state frequency of 59.81 Hz at the 2.24 seconds.

The ESS and B1 real power plots, shown in Figure 354 and Figure 355 respectively, demonstrate that the real power output from each unit varies by 13 kW during steady-state. Specifically, B1 varies from 86 kW to 99 kW thus appearing that B1 is wandering in and out of its P_{max} functionality. The fluctuation in real power and frequency during "steady-state" conditions is considerably more significant than occurred in the ESS/A1 system.

There is transient reactive power flow between the ESS and B1 after the transition to the islanded condition as shown in Figure 356 and Figure 357. The ESS initially supplies the additional 14 kVAr of reactive power required in the microgrid. The transient is damped and settles to a steady-state in 3.5 seconds.

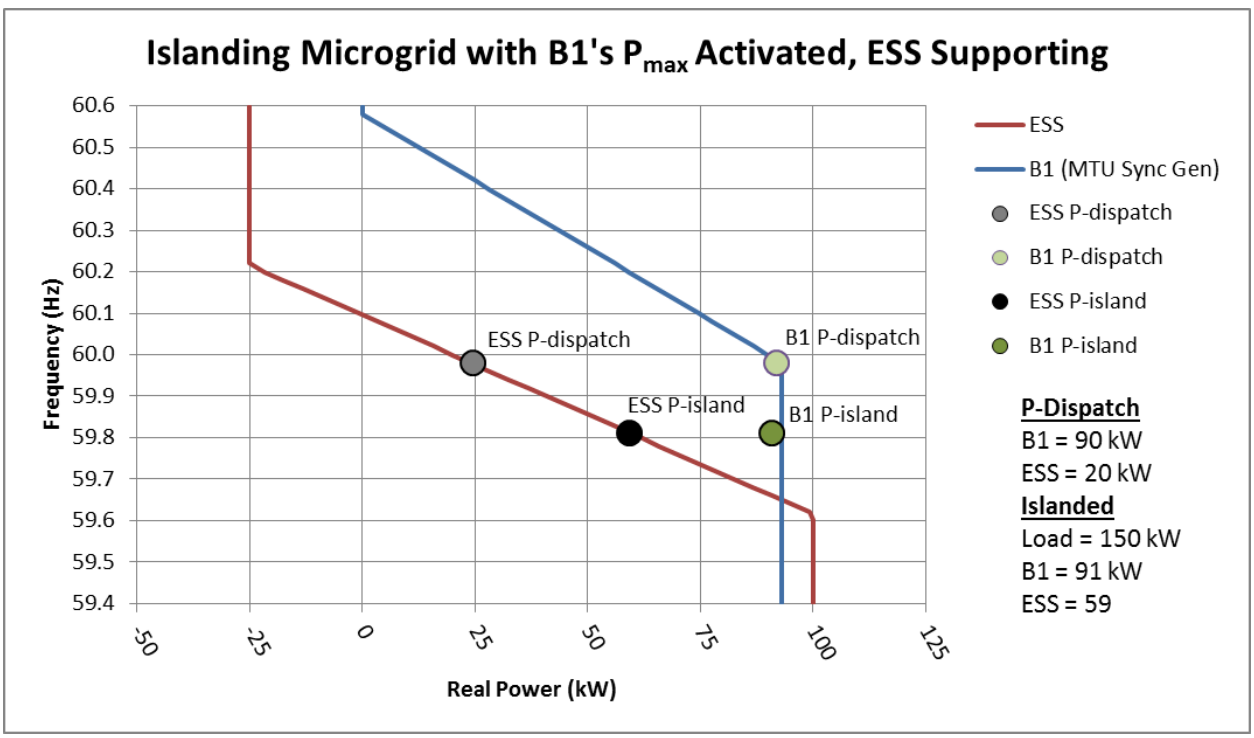

Figure 353: Pmax, Multi-unit, ESS B1, Composite Frequency Droop, Event G

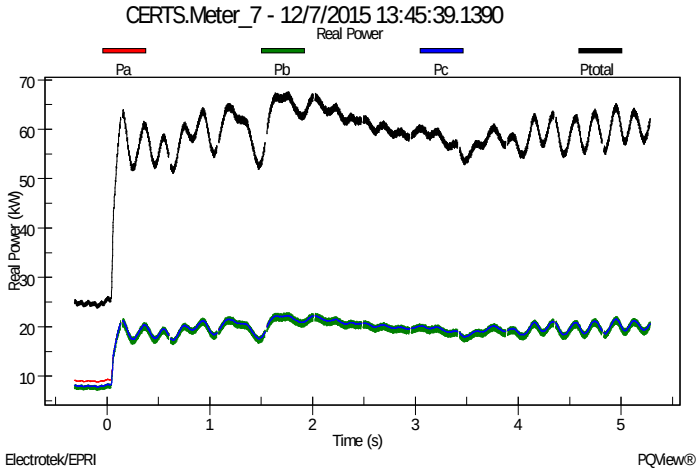

Figure 354: Pmax, Multi-unit, ESS B1, ESS Real Power, Event G

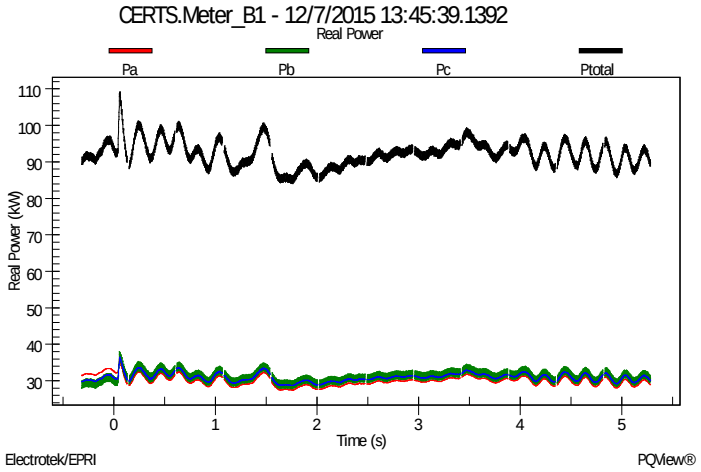

Figure 355: Pmax, Multi-unit, ESS B1, B1 Real Power, Event G

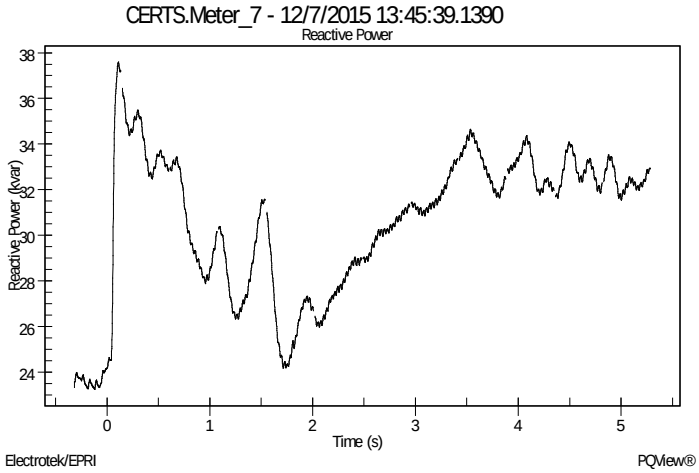

Figure 356: Pmax, Multi-unit, ESS B1, ESS Reactive Power, Event G

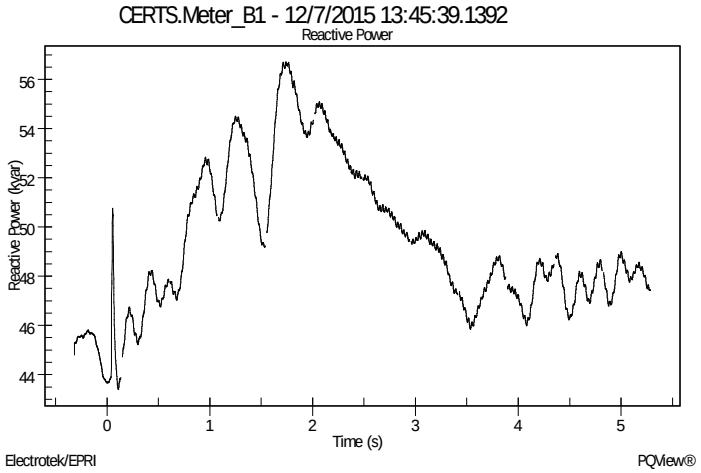

Figure 357: Pmax, Multi-unit, ESS B1, B1 Reactive Power, Event G

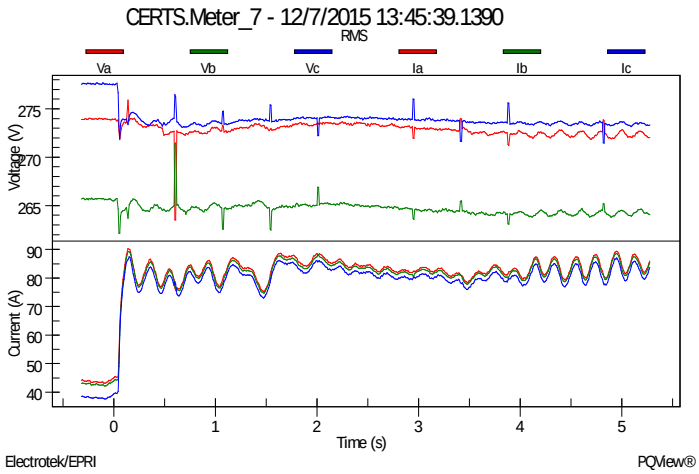

Figure 358: Pmax, Multi-unit, ESS B1, ESS RMS V&I, Event G

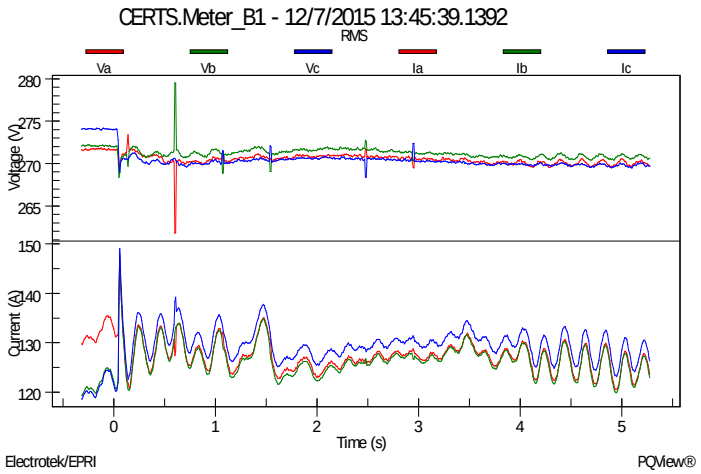

Figure 359: Pmax, Multi-unit, ESS B1, B1 RMS V&I, Event G

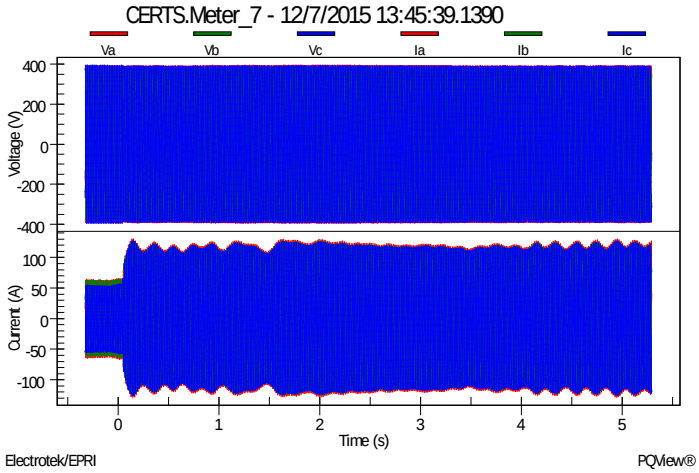

Figure 360: Pmax, Multi-unit, ESS B1, ESS V&I Waveform, Event G

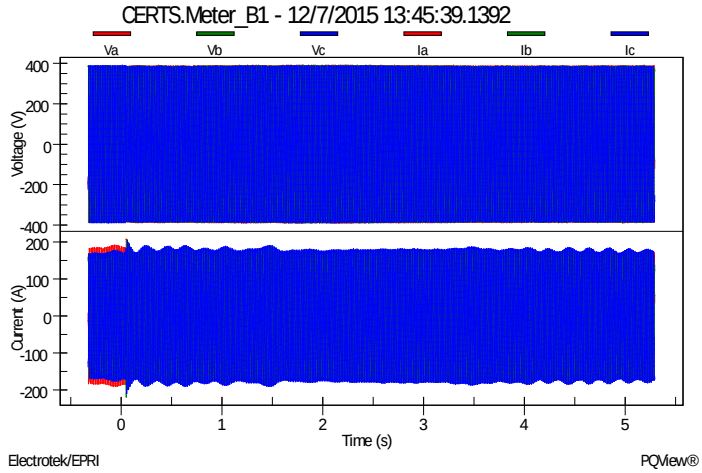

Figure 361: Pmax, Multi-unit, ESS B1, B1 Waveform V&I, Event G

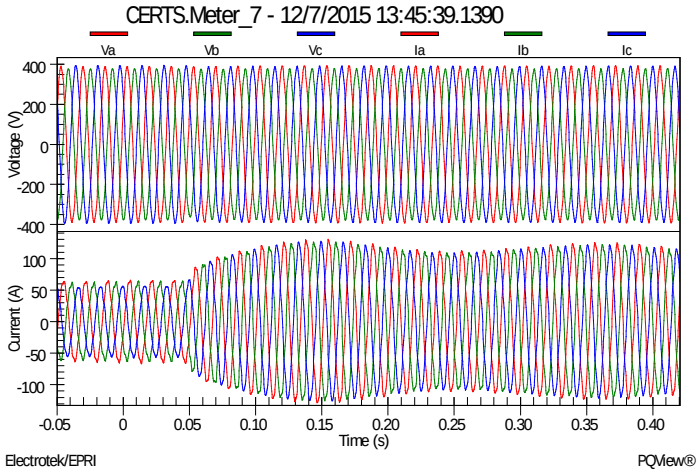

Figure 362: Pmax, Multi-unit, ESS B1, ESS V&I Waveform (Zoomed), Event G

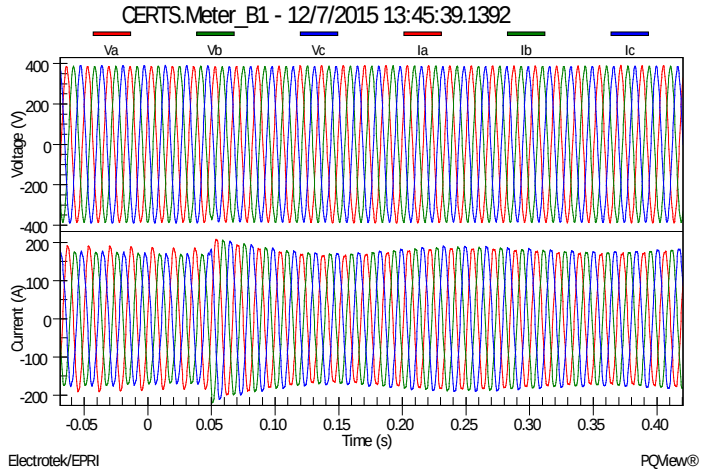

Figure 363: Pmax, Multi-unit, ESS B1, B1 V&I Waveform (Zoomed), Event G

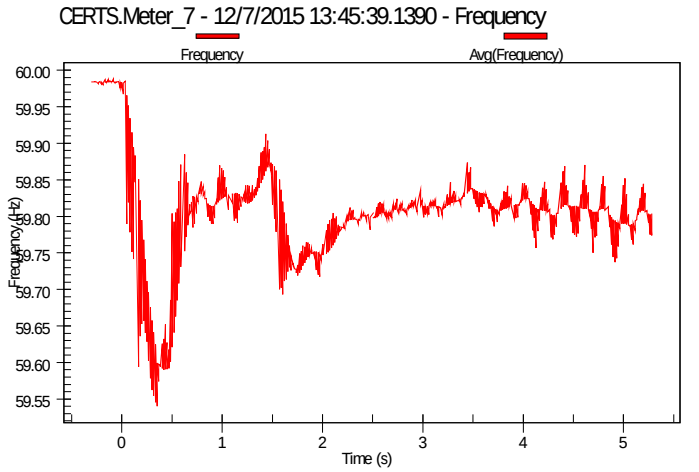

Figure 364: Pmax, Multi-unit, ESS B1, ESS Frequency, Event G

Test Event I was initially intended to test the condition where B1 is dispatched to 20 kW, the ESS to 90 kW, and the load in the microgrid is 150 kW. This test fails with the ESS's inverter tripping and providing an IGBT Bridge Error Fault. It was decided to increase B1's dispatch value in 10 kW increments to determine at what point the system would survive under the modified conditions. This resulted in two additional test events, I2 and I3, where B1 is dispatched to 30 kW and 40 kW respectively. In Event I2 the ESS trips but in Event I3 the ESS survives.

Test Event I2's results are shown in Figure 365 through Figure 375 where B1 is dispatched to 30 kW, the ESS to 90 kW, and the load in the microgrid is 150 kW. Initially the ESS picks up the majority of the real load reaching a peak output of 116 kW. The ESS's P_{max} is activated and drives the frequency down at a rate of 4.3 Hz/s. At the 0.18 second mark the frequency reaches 59.3 Hz and B1 begins increasing its real power output to relieve the ESS. However, there is an unstable transient reactive power flow from the ESS and B1 resulting in wide swings of sourcing the reactive power. While the real power output of the ESS is decreasing, the reactive power flow contributes to holding the current at an elevated level.

The ESS's inverter specifications list a maximum output current of 142 Amperes however a time for that current limit is not specified. At the 0.083 second mark the inverter's current reaches 144 Amperes and continues to exceed 142 amperes until the 0.317 second mark when the inverter trips. At this time the entire load is transferred to B1 which does not have the capability to serve it. B1 eventually stalls at some time after the metering time limit of about 5 seconds.

Test Event K where B1 is dispatched to 30 kW, the ESS to 70 kW, and the load in the microgrid is 180 kW fails in the same way as Event I2.

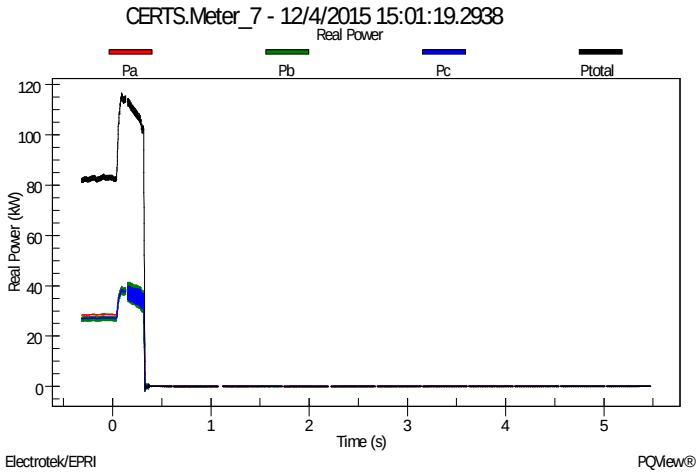

Figure 365: Pmax, Multi-unit, ESS B1, ESS Real Power, Event I2

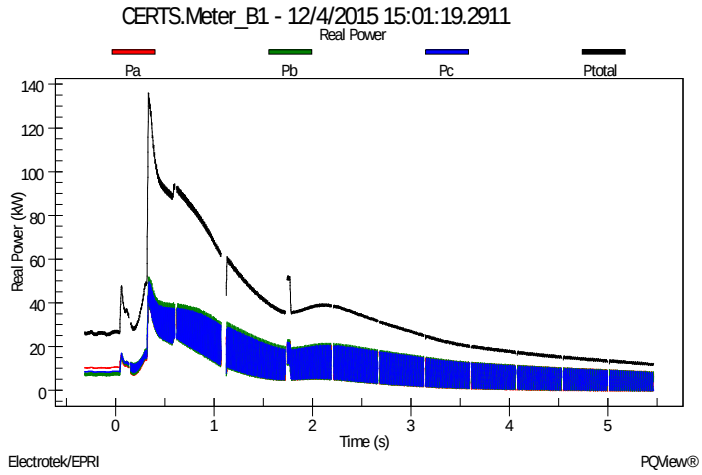

Figure 366: Pmax, Multi-unit, ESS B1, B1 Real Power, Event I2

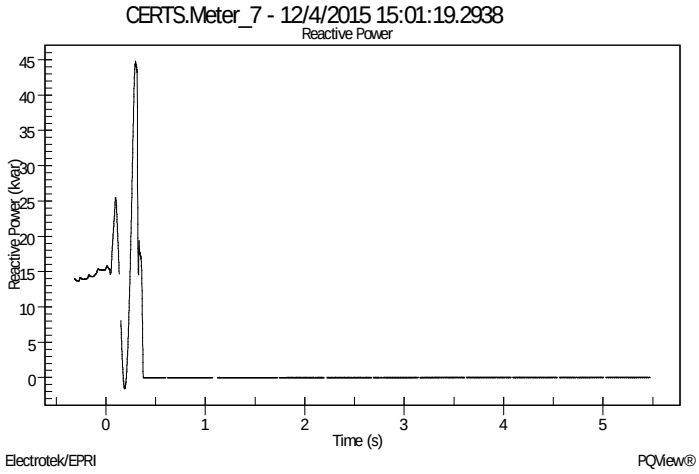

Figure 367: Pmax, Multi-unit, ESS B1, ESS Reactive Power, Event I2

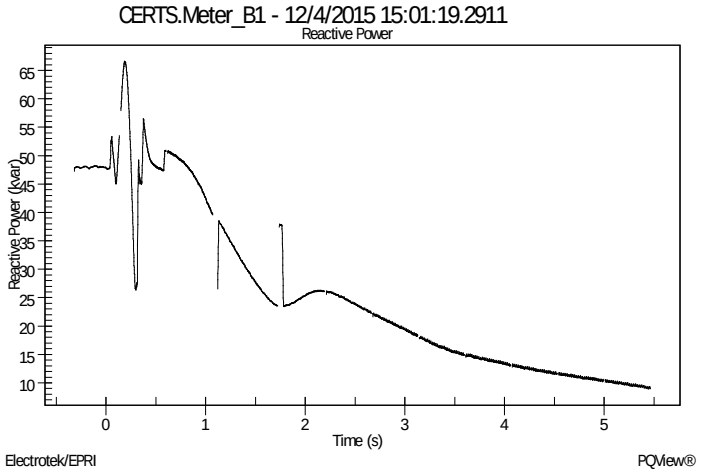

Figure 368: Pmax, Multi-unit, ESS B1, B1 Reactive Power, Event I2

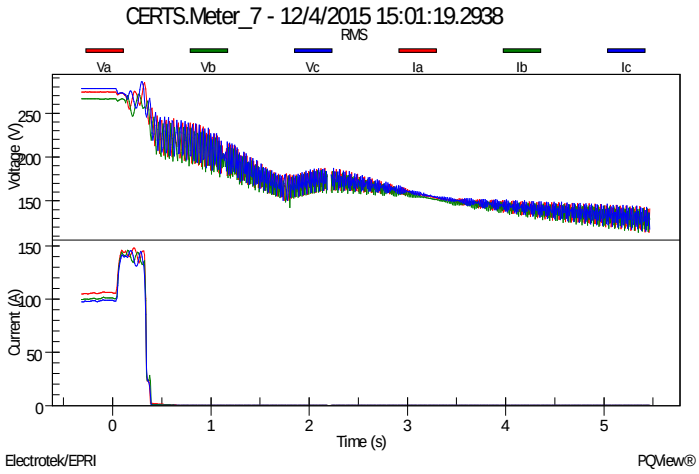

Figure 369: Pmax, Multi-unit, ESS B1, ESS RMS V&I, Event I2

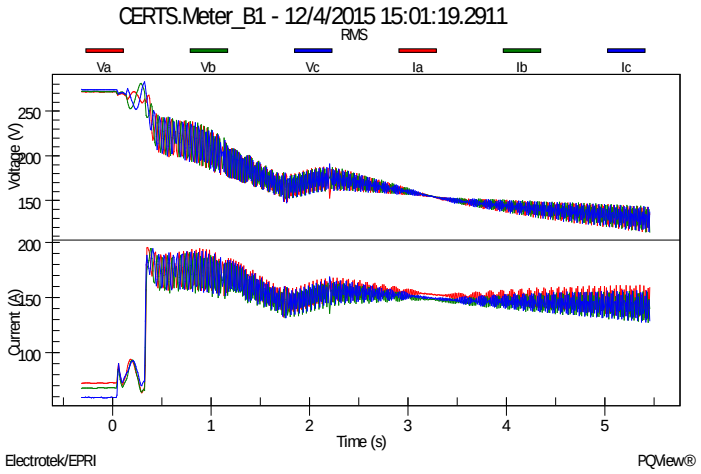

Figure 370: Pmax, Multi-unit, ESS B1, B1 RMS V&I, Event I2

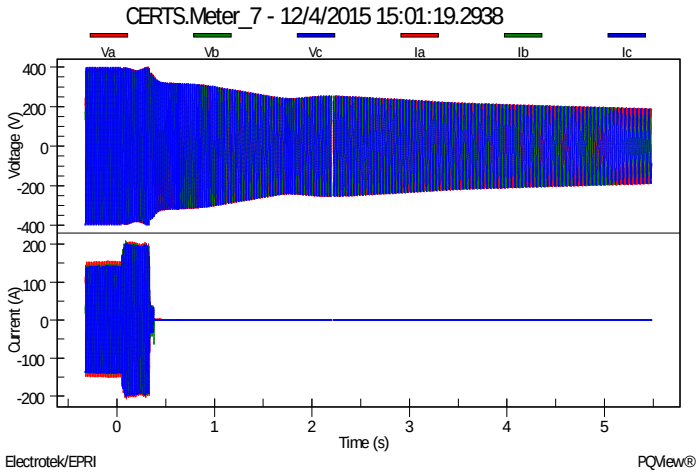

Figure 371: Pmax, Multi-unit, ESS B1, ESS V&I Waveform, Event I2

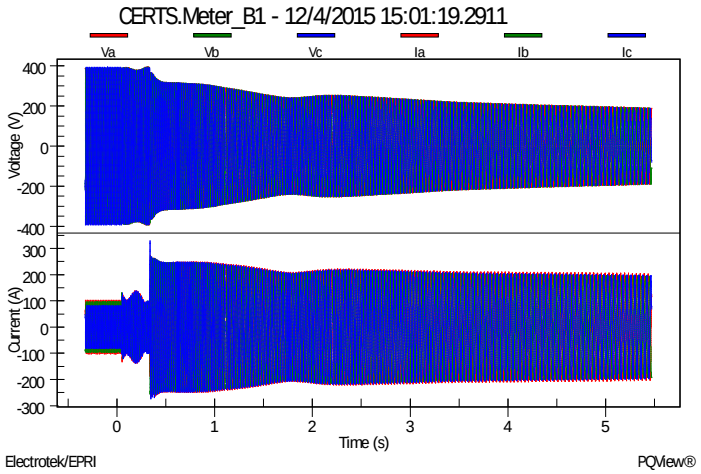

Figure 372: Pmax, Multi-unit, ESS B1, B1 Waveform V&I, Event I2

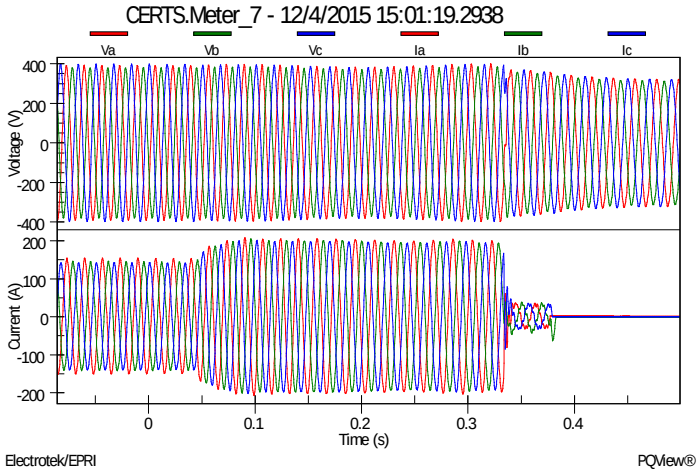

Figure 373: Pmax, Multi-unit, ESS B1, ESS V&I Waveform (Zoomed), Event I2

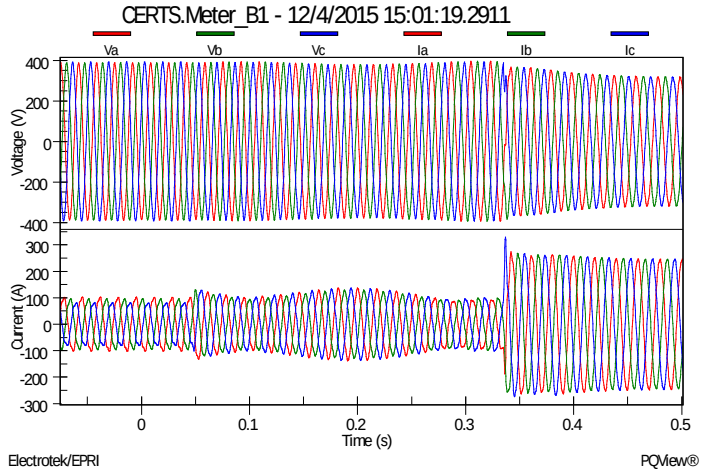

Figure 374: Pmax, Multi-unit, ESS B1, B1 V&I Waveform (Zoomed), Event I2

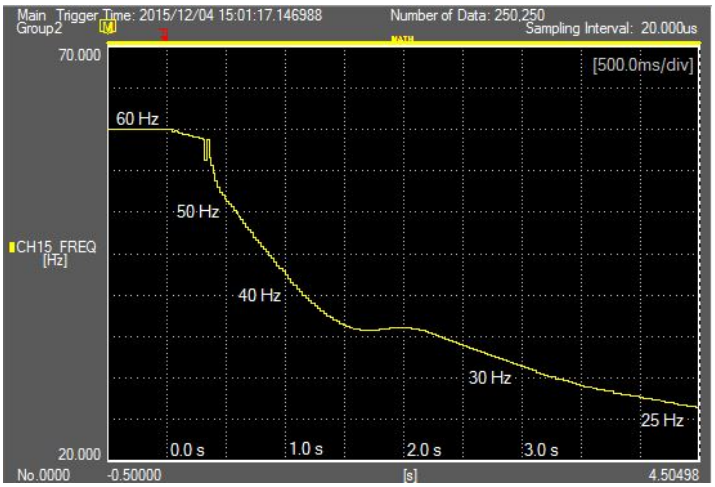

Figure 375: Pmax, Multi-unit, ESS B1, ESS Frequency, Event I2

Test Event I3's results are shown in Figure 376 through Figure 387 where B1 is dispatched to 40 kW, the ESS to 90 kW, and the load in the microgrid is 150 kW. Figure 353 shows the transition for both units on a composite frequency droop curve where it appears that the units do not achieve the expected steady-state conditions. Specifically, the frequency settles at 59.96 Hz instead of the expected 59.93 Hz. It has been observed in other islanded tests with the ESS and B1 that on occasion the frequency will appear to reach an unexpected steady-state frequency only to correct itself several seconds later. It is possible and probably likely that the correct steady-state frequency is achieved after the 5 second metering window.

The frequency response shown in Figure 387 indicates that the ESS's P_{max} is activated after islanding until the 0.5 second mark. During this time a linear decline in frequency at a rate of 2.6 Hz/s to a minimum frequency of 58.7 Hz. At this point the ESS's P_{max} is released and the system reaches a steady-state frequency of 59.96 Hz at the 1.76 second mark.

The ESS and B1 real power plots, shown in Figure 377 and Figure 378 respectively, demonstrate that the ESS initially serves the additional real power load of 20 kW. B1 ramps up the amount of real load it serves until the units reach the desired steady-state is reached.

There is transient reactive power flow between the ESS and B1 after the transition to the islanded condition as shown in Figure 379 and Figure 380. The ESS initially supplies the additional 17 kVAr of reactive power required in the microgrid. The transient is damped and settles to a steady-state after the 5 second metering window.

This event differs from Event I2 in that B1 is dispatched to 40 kW instead of 30 kW. This reduces the initial amount of real and reactive power that the ESS picks up. In this case, the maximum RMS current out of the ESS is 139 Amperes, just below the 142 Ampere limit of the ESS's inverter.

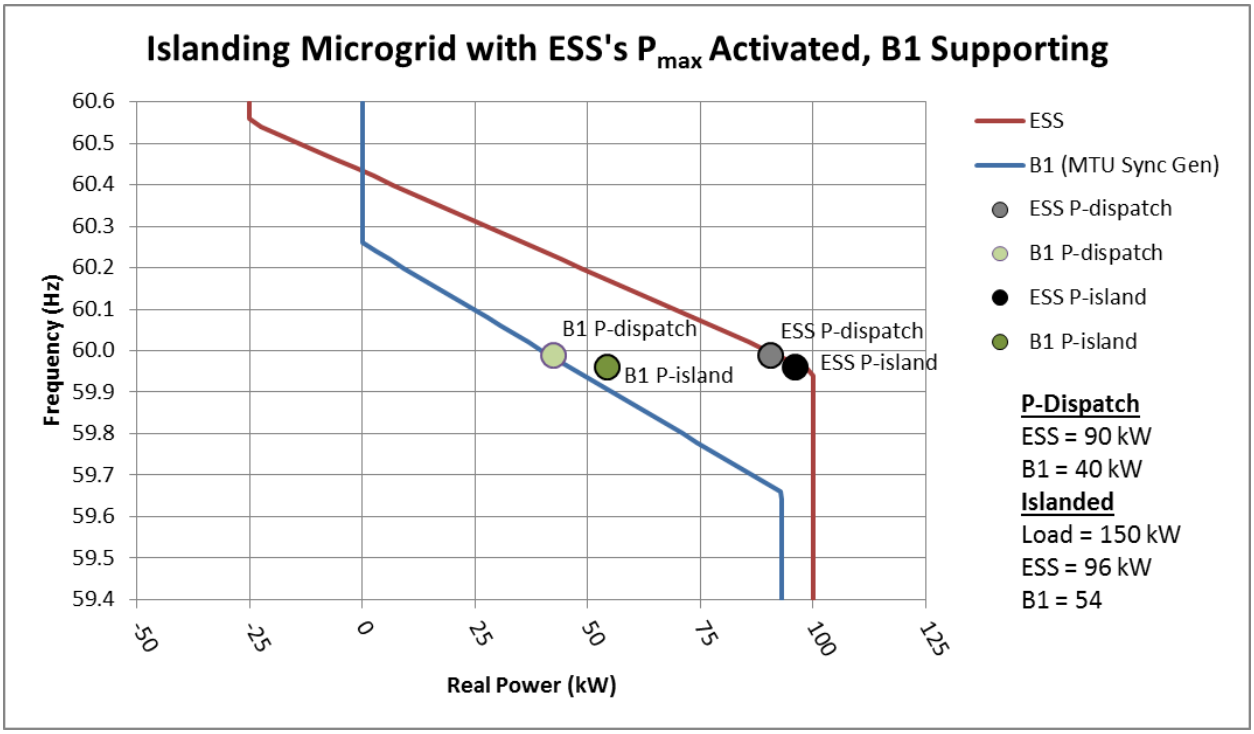

Figure 376: Pmax, Multi-unit, ESS B1, Composite Frequency Droop, Event I3

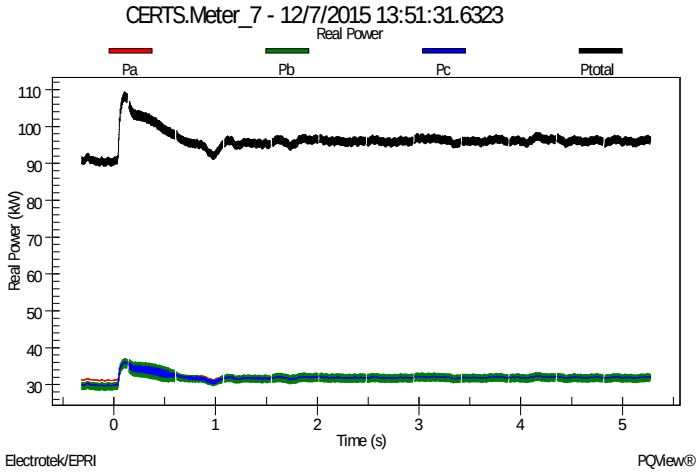

Figure 377: Pmax, Multi-unit, ESS B1, ESS Real Power, Event I3

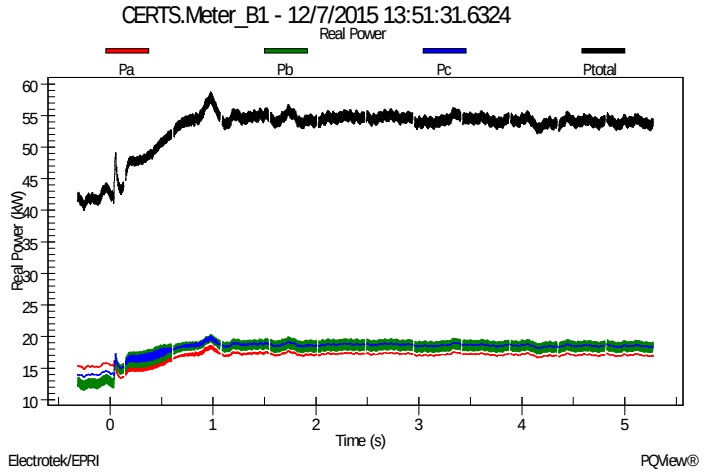

Figure 378: Pmax, Multi-unit, ESS B1, B1 Real Power, Event I3

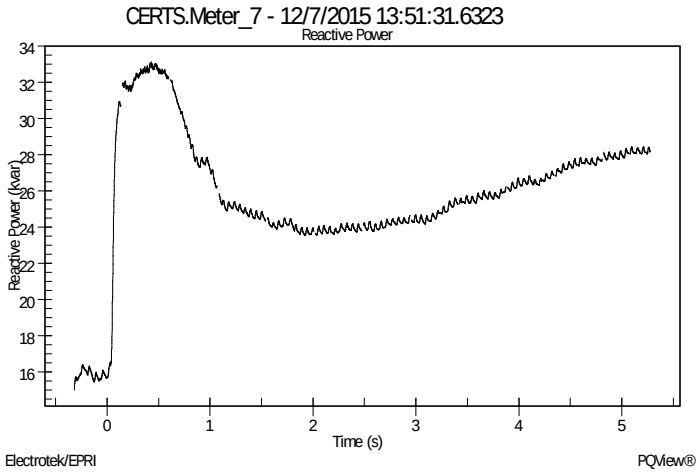

Figure 379: Pmax, Multi-unit, ESS B1, ESS Reactive Power, Event I3

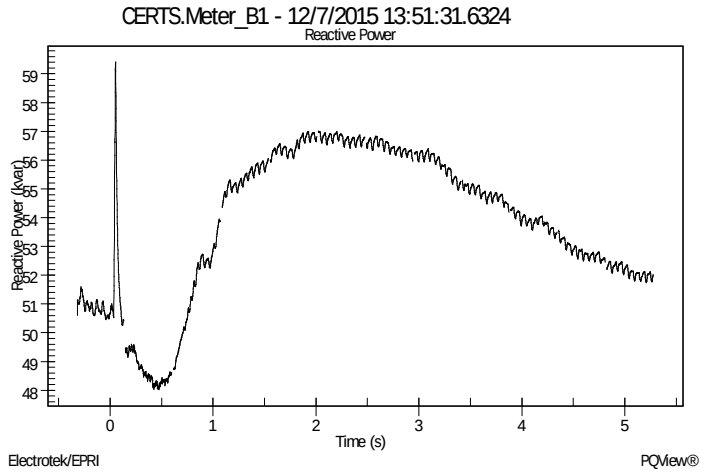

Figure 380: Pmax, Multi-unit, ESS B1, B1 Reactive Power, Event I3

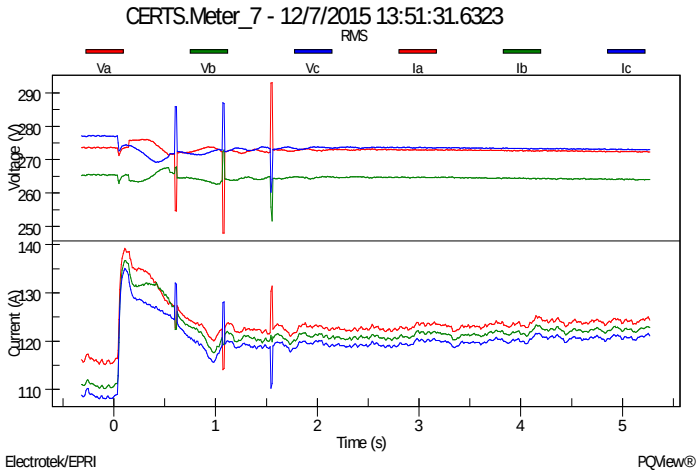

Figure 381: Pmax, Multi-unit, ESS B1, ESS RMS V&I, Event I3

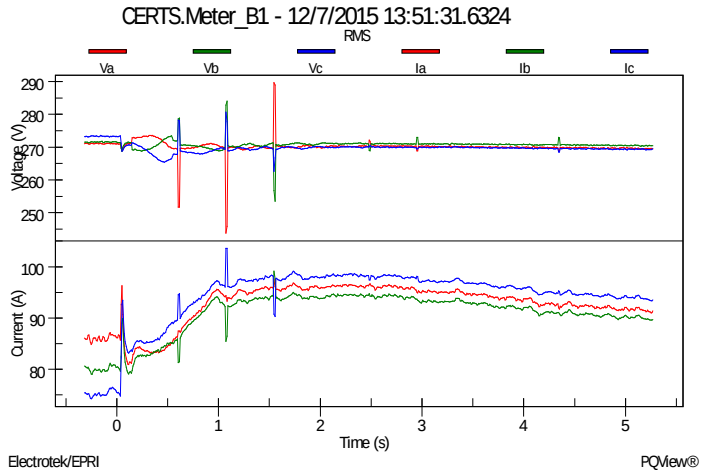

Figure 382: Pmax, Multi-unit, ESS B1, B1 RMS V&I, Event I3

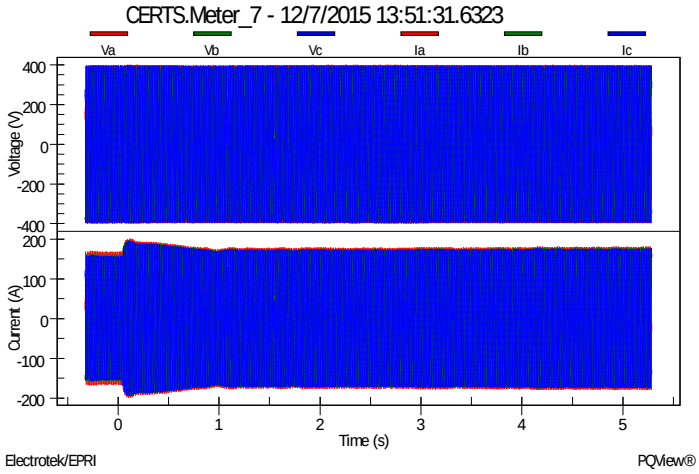

Figure 383: Pmax, Multi-unit, ESS B1, ESS V&I Waveform, Event I3

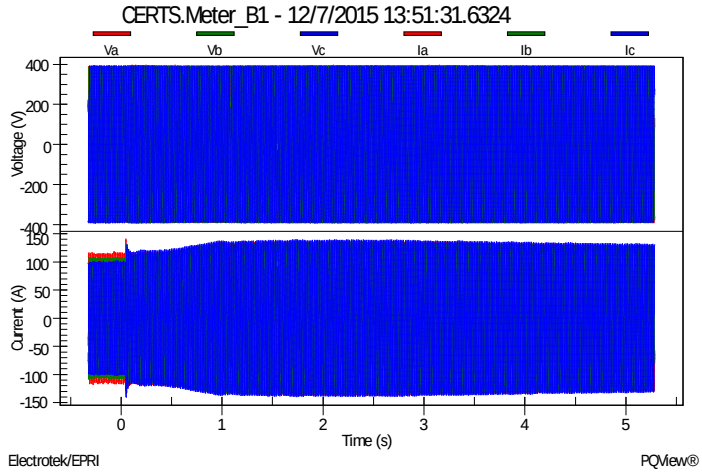

Figure 384: Pmax, Multi-unit, ESS B1, B1 Waveform V&I, Event I3

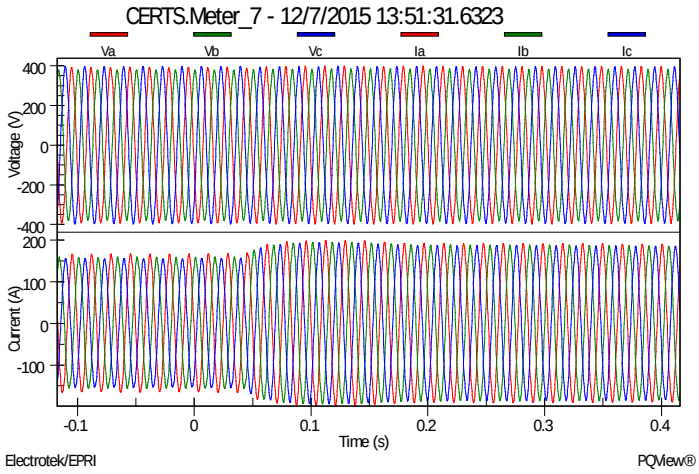

Figure 385: Pmax, Multi-unit, ESS B1, ESS V&I Waveform (Zoomed), Event I3

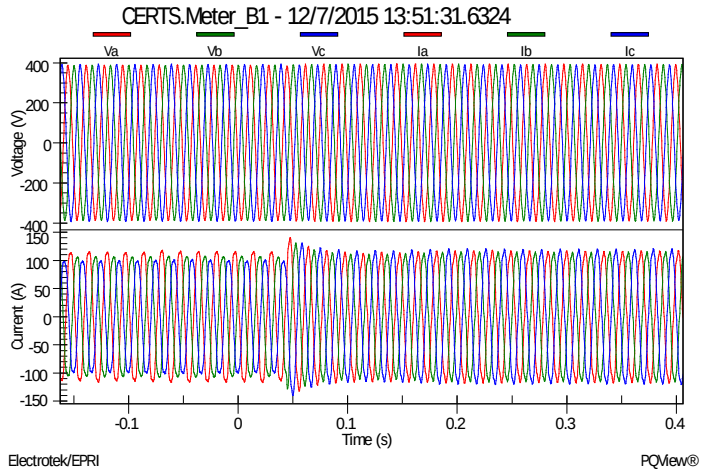

Figure 386: Pmax, Multi-unit, ESS B1, B1 V&I Waveform (Zoomed), Event I3

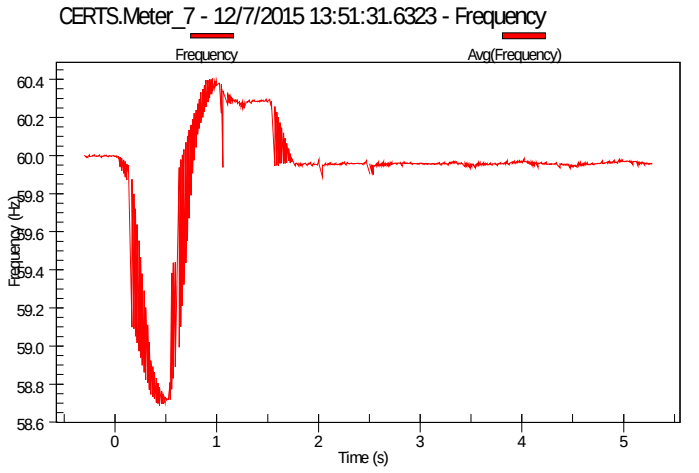

Figure 387: Pmax, Multi-unit, ESS B1, ESS Frequency, Event I3

5.15 Pmin Control – Multiple Sources, Islanded

Performance Goal

The intent of this testing is to ensure proper implementation of the CERTS P_{min} function when a pair of DERs are operating in the islanded microgrid. The P_{min} function is activated when the DER is operating at its minimum limit of real power capability. This function responds to the minimum load condition by driving the output frequency higher to allow other CERTS DERs in the microgrid the opportunity to reject load and therefore achieve stable operating conditions. The DER should demonstrate a predictable adjustment in frequency when the real power it is producing is at or below its P_{min} setting.

These tests examine how the sources share load when P_{min} is activated on one source, either the ESS or the accompanying gen-set. These tests are performed with the ESS and A1 to see how load sharing works with another inverter-connected source and then with the ESS and the synchronous generator, B1.

Description of Procedure

The pair of DERs will initially be grid-connected. One unit's $P_{dispatch}$ is set rather low and the other is set high. A load is applied in the microgrid, so that when islanded it is sufficient to drive the unit with the lower $P_{dispatch}$ setting to its minimum capability but not both units. The microgrid is then be disconnected from the utility. This should result in the unit whose $P_{dispatch}$ is set low to have its P_{min} activated thus driving the system frequency higher. The result should be that the other unit will decrease its output and limit the lower dispatched unit to its P_{min} setting while achieving a stable microgrid.

The units are dispatched to various real power settings. Otherwise, all units are dispatched to 1% Frequency Droop, 480 V_{LL}, 5% Voltage Droop.

Test Settings

For these tests the following parameter settings are made:

<u>ESS</u>

Pdispatch = Varies
Frequency Droop = 1%
Real Power-Frequency Droop = -.0048 Hz/kW
P_{max} = 100 kW (P_{max} = Battery Power Limit Max parameter on inverter)
P_{min} = -25 kW (P_{min} = Battery Power Limit Min parameter on inverter)
Voltage Set Point = 480 V_{LL} (Inverter Voltage Reference = 102.2)
Voltage Droop = -0.24 V_{LL}/kVAr (5%)
Voltage Regulation P-gain = 0.4
Voltage Regulation I-gain = 16

<u>A1 (Inverde 100)</u>

Pdispatch = Varies
Frequency Droop = 1%
Real Power-Frequency Droop = -.006 Hz/kW

P_{max} = 100 kW
P_{min} = 0 kW
Voltage Set Point = 480 V_{LL}
Voltage Droop = -0.14 V_{LN}/kVAr (5%)

<u>B1 (Sync Gen)</u>
Pdispatch = Varies
Frequency Droop = 1%
Real Power-Frequency Droop = -.006452 Hz/kW
P_{max} = 93 kW
P_{min} = 0 kW
Voltage Set Point = 480 V_{LL}
Voltage Droop = -0.24 V_{LL}/kVAr (5%)

During each sequence of tests in Table 31, a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers "Closed"; load banks are set as close as possible to the prescribed values; reactive load is set to achieve a power factor of approximately 0.9 lagging inside the microgrid (excludes load bank 6 which is outside of the microgrid); and events are triggered based on the transition of the GIS.

Test Events A, B, G, and H are designed to activate P_{min} in the accompanying gen-set A1 or B1. The remaining tests are designed to activate P_{min} on the ESS.

	Dispatch			Pre-Event Loads (pf = 0.9)			Pre-Event Meter Values					Islanded Freq (Hz)	
Test Event	A1 (kW)	ESS (kW)	B1 (kW)	L 3 (kW)	L 4 (kW)	L 6 (kW)	A1 (kW)	Meter 3 (kW)	Meter 5 (kW)	Meter 7 (kW)	SS (kW)		GIS
A	30	70	-	20	-	90	30	-10	0	-70	-80	60.24	Closed → Open
B	30	70	-	20	-	90	0	20	0	-20	-	60.24	Open → Closed
C	90	-20	-	20	-	60	90	-70	0	20	-50	60.27	Closed → Open
D	90	-20	-	20	-	60	45	-25	0	25	-	60.27	Open → Closed
E	75	-10	-	10	-	65	75	-65	0	10	-55	60.24	Closed → Open
F	75	-10	-	10	-	65	35	-25	0	25	-	60.24	Open → Closed
G	-	60	20	20	-	90	0	20	-30	-70	-80	60.24	Closed → Open
H	-	60	20	20	-	90	0	20	0	-20	-	60.24	Open → Closed
I	-	-20	90	20	-	60	0	20	-90	20	-50	60.29	Closed → Open
J	-	-20	90	20	-	60	0	20	-45	25	-	60.29	Open → Closed
K	-	-10	75	10	-	65	0	10	-75	10	-55	60.258	Closed → Open
L	-	-10	75	10	-	65	0	10	-35	25	-	60.258	Open → Closed

Table 31: Pmin Control – Multiple Sources, Islanded, Test Settings

Test Results

The test results for the P_{min} control, multiple sources, and islanded test events are shown in the following two tables. Table 32 shows the results for tests performed using the ESS and A1 as sources and Table 33 contains the results for tests using the ESS and B1.

Test Event	Pre-Event				Transient Extremum		Post-Event					Pass/Fail
	A1	ESS	Microgrid Bus		A1	ESS	A1	ESS	Microgrid Bus		Total Real Power (kW)	
	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)		
A	24.4	69.1	224.4	60.00	-7.8	23.8	-0.5	24.3	214.3	60.21	23.8	Pass
B	-0.5	24.1	275.6	60.22	24.3	71.5	22.7	67.3	274.7	60.00	90.0	Pass
C	82.5	-21.7	274.1	60.01	54.9	-45.1	52.0	-28.0	275.3	60.19	24.0	Pass
D	51.2	-27.4	275.3	60.20	84.0	-14.2	80.9	-23.6	273.9	60.02	57.4	Pass
E	70.0	-10.7	274.0	60.00	46.2	-40.3	40.0	-28.2	275.5	60.18	11.8	Pass
F	39.1	-27.3	275.5	60.18	74.1	-3.7	71.9	-7.9	273.8	59.99	64.0	Pass

Table 32: Pmin Control – Multiple Sources, Islanded, Test Results ESS A1

Test Event	Pre-Event				Transient Extremum		Post-Event					Pass/Fail	Notes
	B1	ESS	Microgrid Bus		B1	ESS	B1	ESS	Microgrid Bus		Total Real Power (kW)		
	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Real Power (kW)	Voltage (V)	Frequency (Hz)			
G	17.9	57.6	275.8	60.01	-11.9	-8.4	0.7	18.3	275.1	60.19	19.0	Fail	B1 Pmin Not Activated
H	4.4	14.8	276.2	60.21	16.1	61.3	36.8	59.0	276.4	60.00	95.8	Pass	
I	91.8	-22.5	276.3	60.01	62.2	-63.8	43.6	-25.5	275.1	59.99	18.2	Pass	
J	47.0	-27.7	276.5	60.22	73.2	-7.4	95.8	-23.3	276.7	59.99	72.5	Pass	
K	80.2	-9.2	275.2	59.99	46.5	-68.1	35.6	-24.1	276.0	60.23	11.5	Pass	
L	39.5	-27.5	276.7	60.42	57.0	4.2	86.4	-12.3	275.7	60.00	74.1	Pass	

Table 33: Pmin Control – Multiple Sources, Islanded, Test Results ESS B1

Analysis

The ESS in combination with A1 successfully passes all P_{min} Control islanding tests conducted. Both units respond quickly to the load rejection. The P_{min} functionality is activated on the unit that is driven to its minimum real power capability; this drives the frequency up in a linear manner. The supporting unit relieves the minimally loaded unit and the system achieves steady-state conditions in one to a few seconds.

Both A1 and the ESS exceed (become more negative than) their P_{min} setting during the transition from grid-connected to the islanded steady-state condition. This is more pronounced on the ESS as it exceeds its P_{min} setting by 20 kW, reaching a minimum of -45 kW, while A1 exceeds its P_{min} by 8 kW reaching a minimum of -8 kW.

The ESS's P_{min} setting is functionally applied by setting a minimum battery power limit according to the inverter's manufacturer. Since this is applied to the D.C. real power, the actual real power input to the ESS will be larger than the P_{min} setting by the losses in the inverter. It can be seen in Table 32, Events C and E, that the actual A.C. real power input to the ESS is approximately 28 kW when its P_{min} is set to -25 kW.

The ESS in combination with B1 does not successfully pass all P_{min} Control islanding tests conducted. Specifically in Event G B1's P_{min} functionality should have been activated but it is not. The ESS reacted more quickly to the load change and prevented B1 from reaching its P_{min} setting. It should be noted that the P_{min} functionality on the synchronous gen-set B1 has not previously been tested or confirmed. When the test intends for the ESS's P_{min} functionality to be activated, it does so successfully. The ESS does again exceed its P_{min} setting during the transition to the islanded condition. In Event K this is rather significant reaching a minimum of -68 kW, exceeding its P_{min} setting of -25 kW by 43 kW. This suggests that in a mixed environment with a battery energy storage system and synchronous gen-sets, that a sufficiently large load rejection could cause the ESS to exceed its rated capability and trip due to the transient overload.

Test Event A's results are shown in Figure 388 through Figure 399 where A1 is dispatched to 30 kW, the ESS to 70 kW, and the load in the microgrid is 24 kW. After grid separation, A1's P_{min} is activated and the units transition smoothly and predictably to the steady-state condition in about 1.5 seconds. Figure 388 shows the transition for both units on a composite frequency droop curve where it is shown that the actual steady state results agree well with the predicted values.

A1's real power graph, Figure 390, shows its P_{min} is activated, i.e. real power output falls below 0 kW, until 0.35 seconds. During this time the frequency plot, Figure 399, shows a linear increase in frequency at a rate of 1.8 Hz/s to a maximum frequency of 60.6 Hz. A1's P_{min} is then released and the system reaches a steady-state frequency of 60.21 Hz at 1.5 seconds.

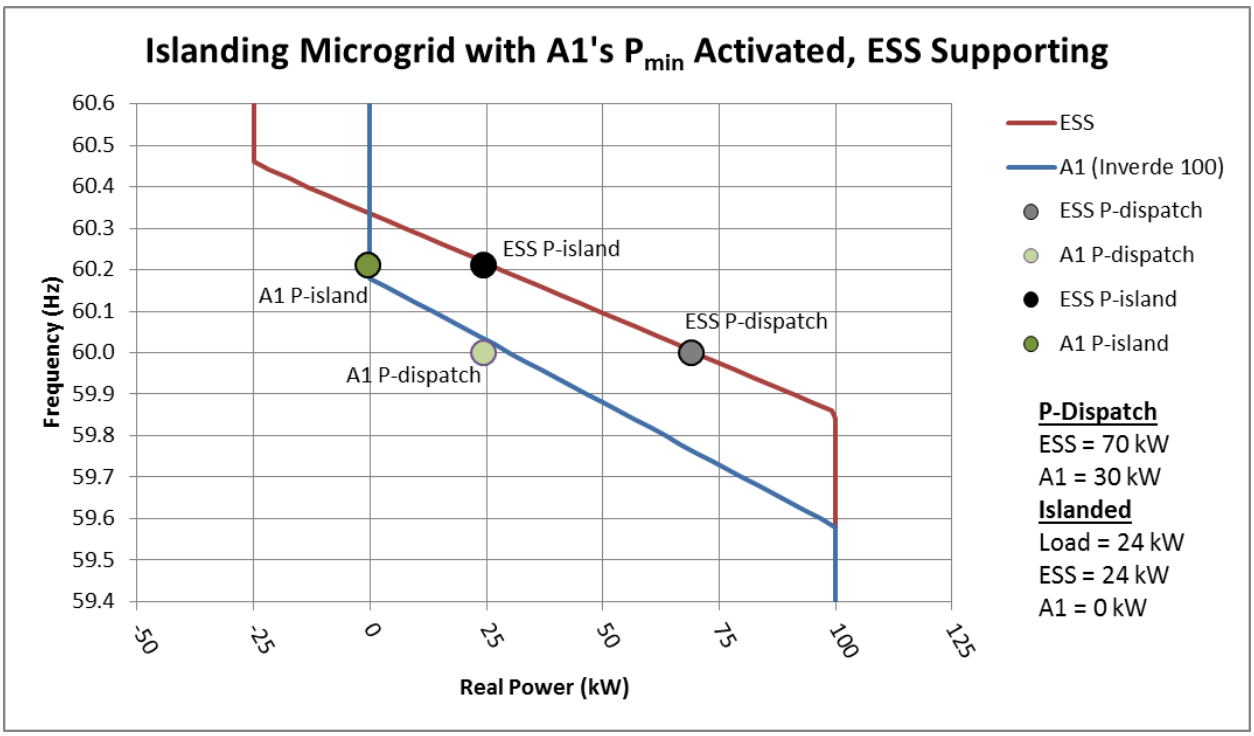

Figure 388: Pmin, Multi-unit, ESS A1, Composite Frequency Droop, Event A

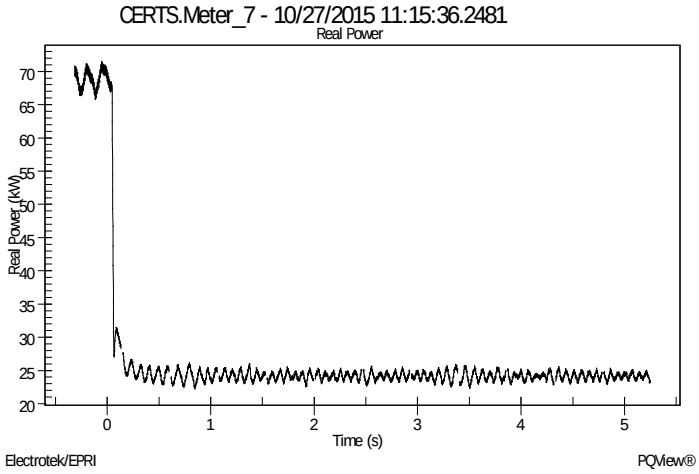

Figure 389: Pmin, Multi-unit, ESS A1, ESS Real Power, Event A

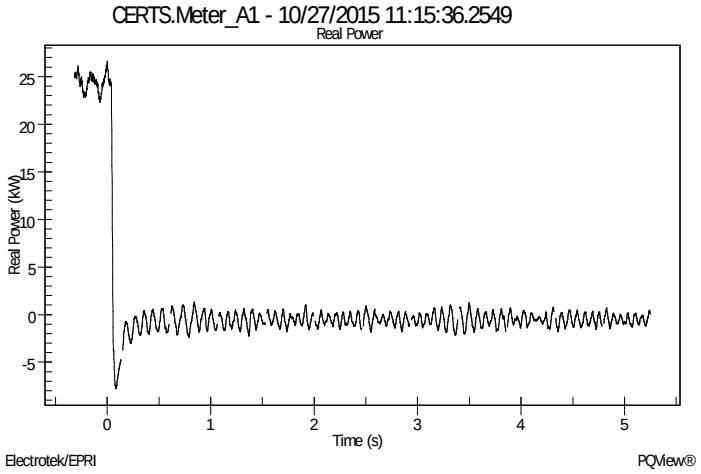

Figure 390: Pmin, Multi-unit, ESS A1, A1 Real Power, Event A

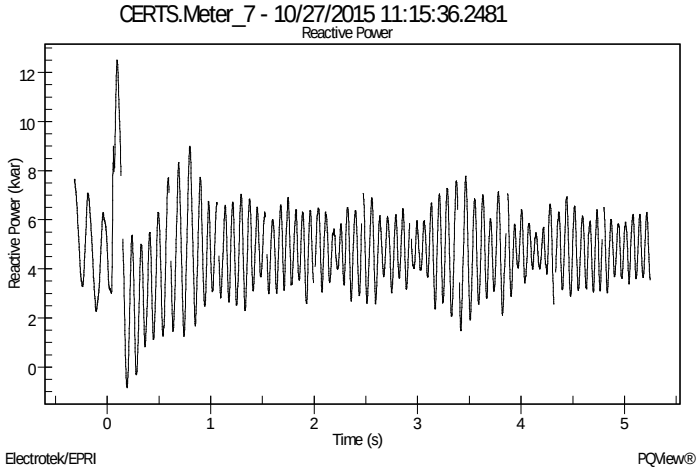

Figure 391: Pmin, Multi-unit, ESS A1, ESS Reactive Power, Event A

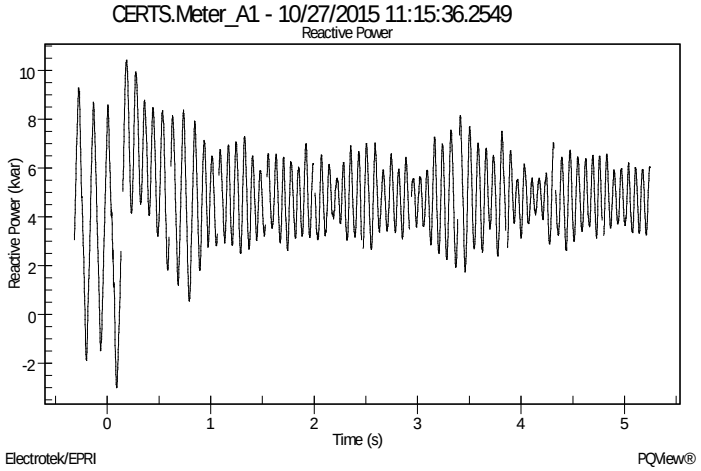

Figure 392: Pmin, Multi-unit, ESS A1, A1 Reactive Power, Event A

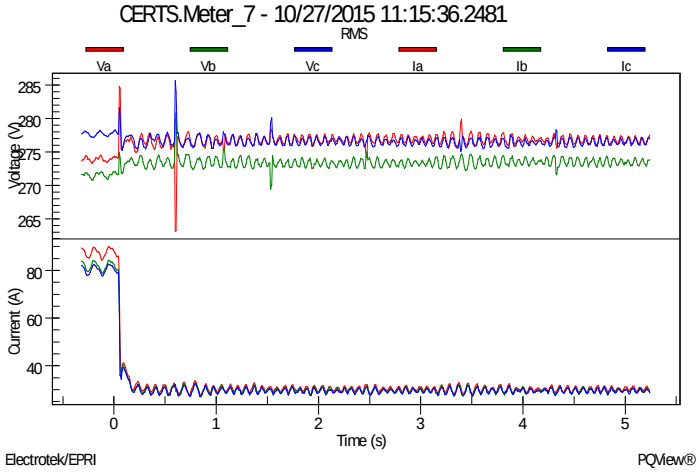

Figure 393: Pmin, Multi-unit, ESS A1, ESS RMS V&I, Event A

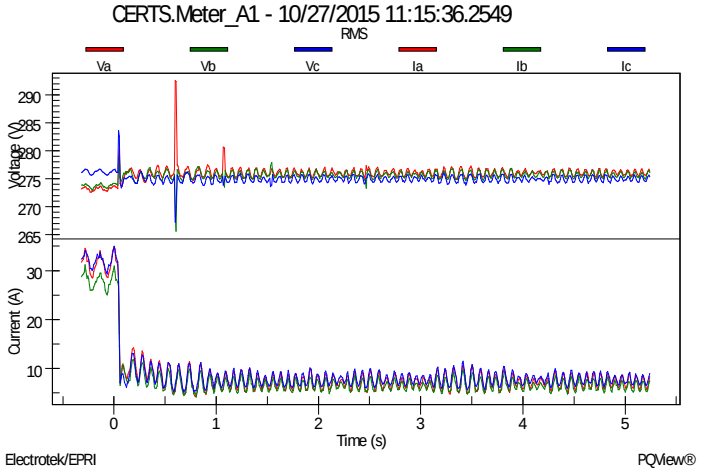

Figure 394: Pmin, Multi-unit, ESS A1, A1 RMS V&I, Event A

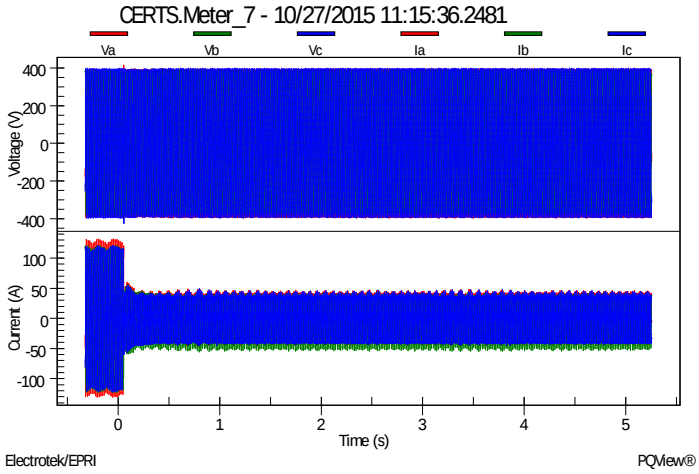

Figure 395: Pmin, Multi-unit, ESS A1, ESS V&I Waveform, Event A

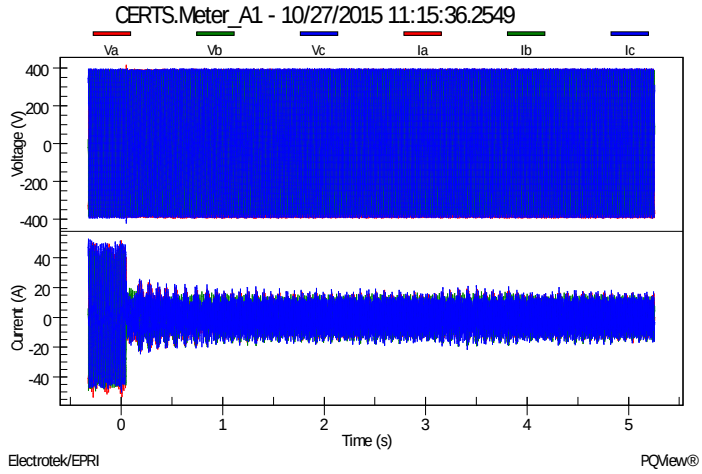

Figure 396: Pmin, Multi-unit, ESS A1, A1 Waveform V&I, Event A

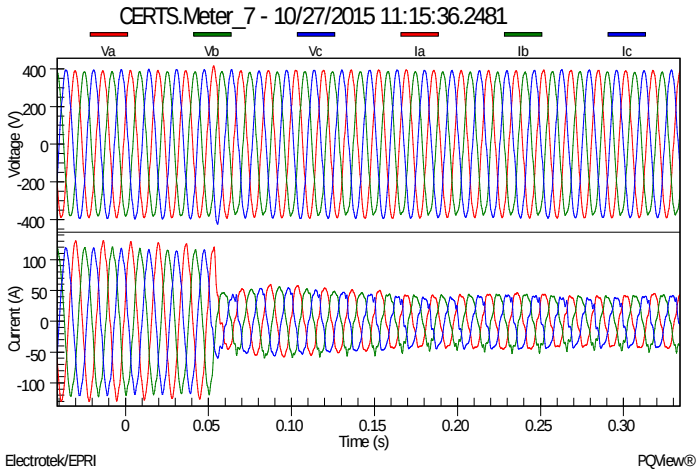

Figure 397: Pmin, Multi-unit, ESS A1, ESS V&I Waveform (Zoomed), Event A

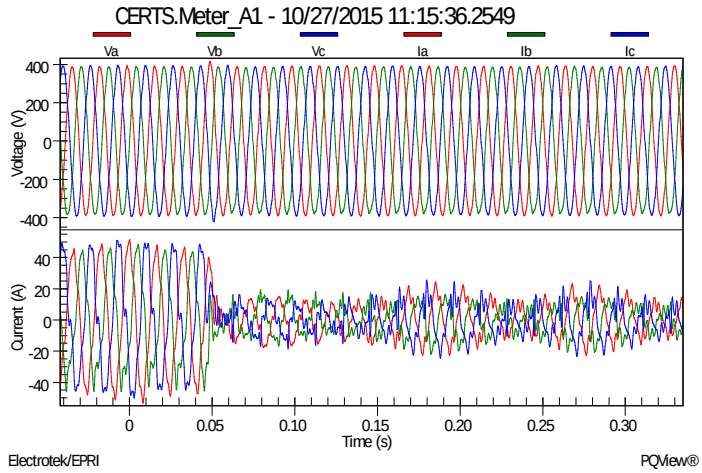

Figure 398: Pmin, Multi-unit, ESS A1, A1 V&I Waveform (Zoomed), Event A

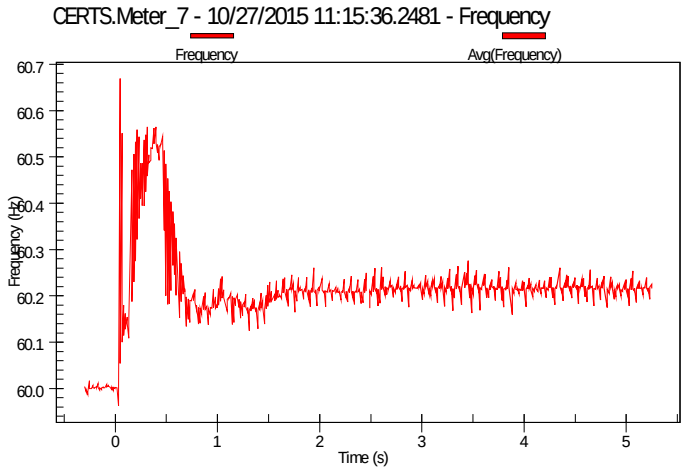

Figure 399: Pmin, Multi-unit, ESS A1, ESS Frequency, Event A

Test Event C's results are shown in Figure 400 through Figure 411 where A1 is dispatched to 90 kW, the ESS to -20 kW, and the load in the microgrid is 24 kW. After grid separation, the ESS's P_{min} is activated and the units transition smoothly and predictably to the steady-state condition in about 4.5 seconds. Figure 400 shows the transition for both units on a composite frequency droop curve where it is shown that the actual steady state results agree well with the predicted values.

The ESS's real power graph, Figure 401, shows its P_{min} is activated, i.e. real power output falls below -28 kW A.C. (which corresponds to the P_{min} setting of -25 kW D.C.), until approximately the 3 second mark. However, the frequency plot, Figure 411, indicates that P_{min} is only active until the 0.4 second mark. During this time the frequency plot shows a linear increase in frequency at a rate of 1.2 Hz/s to a maximum frequency of 60.4 Hz. The ESS's P_{min} is then released and the system reaches a steady-state frequency of 60.19 Hz at about 4.5 seconds based on the real power flow.

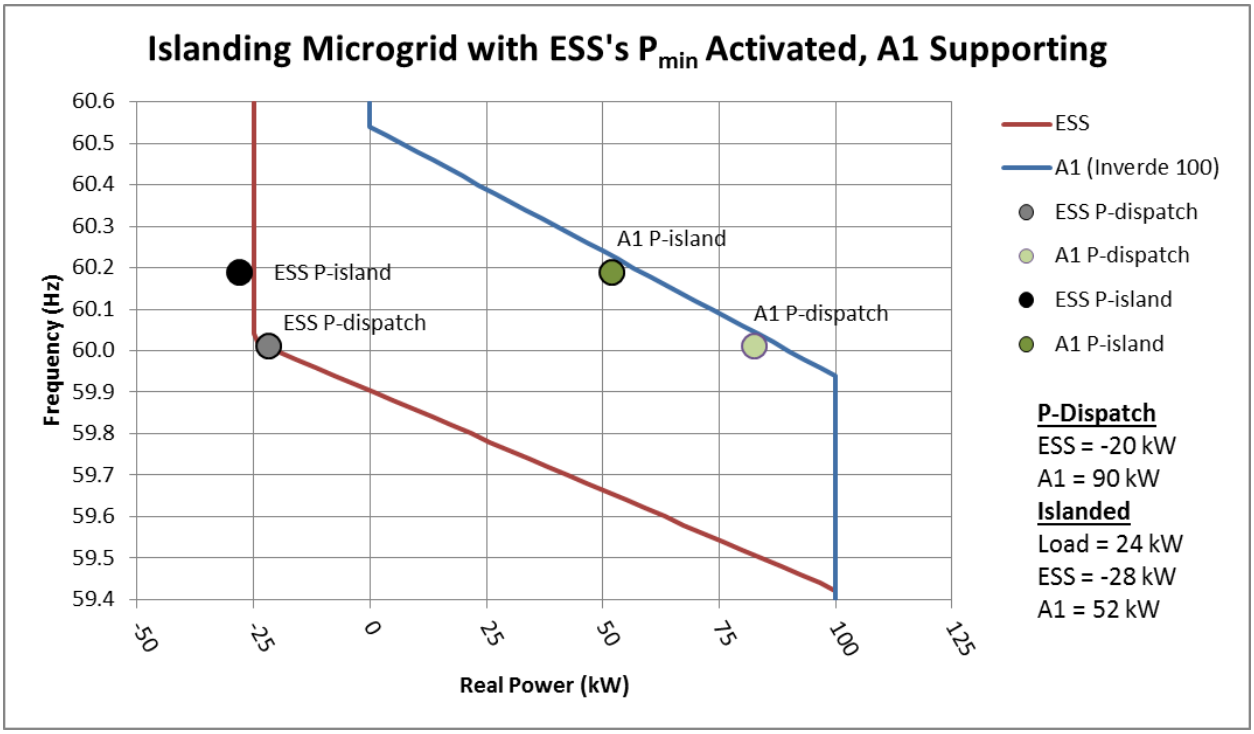

Figure 400: Pmin, Multi-unit, ESS A1, Composite Frequency Droop, Event C

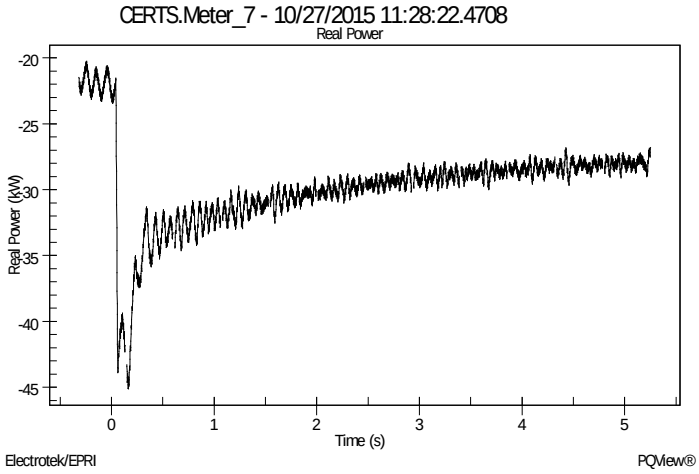

Figure 401: Pmin, Multi-unit, ESS A1, ESS Real Power, Event C

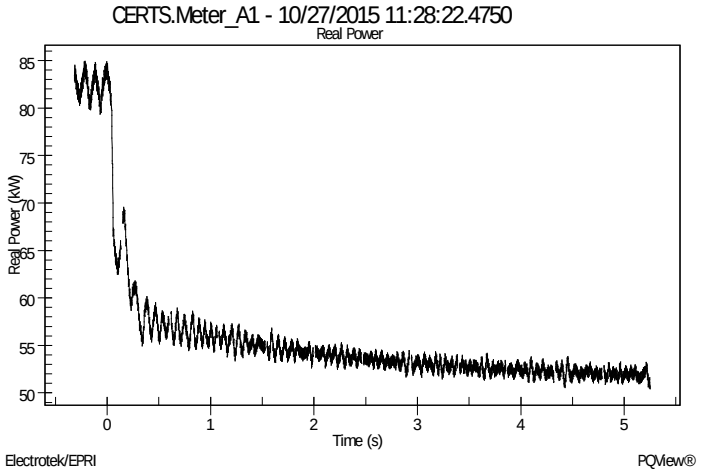

Figure 402: Pmin, Multi-unit, ESS A1, A1 Real Power, Event C

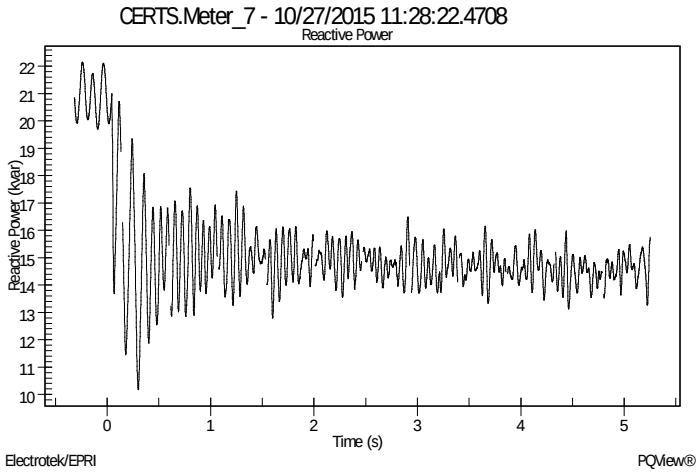

Figure 403: Pmin, Multi-unit, ESS A1, ESS Reactive Power, Event C

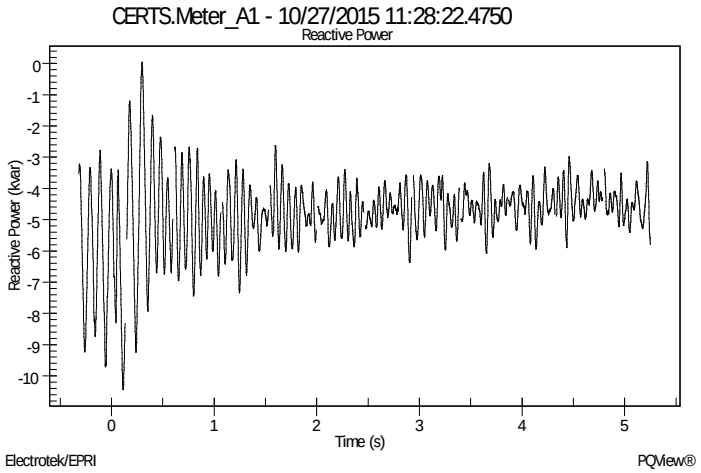

Figure 404: Pmin, Multi-unit, ESS A1, A1 Reactive Power, Event C

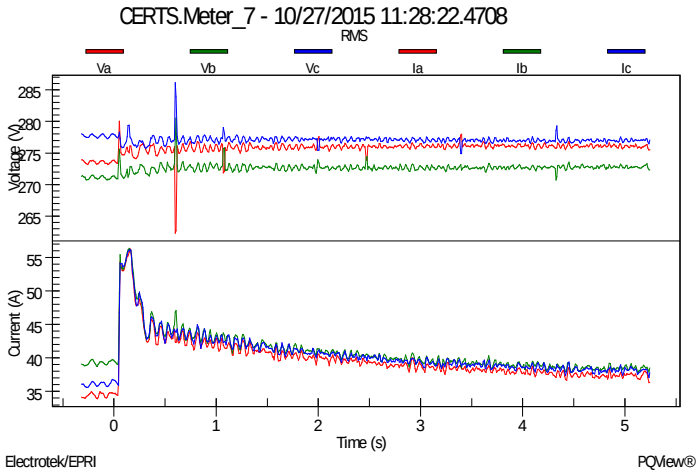

Figure 405: Pmin, Multi-unit, ESS A1, ESS RMS V&I, Event C

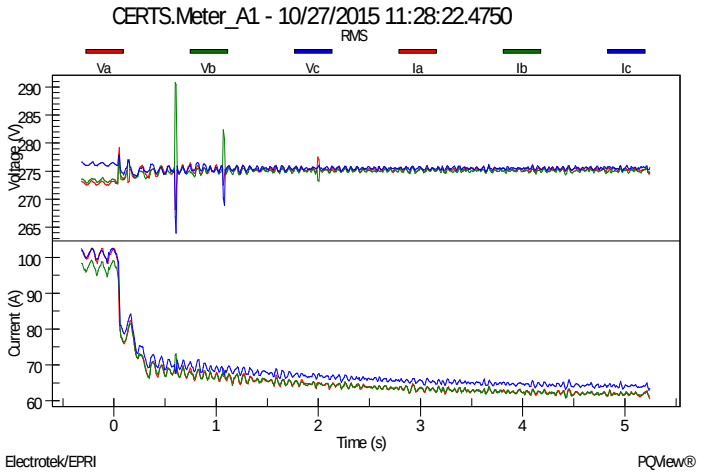

Figure 406: Pmin, Multi-unit, ESS A1, A1 RMS V&I, Event C

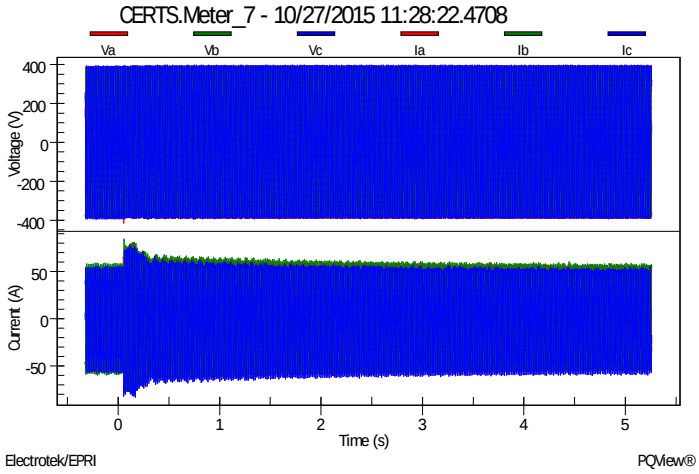

Figure 407: Pmin, Multi-unit, ESS A1, ESS V&I Waveform, Event C

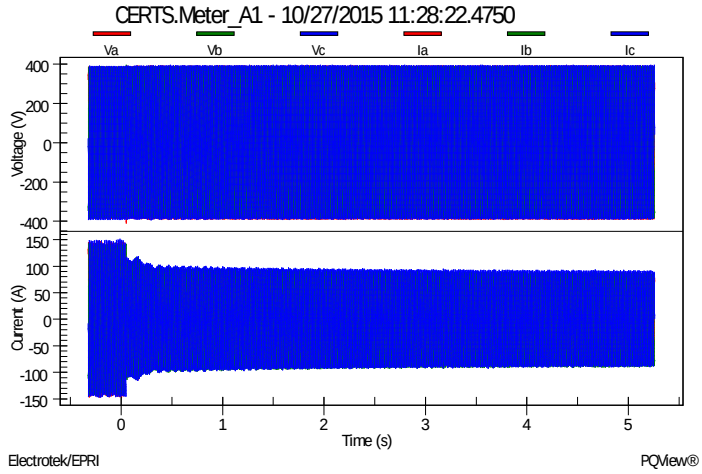

Figure 408: Pmin, Multi-unit, ESS A1, A1 Waveform V&I, Event C

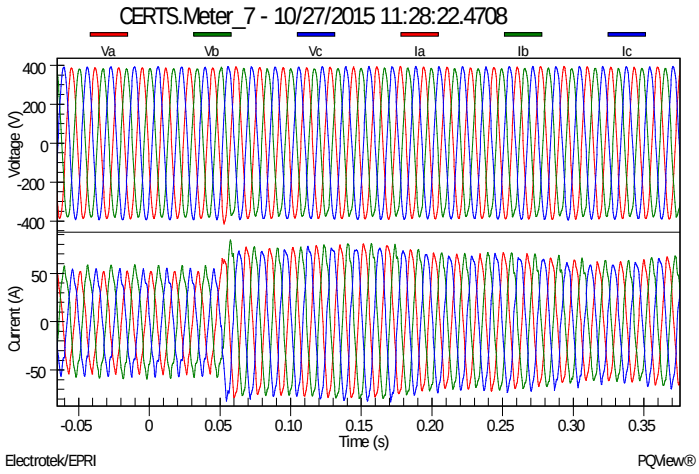

Figure 409: Pmin, Multi-unit, ESS A1, ESS V&I Waveform (Zoomed), Event C

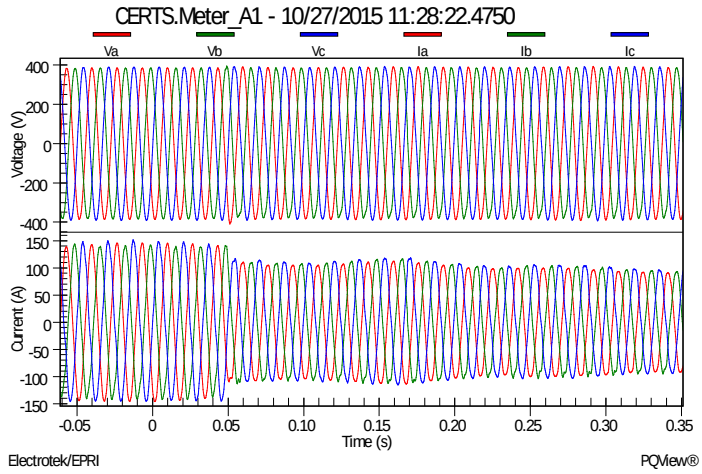

Figure 410: Pmin, Multi-unit, ESS A1, A1 V&I Waveform (Zoomed), Event C

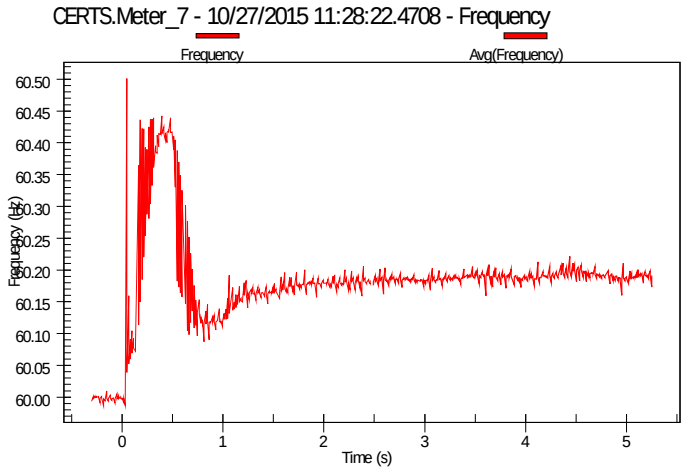

Figure 411: Pmin, Multi-unit, ESS A1, ESS Frequency, Event C

Test Event G's results are shown in Figure 412 through Figure 423 where B1 is dispatched to 20 kW, the ESS to 60 kW, and the load in the microgrid is 19 kW.

After grid separation, it is expected that B1's P_{min} would be activated but it is not. However, the units do transition smoothly and predictably to the steady-state condition in about 2.4 seconds. This test event is failed since B1's P_{min} is not activated.

During the transition to the islanded condition 60 kW of load is rejected. B1 should have rejected 20 kW thus activating its P_{min} functionality while the ESS would have rejected the other 40 kW of load. Instead, because the ESS responds to load changes much more quickly than B1, the ESS rejects the full 60 kW of load. Neither of units' P_{min} functionality is activated however the system does achieve the expected steady-state condition via their normal frequency vs. real power droop controls.

Figure 412 shows the transition for both units on a composite frequency droop curve where it is shown that the actual steady state results agree well with the predicted values.

B1's real power graph, Figure 414, shows its P_{min} is not activated, i.e. real power output does not fall below 0 kW, except for 26 ms during the transient. Also, the frequency plot, Figure 423, does not show the characteristic rise and fall in frequency associated with the activation of the P_{min} functionality. Instead, the real power transitions at a rate of 8.5 kW/s to the steady-state condition at 2.4 seconds. During this time the frequency initially jumps to 60.24 Hz until the 0.8 second mark and then declines at the rate of 0.03 Hz/s to the steady-state value of 60.19 Hz at the 2.4 second mark.

The reactive power from the ESS and B1 are shown in Figure 415 and Figure 416 respectively. Initially, while grid-connected, the microgrid is supplying 23 kVAr, of which approximately 10 kVAr is inside the microgrid and the other 13 kVAr is supplied to the utility. During transition the ESS rejects the majority of the reactive power, 11 kVAr, supplied to the utility, again due to its faster response. The reactive load supplied between the two units then begins a slow oscillation towards a steady-state condition that is not reached until after the 5 second mark which is the limit of the recorded data for this test event.

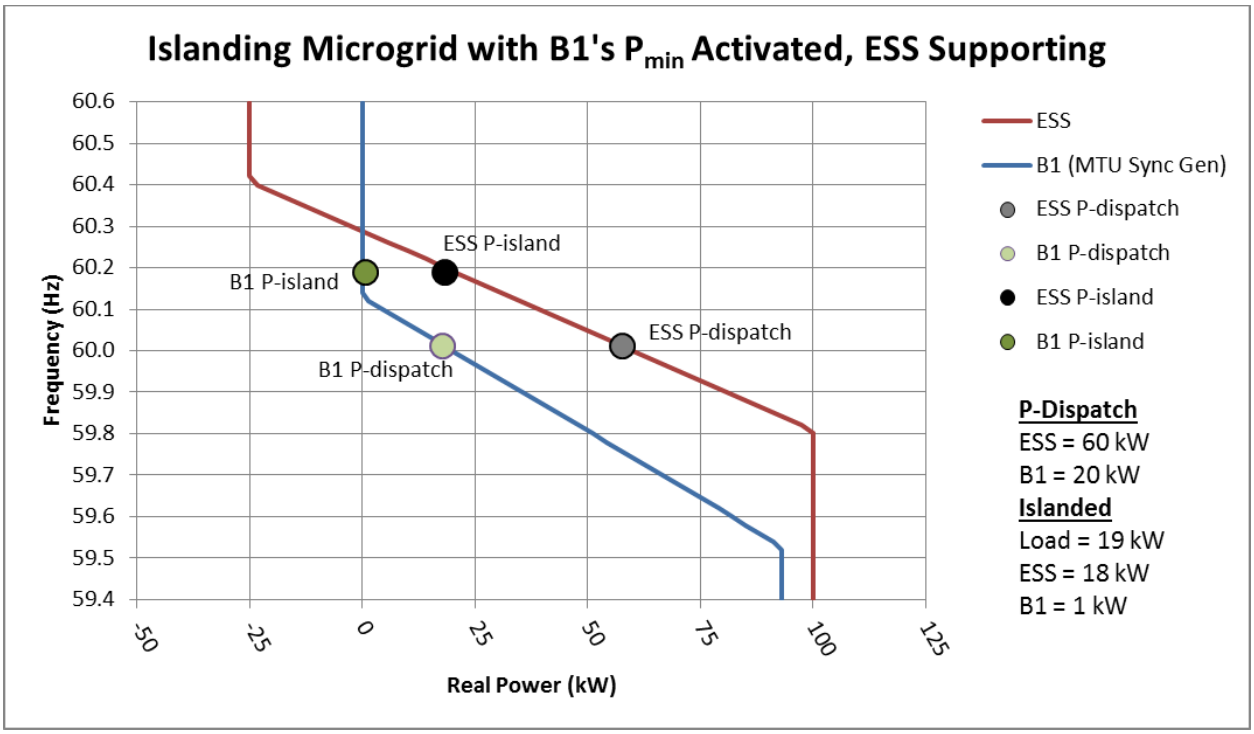

Figure 412: Pmin, Multi-unit, ESS B1, Composite Frequency Droop, Event G

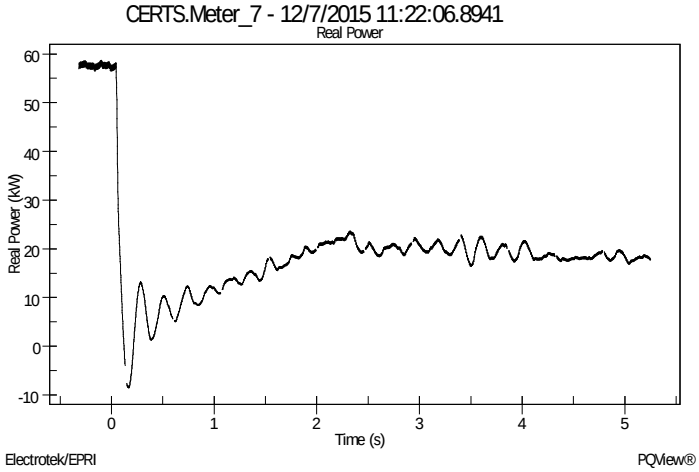

Figure 413: Pmin, Multi-unit, ESS B1, ESS Real Power, Event G

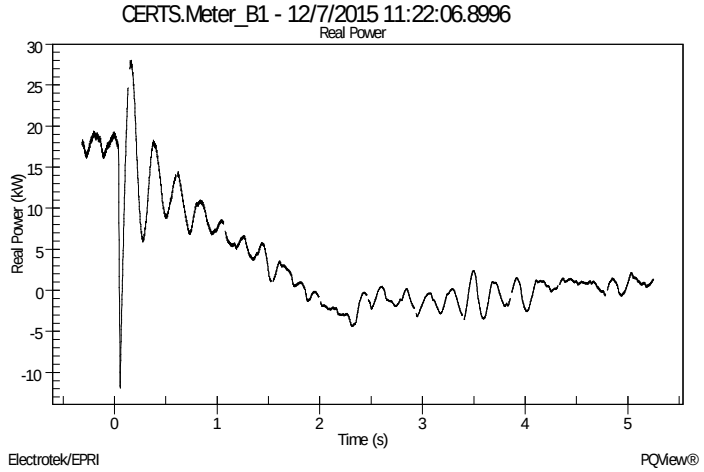

Figure 414: Pmin, Multi-unit, ESS B1, B1 Real Power, Event G

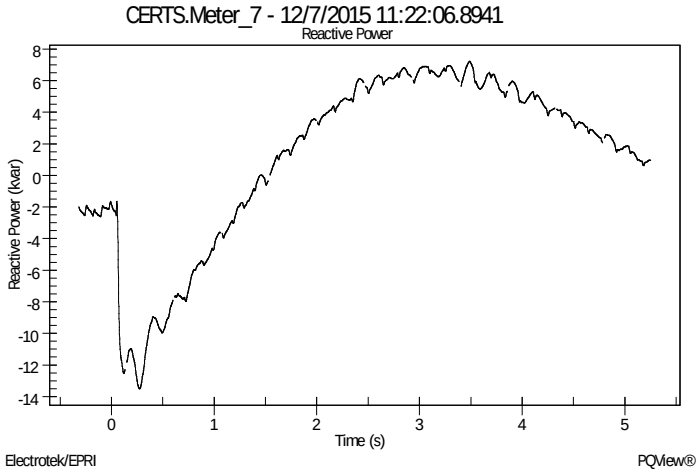

Figure 415: Pmin, Multi-unit, ESS B1, ESS Reactive Power, Event G

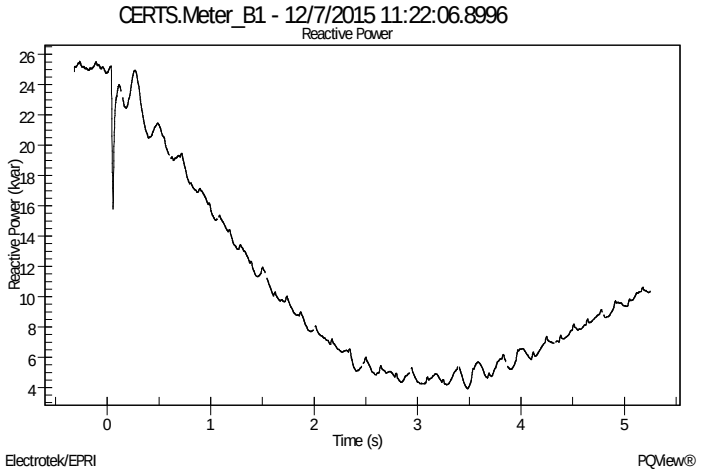

Figure 416: Pmin, Multi-unit, ESS B1, B1 Reactive Power, Event G

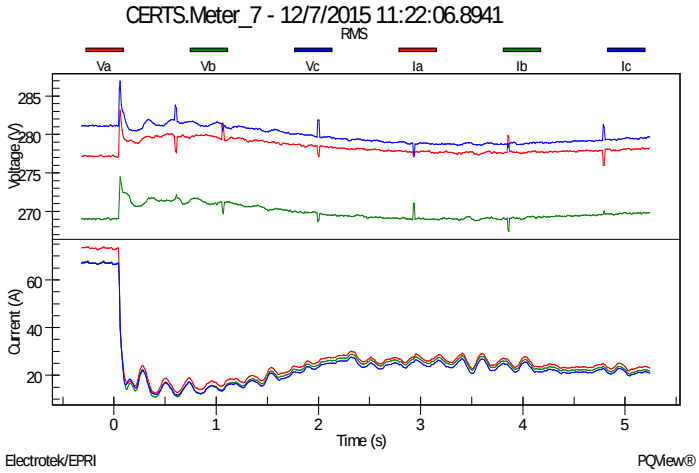

Figure 417: Pmin, Multi-unit, ESS B1, ESS RMS V&I, Event G

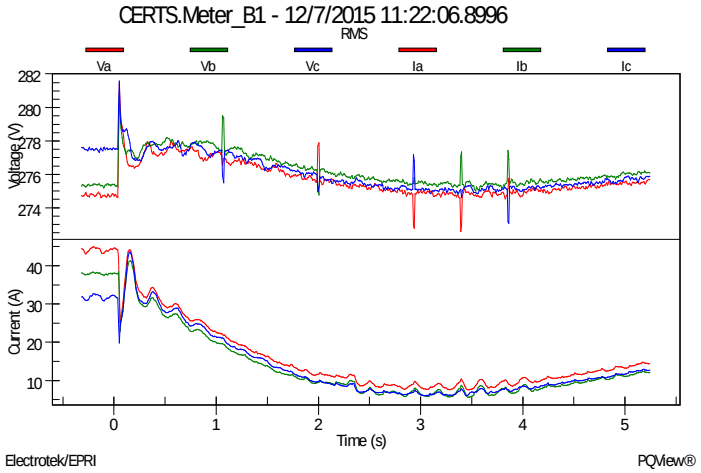

Figure 418: Pmin, Multi-unit, ESS B1, B1 RMS V&I, Event G

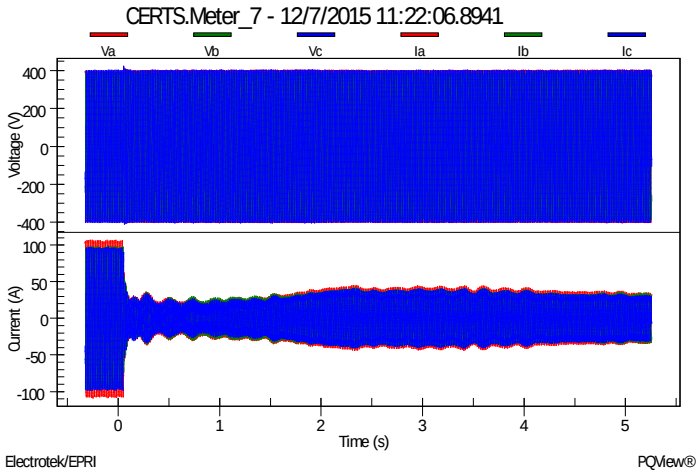

Figure 419: Pmin, Multi-unit, ESS B1, ESS V&I Waveform, Event G

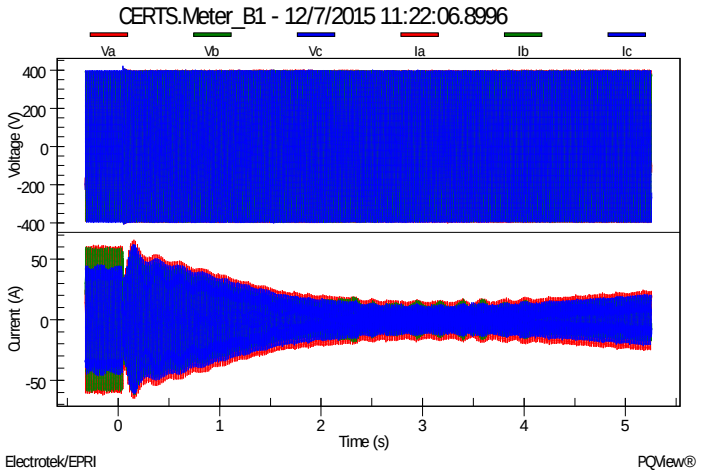

Figure 420: Pmin, Multi-unit, ESS B1, B1 Waveform V&I, Event G

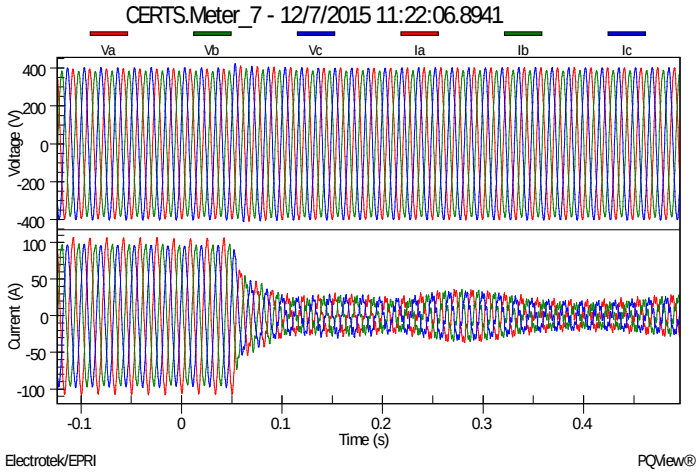

Figure 421: Pmin, Multi-unit, ESS B1, ESS V&I Waveform (Zoomed), Event G

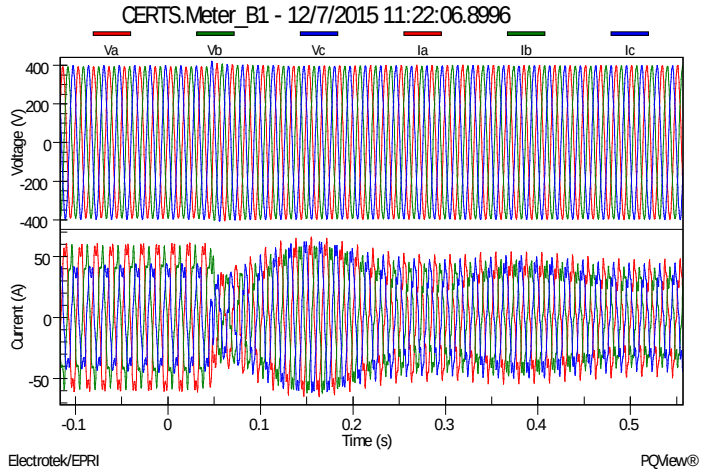

Figure 422: Pmin, Multi-unit, ESS B1, B1 V&I Waveform (Zoomed), Event G

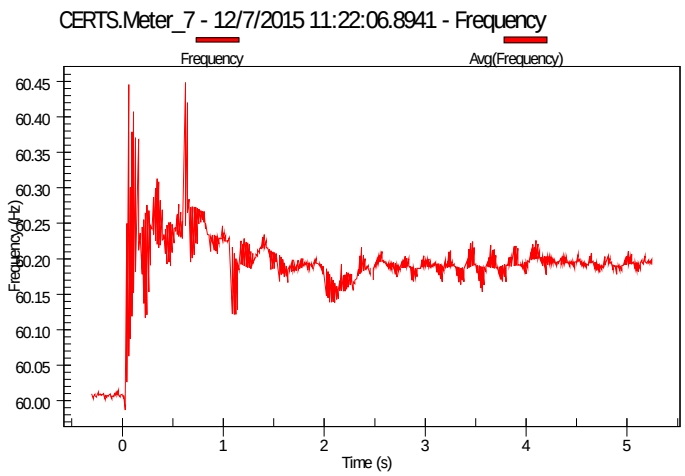

Figure 423: Pmin, Multi-unit, ESS B1, ESS Frequency, Event G

Test Event K's results are shown in Figure 424 through Figure 435 where B1 is dispatched to 75 kW, the ESS to -10 kW, and the load in the microgrid is 12 kW. After grid separation, the ESS's P_{min} is activated and the units transition to the steady-state condition in about 11 seconds. Figure 424 shows the transition for both units on a composite frequency droop curve where it is shown that the actual steady state results agree well with the predicted values.

The ESS's real power graph, Figure 425, shows its P_{min} is activated, i.e. real power output falls below -28 kW A.C. (which corresponds to the P_{min} setting of -25 kW D.C.), until approximately the 0.7 second mark. However, the frequency plot, Figure 435, indicates that P_{min} is only active until the 0.3 second mark. During this time the frequency plot shows a linear increase in frequency at a rate of 4.8 Hz/s to a maximum frequency of 61.6 Hz. The ESS's P_{min} is then released and the system reaches a steady-state frequency of 60.23 Hz at about 11 seconds.

As in Test Event G, during transition to the islanded mode the ESS rejects the majority of the reactive power supplied to the utility again due to its faster response. The reactive load supplied between the two units, shown in Figure 427 and Figure 428, then begins a slow oscillation towards a steady-state condition that is not reached until after the 5 second mark which is the limit of the recorded data for this test event.

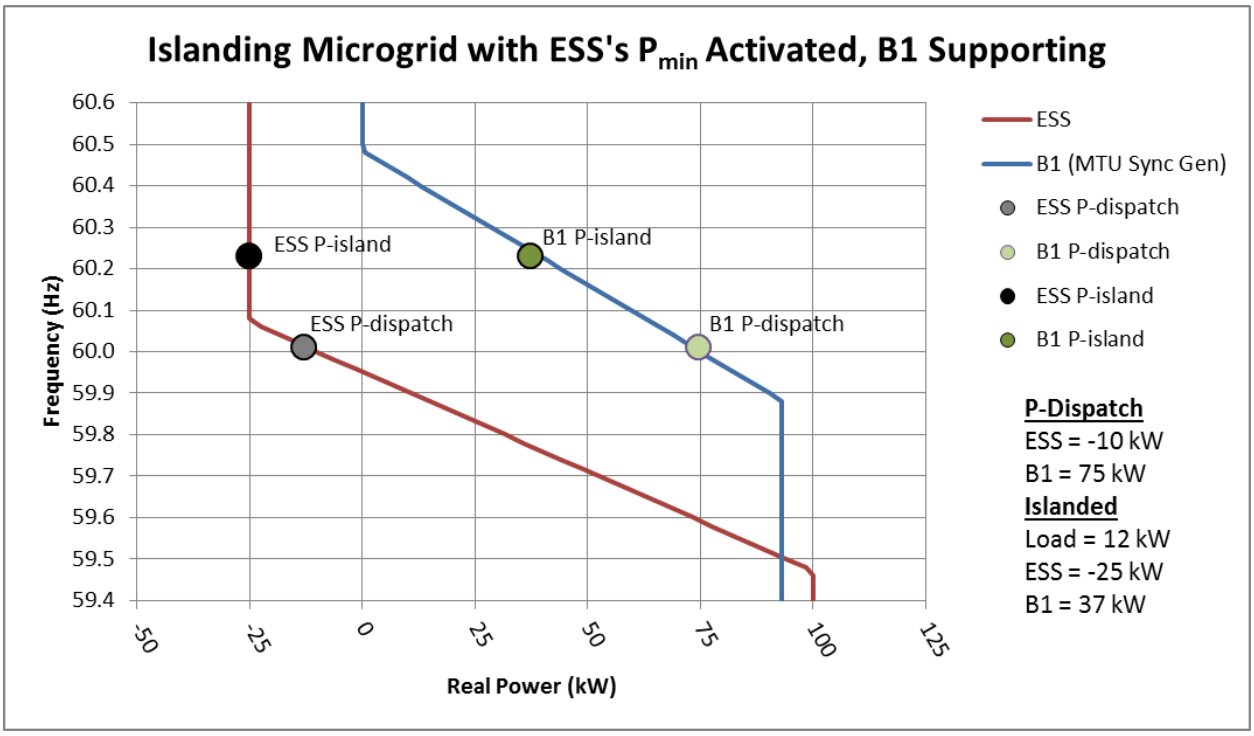

Figure 424: Pmin, Multi-unit, ESS B1, Composite Frequency Droop, Event K

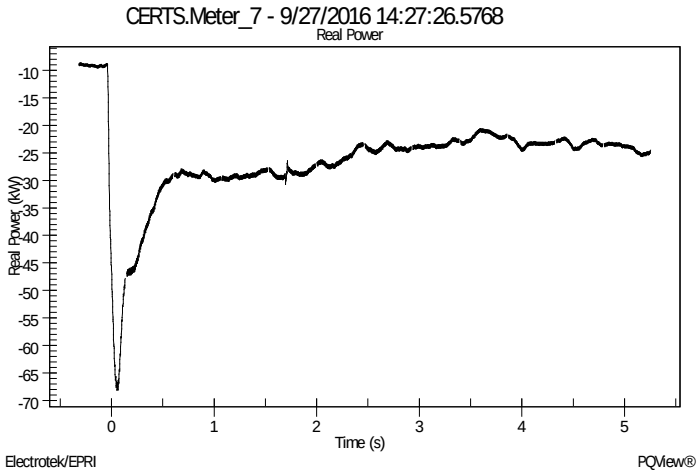

Figure 425: Pmin, Multi-unit, ESS B1, ESS Real Power, Event K

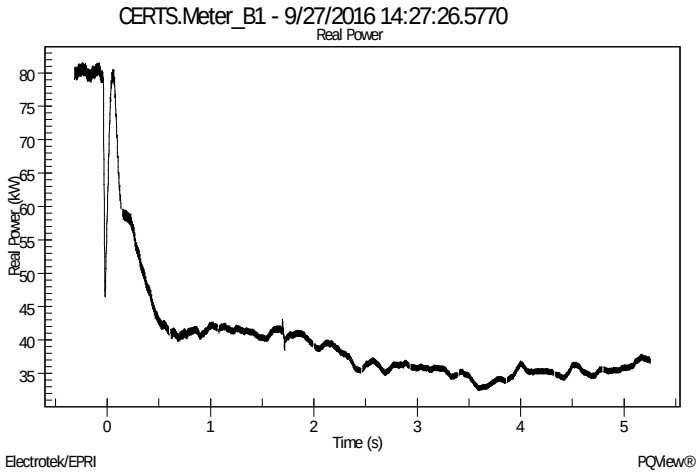

Figure 426: Pmin, Multi-unit, ESS B1, B1 Real Power, Event K

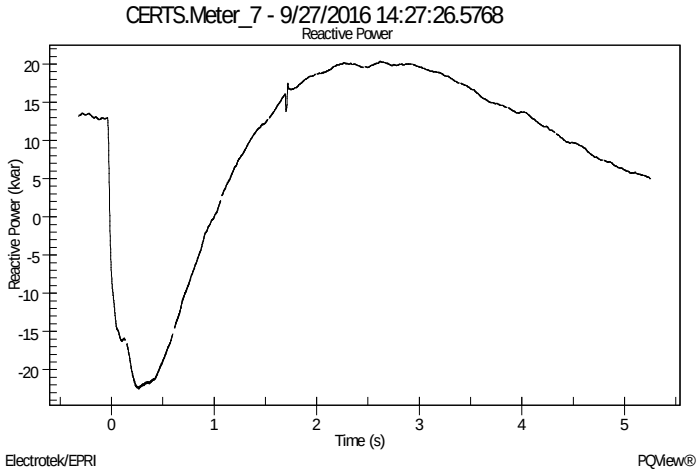

Figure 427: Pmin, Multi-unit, ESS B1, ESS Reactive Power, Event K

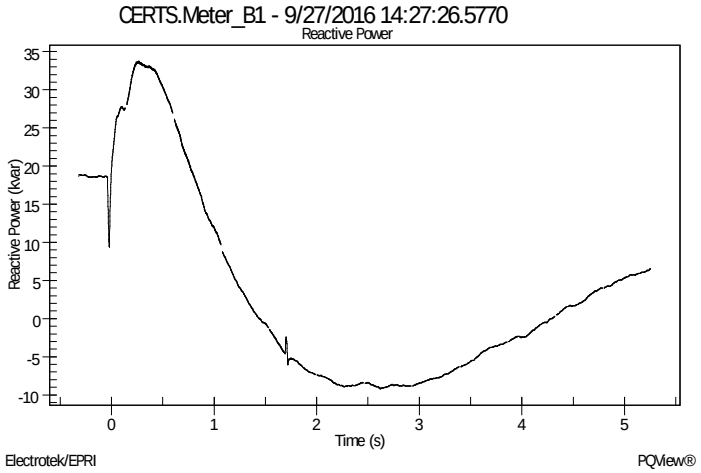

Figure 428: Pmin, Multi-unit, ESS B1, B1 Reactive Power, Event K

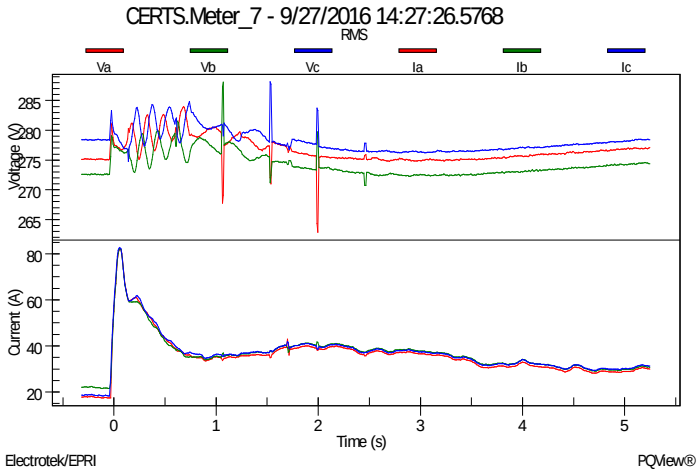

Figure 429: Pmin, Multi-unit, ESS B1, ESS RMS V&I, Event K

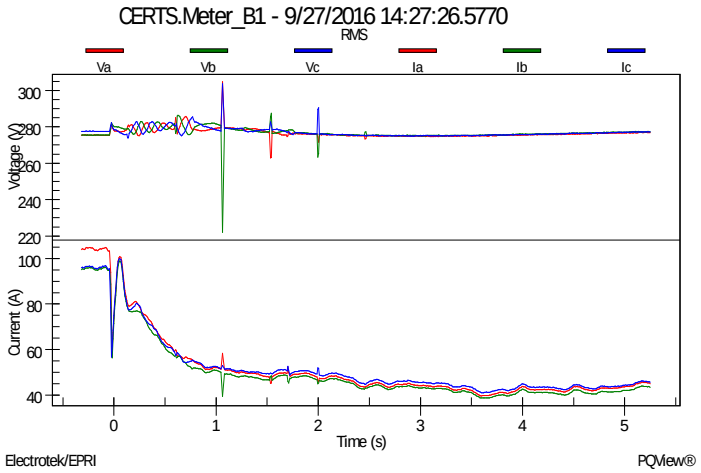

Figure 430: Pmin, Multi-unit, ESS B1, B1 RMS V&I, Event K

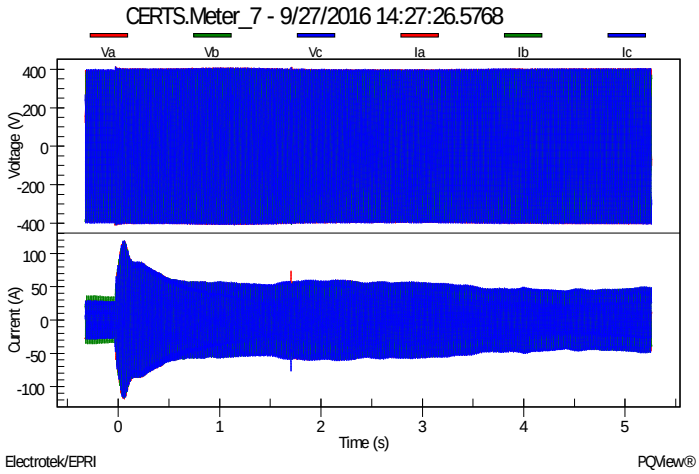

Figure 431: Pmin, Multi-unit, ESS B1, ESS V&I Waveform, Event K

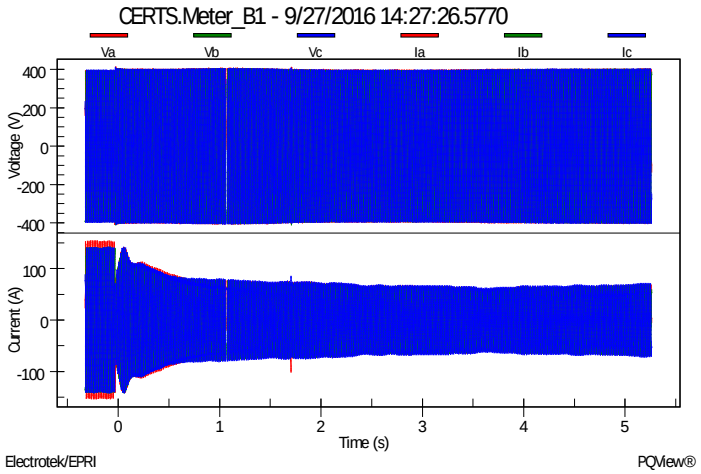

Figure 432: Pmin, Multi-unit, ESS B1, B1 Waveform V&I, Event K

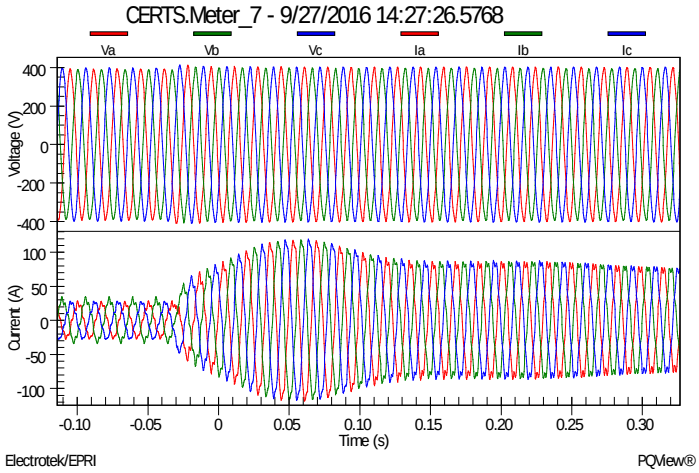

Figure 433: Pmin, Multi-unit, ESS B1, ESS V&I Waveform (Zoomed), Event K

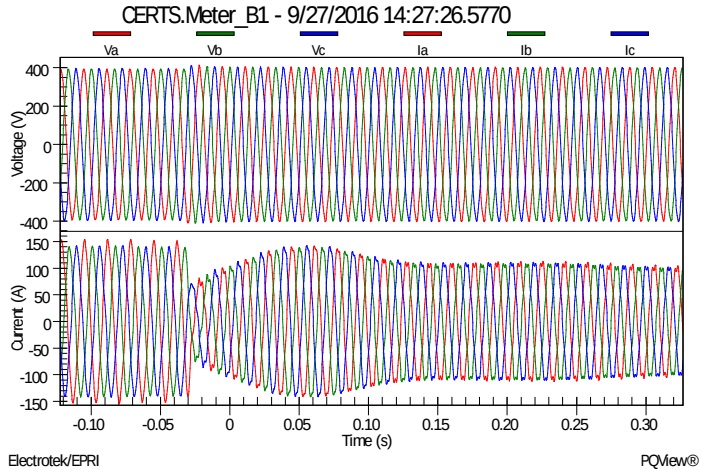

Figure 434: Pmin, Multi-unit, ESS B1, B1 V&I Waveform (Zoomed), Event K

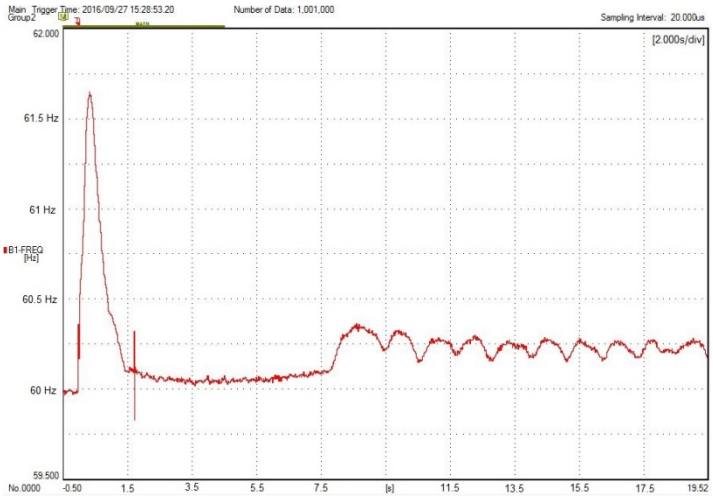

Figure 435: Pmin, Multi-unit, ESS B1, B1 Frequency, Event K

6.0 Conclusions

The ESS performs well in all standalone tests related to the CERTS functionality. There are a couple of issues where the ESS does not behave as anticipated but these are due to operating limits of the inverter and not related to the CERTS algorithm. First, the ESS is not able to handle load rejections larger than 85 kW even though it is rated for 100 kW. The manufacturer was made aware of this finding and a solution would have to be implemented by them. Second, the ESS does not recover from a steady state overload above 105 kW to some value less than 100 kW. This is not a major concern since operating the unit above its rated capability should be avoided to begin with.

For the cases where the ESS is paired with other DERs, either the synchronous generator or the inverter-connected gen-set, the ESS performs well with regards to sharing load with both types of DERs in the microgrid. It also performs well in the P_{max} and P_{min} control tests with the inverter-connected gen-set.

However, there are issues with the P_{max} and P_{min} control tests when the ESS is paired with the synchronous generator. In those cases the ESS responds to the load transition much more quickly than the synchronous generator. During the P_{max} control tests, under certain conditions, the ESS exceeds its capability and trips off. During the P_{min} control tests, the ESS rejects the entire load during transition from grid-connected to islanded mode thus preventing the synchronous generator from activating its P_{min} functionality. However, in this case the microgrid does survive and achieve the expected steady-state conditions.

Overall, the ESS performs well in both the standalone and multiple DER configurations. The conditions identified where survivability could be jeopardized could likely be avoided by proper engineering, design, and operational considerations of the microgrid implementation. In addition, these conditions could also likely be avoided by adjustments to the inverter design and control implementation.