CERTS Microgrid Test Bed

Smart Load Report: Phase 2

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1.0 Introduction

This document is a report on testing conducted regarding Smart Loads with load shedding capability connected to the CERTS Microgrid Test Bed, located at American Electric Power's Walnut Test Site in Groveport, OH. The tests conducted for the CERTS Smart Loads Phase 2 project were designed primarily to examine two areas of interest: 1) could the smart load shedding routine implemented at the test bed be a useful tool for improving the survivability of an overloaded, islanded microgrid; and 2) could envelope of survivability curves be developed for each DER such that load shedding could be used in coordination with standard protective equipment such as fuses and reclosers to avoid the operation of such protective equipment unless absolutely necessary thus avoiding a momentary or permanent outage of critical load.

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/h 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 power and 60 kVAr of reactive (inductive) power. 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 by approximately 10% to 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. Load Bank 5 was also modified during the course of these tests to be a "Smart Load" capable of shedding non-critical load. 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.***

Load Shed Frequency (Hz): A predetermined, measured frequency at which the Load Shedding Time Delay begins. ***Also referred to as "LSF".***

Load Shed Rate (pu/s): A predetermined rate at which non-critical load is shed until the system frequency recovers above the Minimum Bus Frequency. This rate is per unit of dispatched non-critical load and occurs at the smallest load step resolution available by the Smart Load. ***Also referred to as "LSR".***

Load Shed Time Delay (s): A predetermined time delay after the Load Shedding Frequency has been reached which must expire before load shedding occurs. ***Also referred to as "LSTD".***

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.

Minimum Bus Frequency (Hz): The minimum frequency the system bus will experience under all continuously supportable load and dispatch arrangements. For these tests the Minimum Bus Frequency is 59.4 Hz. ***Also referred to as "MBF".***

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 Load Bank 5 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. For this report Load Bank 4 and later Load Bank 5 are Smart Loads 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 Battery Energy Storage System, a CERTS compatible directly coupled synchronous generator, homogenous and heterogeneous 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.

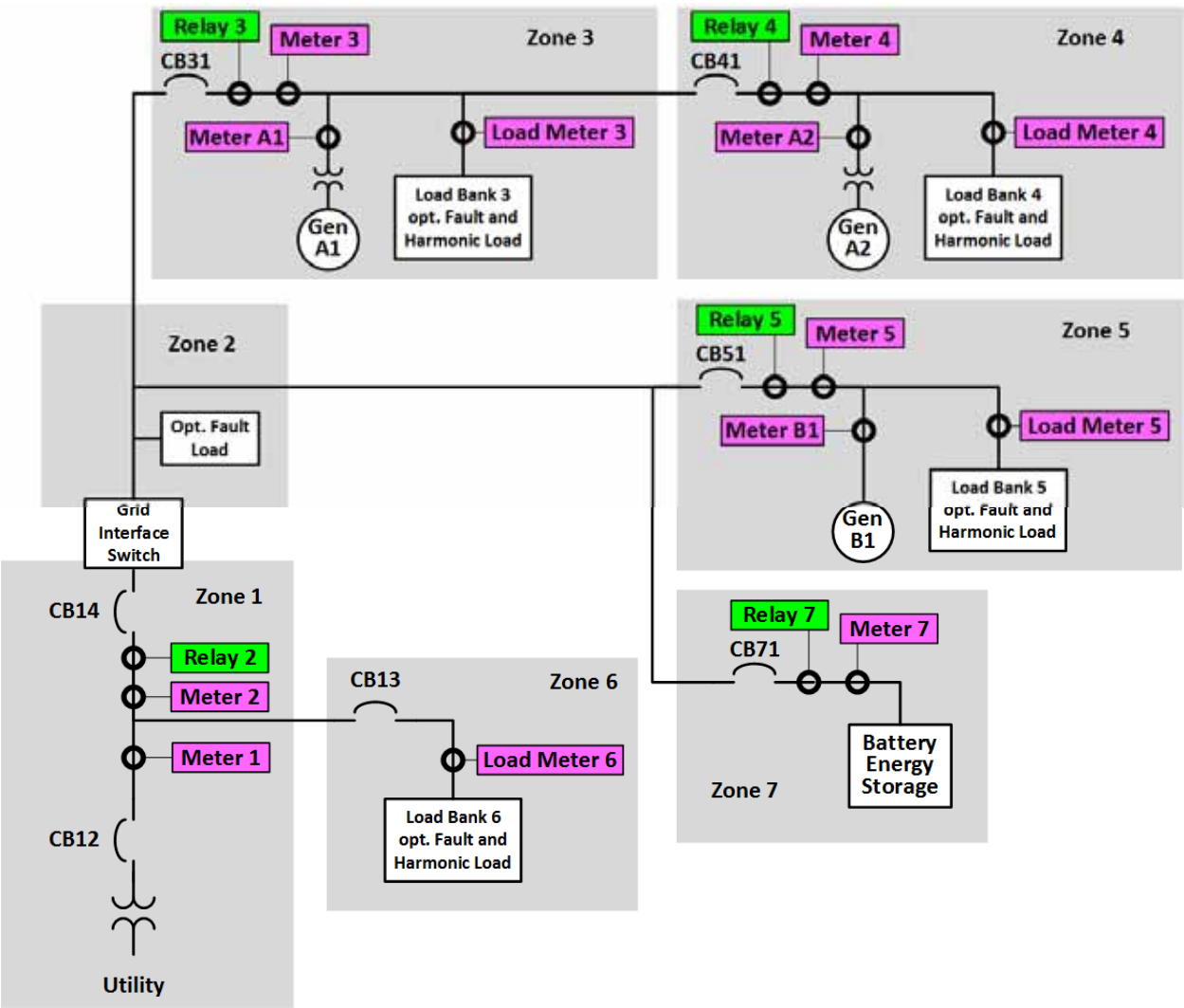

Figure 1: CERTS Microgrid One-line Diagram

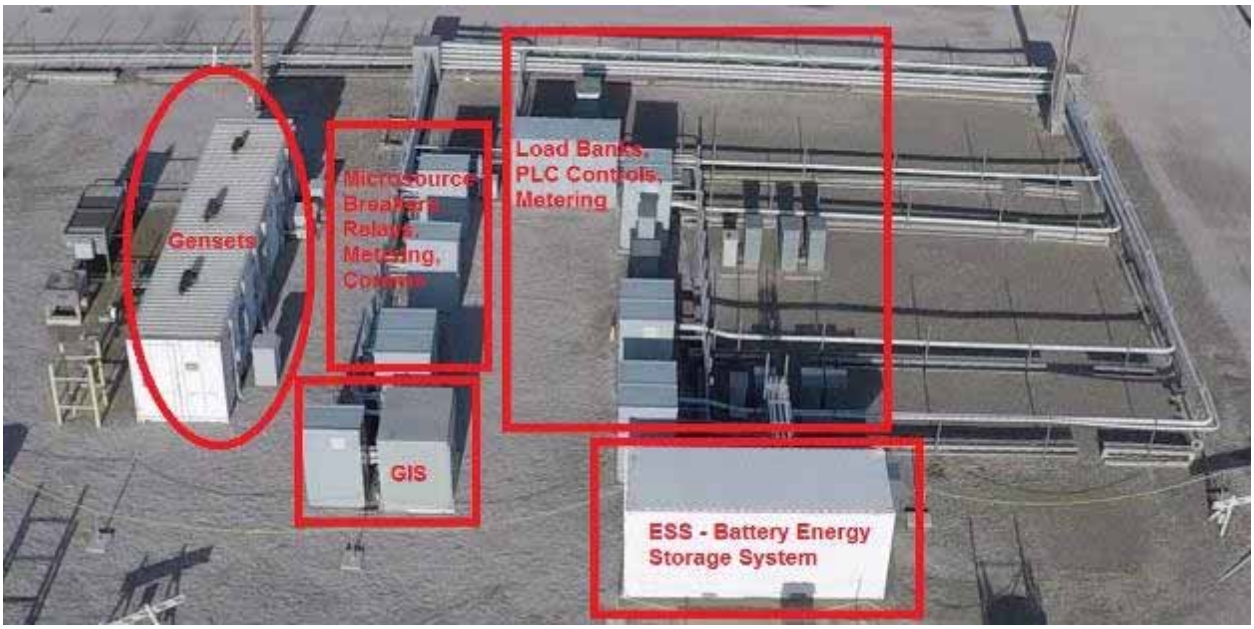

Figure 2: CERTS Microgrid Aerial Photo

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 the islanded microgrid under an overload condition and the ability of smart load devices with load shedding capability to enhance the survivability of the microgrid. The microgrid contains both inverter-connected and synchronous gen-sets with natural gas engine prime movers as well as a battery energy storage system.

The tests conducted for the CERTS Smart Loads Phase 2 project were designed primarily to examine two areas of interest: 1) could the smart load shedding routine implemented at the test bed be a useful tool for improving the survivability of an overloaded, islanded microgrid; and 2) could envelope of survivability curves be developed for each DER such that load shedding could be used in coordination with standard protective equipment such as fuses and reclosers to avoid the operation of such protective equipment unless absolutely necessary thus avoiding a momentary or permanent outage of critical load.

Tests were conducted where an islanded pair of DERs was placed into various overload conditions ranging from mild to severe overloads. Two different pairs of DERs were used for these tests: 1) A1 and B1, an inverter-connected and a synchronous natural gas generator-set, and 2) A1 and A2, both inverter-connected natural gas generator-sets. The load shedding algorithm behaves as expected and operates for all test cases. The time it takes for the load shed algorithm to execute a load shed event ranges from 23 ms to 87 ms which agrees well with the designed range. The microgrid survives all events that it is expected to including the most severe ones where the units are overloaded by at least 40%, the most

that could be applied in the test bed, and then returned to a 95% load condition after the shed event. Given the two different pairs of DERs used in these tests, the load shedding algorithm appears to work well for both a homogenous and heterogeneous set of DERs.

The other area of interest was to determine whether individual DERs have an envelope of survivability such that a smart load could be used to shed load just in time to allow the single DER microgrid to survive. The theory being that the Load Shed Time Delay (LTSD) used to save an overloaded DER would be longer for a unit that is slightly overloaded and would decrease as the unit's overload is increased. Furthermore, that the relationship might be similar to the time-current characteristics curves used in common overcurrent protective devices such as relays, reclosers, and fuses. If this is true, it might be possible to determine a load shedding algorithm for a heterogeneous multi-DER microgrid if the envelope of survivability information is known for each individual DER.

The synchronous gen-set, B1, behaves as expected in that the load shed times are inversely proportional to the load. The LSTD versus percent overload relationship resembles the inverse time-current characteristics curves used in common overcurrent protective devices such as relays, reclosers, and fuses and thus appears to provide the opportunity to coordinate the load shedding characteristics with those protective devices.

The inverter-connected gen-sets, A1 and A2, do not exhibit a clear inverse relationship between the load shed times and the amount of load. This would suggest it would be difficult to coordinate the load shedding characteristics of these DERs with typical protective devices. However, as described in this report, there are some adjustments that could be made to A1 or the load shedding scheme that might allow A1 to be compatible with a protection scheme. A2 suffers from a design constraint that further limits its ability to respond similar to B1, namely that it is programmed not to allow its frequency to go below 59 Hz. If this were changed, it would likely behave similarly to A1.

The Battery Energy Storage System does not exhibit the ability to be saved by load shedding. It has the ability to continuously serve load up to approximately 110% of its 100 kW rating. Above 110% the unit will trip faster than a load shed event can save it.

It was shown that the three gen-sets, A1, A2, and B1, do not share similar load shed time saving characteristics. The inverter-connected units, A1 and A2, have little to no ability to be saved by a load shedding time delay scheme. Any mixed DER system based on these three units would have to effectively use a Load Shed Time Delay of 0 ms.

While these tests explored the envelope of survivability of each individual DER, other factors need to be taken into consideration when using load shedding as an option to increase the survivability of the microgrid. In these cases significant power quality issues were observed in some cases, such as severe voltage depressions, as much as 48%, and frequency excursions down to 27 Hz. For many applications this level of power quality would be unacceptable and alternative methods would be required.

5.0 Load Shedding Background

5.1 Load Shedding Technique

The load shedding function operates by identifying load as either critical or non-critical and allows shedding of the non-critical load when certain criteria are met. This non-critical load shed occurs in response to system overload as determined by the system frequency in an effort to sustain the critical load. The criteria which govern its function are:

- Load Shedding Frequency (Hz) - A predetermined, measured frequency at which the Load Shedding Time Delay begins.
- Load Shedding Time Delay (s) - A predetermined time delay after the Load Shedding Frequency has been reached which must expire before load shedding occurs.
- Load Shedding Rate (pu/s) - A predetermined rate at which non-critical load is shed until the system frequency recovers above the Minimum Bus Frequency. This rate is per unit of dispatched non-critical load and occurs at the smallest load step resolution available by the Smart Load.
- Minimum Bus Frequency (Hz) - The minimum frequency the system bus will experience under all continuously supportable load and dispatch arrangements. For these tests the Minimum Bus Frequency is 59.4 Hz.

Under normal conditions, the microgrid will operate conventionally in that it will support the full amount of both the critical and non-critical load. When a DER becomes overloaded, its P_{max} controller begins to lower the system frequency in an effort to recruit support from other DER units. If all DERs become overloaded the bus frequency will continue to fall until the sources and loads are brought into balance or the microgrid collapses. If the system frequency falls below that of the Load Shedding Frequency for a time equal to the Load Shedding Time Delay, the load shedding process is initiated. Once initiated, the non-critical load is shed at the prescribed Load Shedding Rate. The load shedding process will continue until the system frequency is equal to or greater than the Minimum Bus Frequency. The load remains shed until reset through an energy management system or manual intervention. Future efforts could establish an automatic method for return of load.

5.2 Load Shedding Settings Selection Method

The microgrid sources were configured so that the lowest continuously sustainable frequency is 59.4 Hz, the Minimum Bus Frequency. For this testing, it is assumed that steady state frequencies below 59.4 Hz communicate that the microgrid bus is overloaded. The Load Shedding Frequency is therefore always set below 59.4 Hz. DER A2 was determined to have a lower frequency limit of 59.0 Hz hard coded into its controller which couldn't be changed. Use of a Load Shedding Frequency at or below 59.0 Hz for tests involving A2 is not practical. Therefore a Load Shedding Frequency of 59.2 Hz was used for many of these tests. The exception being multi-unit tests that did not involve A2 for which the Load Shedding Frequency is set to 59.0 Hz.

The Load Shedding Rate is set to the maximum allowed for all tests. This has the effect of shedding the entire non-critical load in one block. Initially the load shedding algorithm had a maximum Load Shedding Rate of 5 pu/s. This was later updated to 100 pu/s because the load shedding algorithm itself was improved and sped up. In both cases this resulted in shedding the entire load as one block.

The Load Shedding Time Delay (LSTD) is set depending on the purpose of the test being performed. In the case where multiple DERs are serving the islanded microgrid and the system is overloaded, the LSTD is set to 0 seconds. For these tests it was desired to observe the transient behavior of the system and determine whether it was possible for load shedding to prevent collapse of the microgrid. In the case of an individual DER serving an islanded microgrid the intent was to determine an envelope of survivability of each source. In these cases the LSTD was gradually increased for each overload amount to determine the maximum LSTD that would result in the microgrid surviving. The hypothesis being that system protection could be designed in such a way as to coordinate with the envelope of survivability of a DER or the combination of DERs in a system.

6.0 Test Results

6.1 Microgrid Survivability Using Original Load Shed Algorithm

Performance Goal

Determine whether the existing load shedding algorithm is able to extend grid survivability in an islanded scenario with three DERs active in the microgrid with a subsequent loss of one DER which results in the two surviving DERs becoming overloaded. In this scenario, the question essentially is whether the load shedding algorithm is fast enough to avoid collapse of the microgrid. The existing algorithm was developed circa 2012, approximately 5 years ago.

Determine the speed of the existing algorithm.

Description of Procedure

Three DERs, A1, B1, and the ESS, will operate as an island. They will be configured and dispatched according to the values listed in the Test Settings section below. They will serve load from Load Banks 3, 4, and 5 also configured as listed in the Test Settings section below. Initially the load is chosen to match the total real power dispatch values of the three DERs so that the islanded microgrid should have a frequency of approximately 60 Hz. Smart Load Bank 4 is set to shed its entire non-critical load at a frequency of 59 Hz with no intentional time delay. The amount of load shed is designed to bring the remaining (critical) load to a value less than the remaining source capabilities thus making it theoretically possible for the microgrid to survive the test event. Test Events E & F are an exception to this in that the load should exceed the capabilities of the remaining sources and result in the collapse of the microgrid.

The ESS will be turned off to simulate a loss of a source. The two remaining sources will become overloaded thus engaging their P_{max} controls which will drive the microgrid frequency down. The non-

critical load will shed from LB4. The data acquisition system will record the event based on the trigger of the loss of the ESS.

Test Settings

For these tests the parameters are set as follows:

<u>ESS</u>

Pdispatch = Varies
Frequency Droop = 1%
Real Power-Frequency Droop = -.004 Hz/kW
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)
Voltage Set Point = 480 V_{LL} (Inverter Voltage Reference = 102.2)
Voltage Droop = -0.24 V_{LL}/kVAr (5%)

<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 = -0.01 V_{LN}/kVAr (12% is minimum attainable due to improper voltage control)

<u>B1 (Sync Gen)</u>

Pdispatch = 90 kW
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%)

<u>Load Bank 4 – Load Shedding</u>

Non-critical (Shedable) Load = Varies (65 kW or 90 kW)
Load Shedding Frequency = 59 Hz
Load Shedding Time Delay = 0 s
Load Shedding Rate = 5 pu/s
Effect is all load will be shed as one block when system frequency drops below 59 Hz with no intended time delay.

During each sequence of tests in Table 1, a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers “Closed”; the microgrid is islanded with the GIS open; load banks are

set as close as possible to the prescribed values; reactive load is set to 0 kVAr; and events are triggered based on the transition of the ESS to off.

Test Event	Gen A1 Pdisp (kW)	Gen B1 Pdisp (kW)	ESS Pdisp (kW)	Load Bank 3 (kW)	Load Bank 5 (kW)	SMART Load 4	
						Critical Load (kW)	Non-Critical Load (kW)
A	75	90	55	95	60	0	65
B	80	90	60	95	70	0	65
C	80	90	70	95	80	0	65
D	80	90	80	95	90	0	65
E	80	90	90	95	95	5	65
F	80	90	100	95	95	15	65
G	80	90	100	95	85	0	90

Table 1: Original Load Shed Algorithm – Microgrid Survivability Test Plan

Test Events A through D are designed to place an increasing overload condition on the two surviving DERs, A1 and B1, before shedding 65 kW of load thus reducing the total load below the 193 kW capability of A1 and B1 combined. Test Event A starts by placing a total of 220 kW (a 27 kW overload) on the combination of A1 and B1 then sheds 65 kW reducing the total load to 155 kW. Test Event D takes this to a total of 250 kW (a 57 kW overload) on the combination of A1 and B1 then sheds 65 kW reducing the total load to 185 kW.

Test Events E and F continue increasing the overload on A1 and B1 but the load shed of 65 kW reduces the total load remaining to 195 kW and 205 kW respectively which is greater than the 193 kW capability of the two units combined.

Finally, Test Event G places 270 kW (a 77 kW overload) on the combination of A1 and B1 then sheds 90 kW reducing the total load to 180 kW.

Test Results

Table 2 below summarizes the results of the microgrid survivability tests using the original load shed algorithm.

Test Event	Real Power (Pre-Event) (kW)				Real Power (Post-Event) (kW)						Load Meter 4 Real Power		Frequency (Hz)			Time (s)			Pass/ Fail
	Genset A1	Genset B1	ESS	Total	Genset A1 Expected	Genset A1 Actual	Genset B1 Expected	Genset B1 Actual	ESS	Total	Pre-event	Post-event	Pre-event	Minimum Pre-shed	Post-event	Event to < 59 Hz	< 59 Hz to Load Shed	Event to Load Shed	
A	72.4	92.3	58.0	222.8	69.5	99.6	84.9	54.8	0.0	154.4	80.6	16.7	60.00	58.50	59.58	0.460	**0.306**	0.766	Pass
B	79.2	86.8	66.9	232.8	76.4	93.0	91.3	74.8	0.0	167.8	79.7	16.8	59.96	58.00	59.91	0.262	**0.376**	0.638	Pass
C1	76.8	93.6	73.1	243.5		0.0		0.0	0.0	0.0	83.0	0.0	60.00	58.08	0.00	0.236	**0.497**	0.733	Fail
C2	77.8	92.6	69.4	239.8		0.0		0.0	0.0	0.0	83.6	0.0	59.99	58.17	0.00	0.239	**0.479**	0.718	Fail

Note: Gensets A1 and B1 did settle to their expected values within approximately 20 seconds after the event.

Table 2: Original Load Shed Algorithm – Microgrid Survivability Test Results

Analysis

The microgrid survives the more mild overloads in Test Events A and B by returning to their expected steady-state conditions within 20 seconds of the beginning of the event. Test Event C is attempted twice with both resulting in the collapse of the microgrid. Additional events are not attempted.

Test Event A places a 30 kW overload on A1 and B1 (combined capability of 193 kW). The system takes 460 ms to reach the LSF of 59.0 Hz. There is a 306 ms time delay from reaching the LSF until the load shed occurs. This is the time it takes the system to detect and respond to the LSF. During this time the system reaches a minimum frequency of 58.50 Hz. Once the load is shed the system returns to a steady-state condition serving 154 kW or 80% of its capability.

Test Event B places a 40 kW overload on A1 and B1. The system takes 262 ms to reach the LSF of 59.0 Hz. There is a 376 ms time delay from reaching the LSF until the load shed occurs. During this time the system reaches a minimum frequency of 58.00 Hz. Once the load is shed the system returns to a steady-state condition serving 168 kW or 87% of its capability.

Test Event C1 places a 50 kW overload on A1 and B1. The system takes 236 ms to reach the LSF of 59.0 Hz. There is a 497 ms time delay from reaching the LSF until the load shed occurs. During this time the system reaches a minimum frequency of 58.08 Hz. The load shed in this case is not sufficient to save the microgrid and it collapses.

In Table 2 it is shown that for these four events there is a time delay from the time the load shed frequency of 59.0 Hz is reached until the load shed occurs which ranges from 306 ms to 497 ms. This experimental data agrees well with the expected time delay of 300 ms to 500 ms based upon the algorithm in use. The team believed that this algorithmic load shed time delay was too long for system survivability when more severe overloads are encountered. It was decided to improve the load shedding algorithm by decreasing this time delay.

First, the results of Test Events A and C1 will be presented.

Figure 3 shows Test Events A's real power graphs for DERs A1, B1, and the ESS along with smart load LB4. Also included is the microgrid frequency on the secondary axis. At t=0 s the ESS is shut off placing a 30 kW overload on A1 and B1 whose combined capability is 193 kW. The system takes 460 ms to reach the LSF of 59.0 Hz. At t = 766 ms, 306 ms after reaching the LSF, LB4 sheds 63.9 kW. This is the time it takes the system to detect and respond to the LSF. During this time the system reaches a minimum frequency of 58.50 Hz. Once the load is shed the system returns to a steady-state condition serving 154.4 kW or 80% of its capability. It should be noted that A1 is dispatched to 75 kW and B1 to 90 kW thus B1 should be supplying more power than A1. The system does settle to the expected steady-state values at approximately t = 20 s.

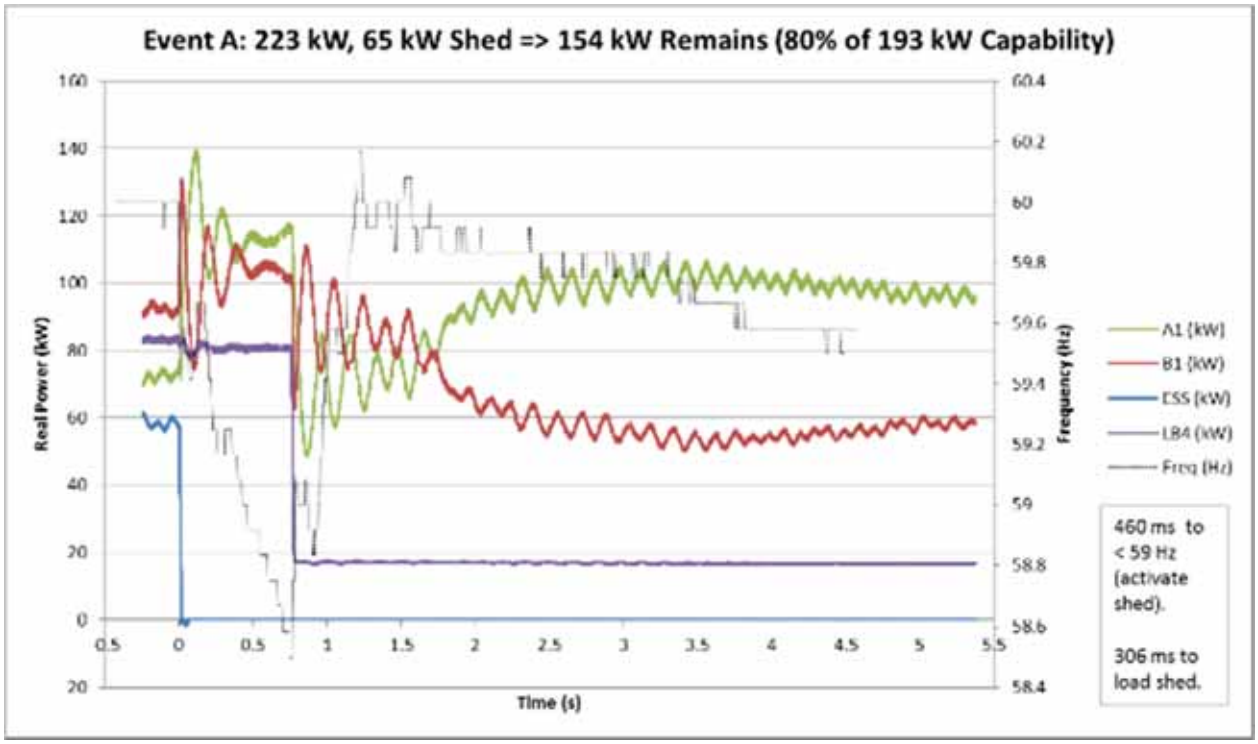

Figure 3: Original Load Shed Algorithm – Microgrid Survivability Test Event A Graph, Real Power and Frequency

Figure 4 shows Test Events C1's real and reactive power graphs for DERs A1, B1, and the ESS along with the real power for smart load LB4. Also included is the microgrid frequency on the secondary axis. At t=0 s the ESS is shut off placing a 51 kW overload on A1 and B1 whose combined capability is 193 kW. The system takes 236 ms to reach the LSF of 59.0 Hz. At t = 733 ms, after a 497 ms time delay from reaching the LSF, LB4 sheds 65 kW. This is the time it takes the system to detect and respond to the LSF. During this time the system reaches a minimum frequency of 58.08 Hz. Also during this time B1 is sourcing an increasing amount of reactive power to A1. It is believed (and later shown) that A1's dc bus voltage is collapsing. Once the load is shed the system's real and reactive power return to nominal, expected values but this is short lived. The voltage continues to decline, presumably due to A1's inability to restore its dc bus voltage, resulting in a runaway flow of reactive power from B1 to A1. This results in A1 tripping due to a SKiiP error condition followed by B1 stalling and the collapse of the microgrid.

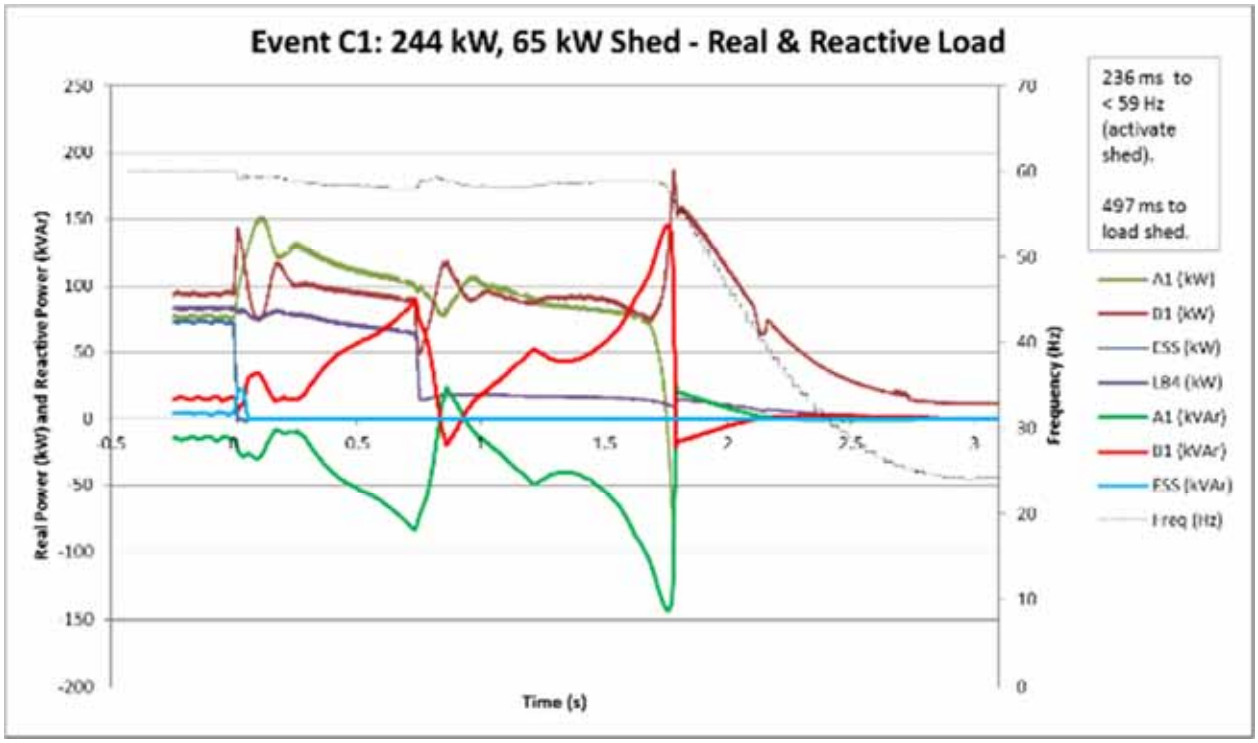

Figure 4: Original Load Shed Algorithm – Microgrid Survivability Test Event C1 Graph, Real and Reactive Power and Frequency

Figure 5 through Figure 10 show the voltage and current graphs for Test Event C1 for DERs A1 and B1.

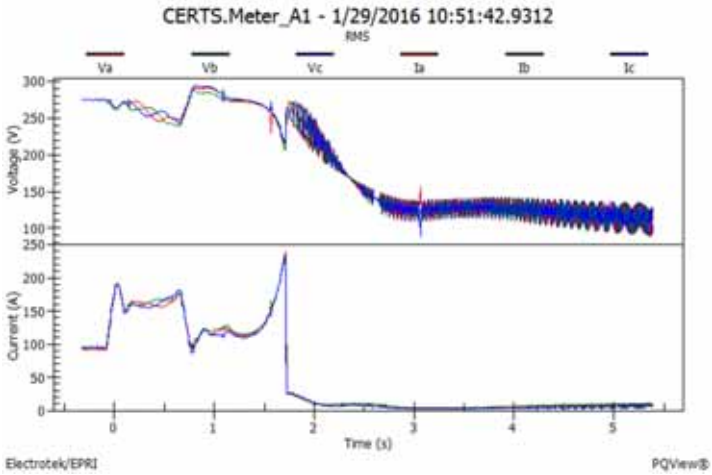

Figure 5: Original Load Shed Algorithm – Microgrid Survivability Test Event C1 Graph, A1's RMS Voltage and Current

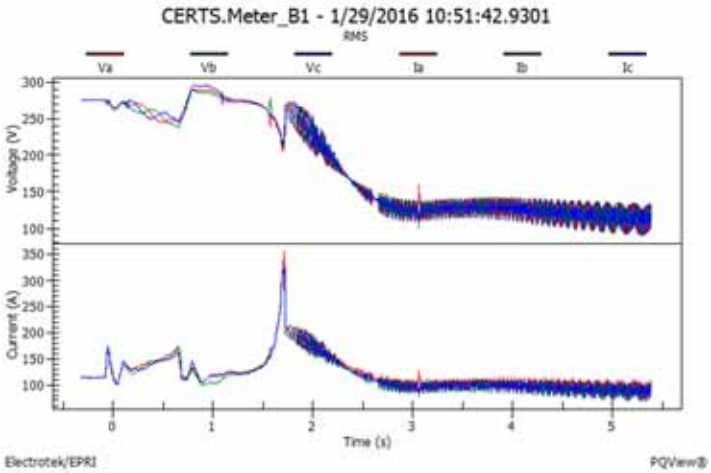

Figure 6: Original Load Shed Algorithm – Microgrid Survivability Test Event C1 Graph, B1's RMS Voltage and Current

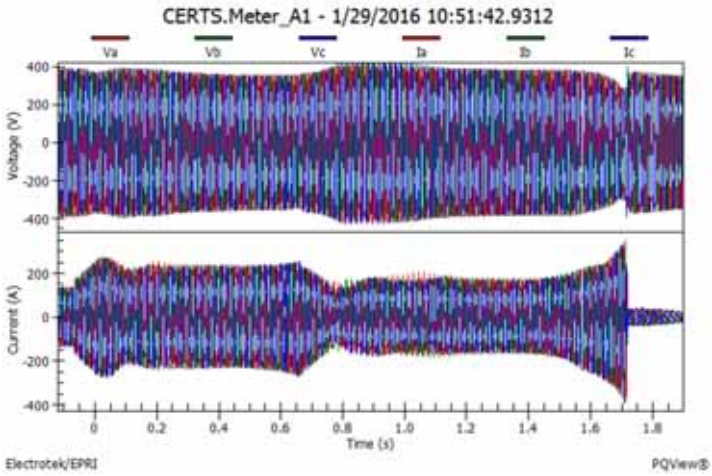

Figure 7: Original Load Shed Algorithm – Microgrid Survivability Test Event C1 Graph, A1's RMS Voltage and Current Waveforms (Zoomed)

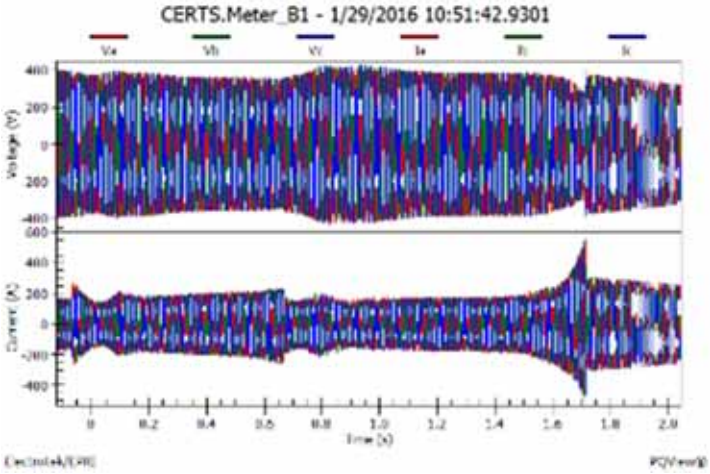

Figure 8: Original Load Shed Algorithm – Microgrid Survivability Test Event C1 Graph, B1's RMS Voltage and Current Waveforms (Zoomed)

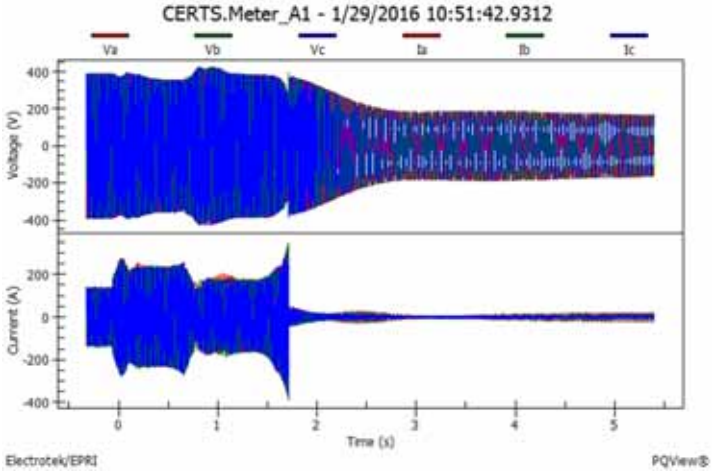

Figure 9: Original Load Shed Algorithm – Microgrid Survivability Test Event C1 Graph, A1's RMS Voltage and Current Waveforms

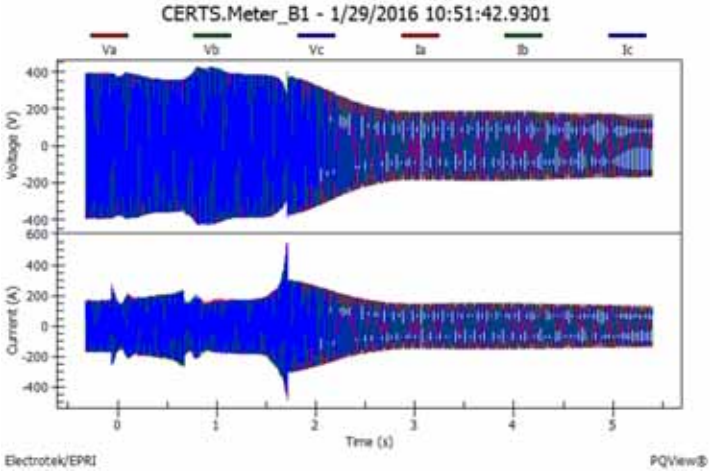

Figure 10: Original Load Shed Algorithm – Microgrid Survivability Test Event C1 Graph, B1's RMS Voltage and Current Waveforms

6.2 Improving the Load Shed Algorithm

Performance Goal

The original algorithm's Load Shed Time Delay was determined to be between 300 ms and 500 ms. This LSTD is too long for load shedding to be effective in providing survivability under at least some overload conditions. The team set a goal of reducing the LSTD to less than 100 ms.

Description of Procedure

This set of tests will be conducted in a three step process. First, Test Event A from the previous section will be performed ten times to obtain some statistics on the behavior of the original load shedding algorithm including average, minimum, and maximum LSTD for the dataset. Second, the load shedding algorithm will be modified with the goal of getting the maximum LSTD to be less than 100 ms. Third, Test Event A will again be performed ten times with the new algorithm to determine if it meets the 100 ms criteria.

Test Settings

For these tests the parameters are set as follows:

<u>ESS</u>

Pdispatch = 55 kW

Frequency Droop = 1%

Real Power-Frequency Droop = -.004 Hz/kW

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)

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

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

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

Pdispatch = 75 kW

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 = -0.01 V_{LN}/kVAr (12% is minimum attainable due to improper voltage control)

<u>B1 (Sync Gen)</u>

Pdispatch = 90 kW

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%)

<u>Load Bank 4 – Load Shedding</u>

Non-critical (Shedable) Load = 65 kW

Load Shedding Frequency = 59.3 Hz during original load shed algorithm; 59.0 Hz for new algorithm. The difference in the LSF is immaterial to these tests since the data of interest is the time from reaching the LSF to actual load shed.

Load Shedding Time Delay = 0 s

Load Shedding Rate = 5 pu/s during original load shed algorithm; 100 pu/s for new algorithm. Effect is all load will be shed as one block when system frequency drops below the load shed frequency (59.3 Hz or 59.0 Hz) with no intended time delay.

During each sequence of tests in Table 3: Load Shed Algorithm Response Time Test Plan, a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers "Closed"; the microgrid is islanded with the GIS open; load banks are set as close as possible to the prescribed values; reactive load is set to 0 kVAr; and events are triggered based on the transition of the ESS to off.

Test Event	Gen A1 Pdisp (kW)	Gen B1 Pdisp (kW)	ESS Pdisp (kW)	Load Bank 3 (kW)	Load Bank 5 (kW)	SMART Load 4	
						Critical Load (kW)	Non-Critical Load (kW)
A	75	90	55	95	60	0	65

Table 3: Load Shed Algorithm Response Time Test Plan

Test Event A is designed to place an overload condition on the two surviving DERs, A1 and B1, before shedding 65 kW of load thus reducing the total load below the 193 kW capability of A1 and B1 combined. Test Event A places a total of 220 kW (a 27 kW overload) on the combination of A1 and B1 then sheds 65 kW reducing the total load to 155 kW.

Test Results

Table 4 below summarizes the results for ten repetitions of Event A using the original load shed algorithm.

Original Load Shedding Algorithm - Response Time Evaluation							
Test Event	Frequency (Hz)			Time (s)			Pass/ Fail
	Pre-event	Minimum Pre-shed	Post-event	Event to < 59.3 Hz	< 59.3 Hz to Load Shed	Event to Load Shed	
A1	59.97	58.25	60.00	0.203	0.391	0.594	**Pass**
A2	59.99	58.50	59.99	0.218	0.339	0.557	**Pass**
A3	59.96	58.17	60.00	0.212	0.494	0.706	**Pass**
A4	60.00	58.25	60.00	0.226	0.391	0.617	**Pass**
A5	59.96	58.42	60.00	0.198	0.357	0.555	**Pass**
A6	59.99	58.42	59.99	0.231	0.340	0.571	**Pass**
A7	59.99	58.33	60.01	0.214	0.425	0.639	**Pass**
A8	59.98	58.25	60.00	0.218	0.391	0.609	**Pass**
A9	59.98	58.42	60.01	0.219	0.323	0.542	**Pass**
A10	60.00	58.42	59.92	0.223	0.322	0.545	**Pass**
Avg		**58.34**		**0.216**	**0.377**	0.594	
Min		58.17		0.198	**0.322**	0.542	
Max		58.50		0.231	**0.494**	0.706	
Range		0.33		0.033	**0.172**	0.164	

Table 4: Original Load Shed Algorithm Response Time Test Results

Table 5 below summarizes the results for ten repetitions of Event A using the improved load shed algorithm.

Improved Load Shedding Algorithm - Response Time Evaluation							
Test Event	Frequency (Hz) (at B1)			Time (s)			Pass/Fail
	Pre-event	Minimum Pre-shed	Post-event	Event to < 59.0 Hz	< 59.0 Hz to Load Shed	Event to Load Shed	
A1	59.98	58.94	59.99	0.410	0.057	0.467	Pass
A2	59.99	58.88	60.03	0.403	0.081	0.484	Pass
A3	59.98	58.93	59.95	0.445	0.059	0.504	Pass
A4	59.98	58.97	59.99	0.444	0.064	0.508	Pass
A5	59.99	58.92	60.02	0.430	0.044	0.474	Pass
A6	59.98	58.95	59.97	0.437	0.061	0.498	Pass
A7	59.97	58.76	60.03	0.395	0.107	0.502	Pass
A8	59.99	58.90	59.97	0.413	0.072	0.485	Pass
A9	59.99	58.95	59.99	0.455	0.050	0.505	Pass
A10	59.99	58.96	60.03	0.440	0.051	0.491	Pass
Avg	59.98	**58.92**	60.00	**0.427**	**0.065**	0.492	
Min	59.97	58.76	59.95	0.395	**0.044**	0.467	
Max	59.99	58.97	60.03	0.455	**0.107**	0.508	
Range	0.03	0.21	0.08	0.060	**0.063**	0.041	

Table 5: Improved Load Shed Algorithm Response Time Test Results

Analysis

The original load shedding algorithm was calculated to have an execution time of between 300 ms and 500 ms based on the code used in the load bank's controller. Results from repeating Test Event A ten times, shown in Table 4, demonstrated a minimum execution time of 322 ms and a maximum time of 494 ms. Looking back at the tests in Section 6.1 and results in Table 2 a minimum execution time of 306 ms and a maximum time of 497 ms is found. These results agree well with the expected execution time.

The load shedding algorithm was improved with the desire to have the execution time be less than 100 ms. The new code is anticipated to provide an execution time between 25 ms and 84 ms. The results of executing Test Event A ten times using the improved algorithm is shown in Table 5. In these tests the minimum execution time experienced is 44 ms and the maximum is 107 ms. From this data there was only one time that exceeded the expected maximum of 84 ms. There could be at least a couple of reasons why this occurred. First, the estimate is not correct and there could be an additional delay in the load shedding code that is not apparent. Second, the frequency measurement for the load shedding routine is taking place locally at the load bank, Load Bank 4 in this case. The frequency measurement used in the tabular data is from a meter located at B1. Since A1 and B1 are both overloaded, their P_{max} functionality is activated and they are independently driving the frequency down to recruit relief from other DER sources which don't exist in this case. It's possible that the frequency measured at the terminals of B1 is slightly different from the frequency seen at Load Bank 4 and that had the measurements been made at Load Bank 4 the result may have been within the expected 84 ms.

Even though there was one load shed event whose execution took longer than the goal of 100 ms, the team felt that the new load shedding algorithm was sufficiently fast to move forward with the desired survivability tests.

6.3 Microgrid Survivability Using Improved Load Shed Algorithm with A1 and B1 as Surviving Units

Performance Goal

Determine whether the improved load shedding algorithm is able to enhance microgrid survivability in an islanded scenario with three DERs active in the microgrid with a subsequent loss of one DER which results in the two surviving DERs becoming overloaded. In this scenario, the question essentially is whether the load shedding algorithm is fast enough to avoid collapse of the microgrid.

Description of Procedure

Three DERs, A1, B1, and the ESS, will operate as an island. They will be configured and dispatched according to the values listed in the Test Settings section below. They will serve load from Load Banks 3, 4, and 5 also configured as listed in the Test Settings section below. Initially the load is chosen to match the total real power dispatch values of the three DERs so that the islanded microgrid should have a frequency of approximately 60 Hz. Smart Load Bank 4 is set to shed its entire non-critical load at a frequency of 59 Hz with no intentional time delay. The amount of load shed is designed to bring the remaining (critical) load to a value less than the remaining source capabilities thus making it theoretically possible for the microgrid to survive the test event. Test Events E & F are an exception to this in that the load should exceed the capabilities of the remaining sources and result in the collapse of the microgrid.

The ESS will be turned off to simulate a loss of a source. The two remaining sources will become overloaded thus engaging their P_{max} controls which will drive the microgrid frequency down. The non-critical load will shed from LB4. The data acquisition system will record the event based on the trigger of the loss of the ESS.

Test Settings

For these tests the parameters are set as follows:

<u>ESS</u>

Pdispatch = Varies

Frequency Droop = 1%

Real Power-Frequency Droop = -.004 Hz/kW

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)

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

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

A1 (InVerde 100)
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 = -0.01 V_{LN}/kVAr (12% is minimum attainable due to improper voltage control)

B1 (Sync Gen)
Pdispatch = 90 kW
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%)

Load Bank 4 – Load Shedding
Non-critical (Shedable) Load = Varies (65 kW or 90 kW)
Load Shedding Frequency = 59 Hz
Load Shedding Time Delay = 0 s
Load Shedding Rate = 100 pu/s
Effect is all load will be shed as one block when system frequency drops below 59 Hz with no intended time delay.

During each sequence of tests in Table 6, a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers "Closed"; the microgrid is islanded with the GIS open; load banks are set as close as possible to the prescribed values; reactive load is set to 0 kVAr; and events are triggered based on the transition of the ESS to off.

Test Event	Gen A1 Pdisp (kW)	Gen B1 Pdisp (kW)	ESS Pdisp (kW)	Load Bank 3 (kW)	Load Bank 5 (kW)	SMART Load 4	
						Critical Load (kW)	Non-Critical Load (kW)
A	75	90	55	95	60	0	65
B	80	90	60	95	70	0	65
C	80	90	70	95	80	0	65
D	80	90	80	95	90	0	65
E	80	90	90	95	95	5	65
F	80	90	100	95	95	15	65
G	80	90	100	95	85	0	90

Table 6: Improved Load Shed Algorithm – Microgrid Survivability Test Plan for A1 & B1

Test Events A through D are designed to place an increasing overload condition on the two surviving DERs, A1 and B1, before shedding 65 kW of load thus reducing the total load below the 193 kW capability of A1 and B1 combined. Test Event A starts by placing a total of 220 kW (a 27 kW overload) on the combination of A1 and B1 then sheds 65 kW reducing the total load to 155 kW. Test Event D takes this to a total of 250 kW (a 57 kW overload) on the combination of A1 and B1 then sheds 65 kW reducing the total load to 185 kW.

Test Events E and F continue increasing the overload on A1 and B1 but the load shed of 65 kW reduces the total load remaining to 195 kW and 205 kW respectively which is greater than the 193 kW combined capability of the two units. In these two cases the microgrid is expected to collapse.

Finally, Test Event G places 270 kW (a 77 kW overload) on the combination of A1 and B1 then sheds 90 kW reducing the total load to 180 kW.

Test Results

Table 7 below summarizes the results of using the improved load shedding algorithm to enhance microgrid survivability in an islanded scenario with three DERs (A1, B1, and ESS) active in the microgrid and a subsequent loss of one DER (ESS) which results in the two surviving DERs becoming overloaded.

Test Event	Real Power (Pre-Event) (kW)				Real Power (Post-Event) (kW)				Load Meter 4 Real Power (kW)		Frequency (Hz)			Time (s)			Pass/Fail
	Genset A1	Genset B1	ESS	Total	Genset A1 Actual	Genset B1 Actual	ESS	Total	Pre-event	Post-event	Pre-event	Minimum Pre-shed	Post-event	Event to < 59 Hz	< 59 Hz to Load Shed	Event to Load Shed	
A	70.9	94.3	56.6	221.8	70.2	85.9	0.0	156.1	65.6	0.0	59.99	58.82	60.01	0.422	0.075	0.497	Pass
B	78.2	87.1	64.9	230.2	81.7	82.8	0.0	164.4	65.5	0.0	59.97	58.90	60.00	0.305	0.044	0.349	Pass
C	78.0	89.2	74.8	242.0	99.0	76.9	0.0	175.9	65.7	0.0	59.97	58.85	59.88	0.225	0.041	0.266	Pass
D	78.0	90.4	83.2	251.5	101.2	83.9	0.0	185.1	65.4	0.0	59.98	58.88	59.87	0.231	0.066	0.297	Pass
E	76.0	91.4	91.0	258.4	0.0	0.0	0.0	0.0	65.1	0.0	59.99	58.88	0.00	0.222	0.075	0.297	Pass
F	83.0	93.2	95.1	271.3	0.0	0.0	0.0	0.0	65.4	0.0	59.95	58.94	0.00	0.087	0.023	0.110	Pass
G	82.1	93.2	95.0	270.2	96.9	85.9	0.0	182.8	86.7	0.0	59.95	58.87	59.92	0.079	0.030	0.109	Pass
														Average =	0.051		

Table 7: Improved Load Shed Algorithm – Microgrid Survivability Test Results for A1 & B1

Analysis

The load shedding algorithm behaves as expected and operates for all seven test cases. The time it takes for the load shed algorithm to execute a load shed event (<LSF of 59 Hz to load shed) ranges from 23 ms to 75 ms with the average equal to 51 ms.

The microgrid survives all events that it is expected to which includes Events A through D and G. Events D and G are particularly difficult since the load shed reduces the microgrid load to approximately 95% of the remaining sources' capability. This indicates that the load shedding algorithm can operate fast enough to allow the microgrid to survive difficult overload conditions. Events E and F do result in the collapse of the microgrid but this is expected since the remaining load on the microgrid, after the load shed event, exceeds the capability of the remaining sources.

Figure 11 and Figure 12 show Test Event A's real and reactive power graphs for DERs A1, B1, and the ESS along with the real power for smart load LB4. Also included is the microgrid frequency on the secondary axis. Figure 12 shows only the first second after the event begins to focus on the area of the most interest.

At t=0 s the ESS is shut off placing a 29 kW overload on A1 and B1 whose combined capability is 193 kW. The system takes 422 ms to reach the LSF of 59.0 Hz. At t = 497 ms, 75 ms after reaching the LSF, LB4 sheds 65 kW. During this time the system reaches a minimum frequency of 58.82 Hz. Once the load is shed the system returns to a steady-state condition serving 156 kW or 81% of its capability. It is noted that the loss of the ESS which initiates the overload and then the load shed event both result in a transient increase in reactive power flow between the two remaining sources, A1 and B1. It is also noted that there is an approximate 7 Hz oscillation in the real and reactive power from A1 and B1 after the event begins which remains until the end of the recording period. It is not clear what is responsible for this phenomenon.

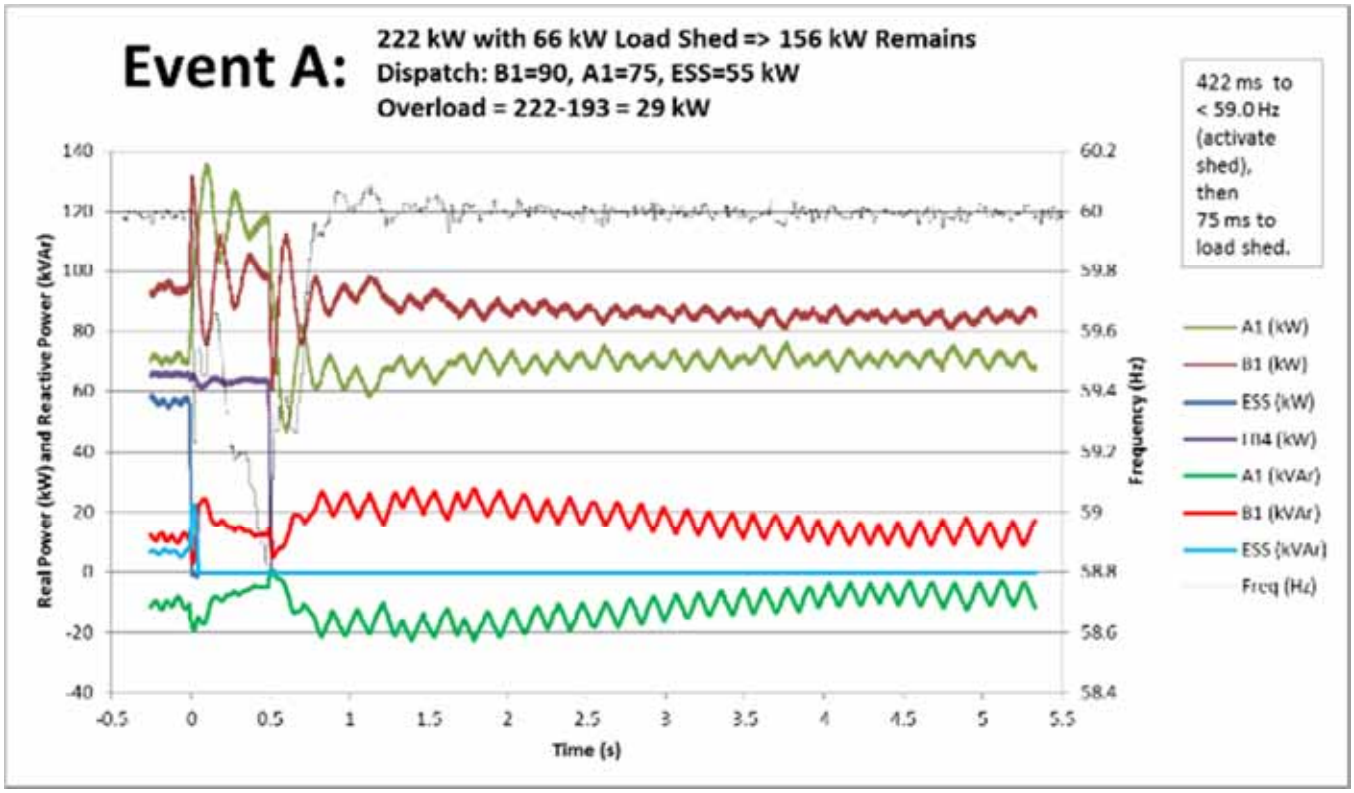

Figure 11: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event A Graph, Real & Reactive Power and Frequency

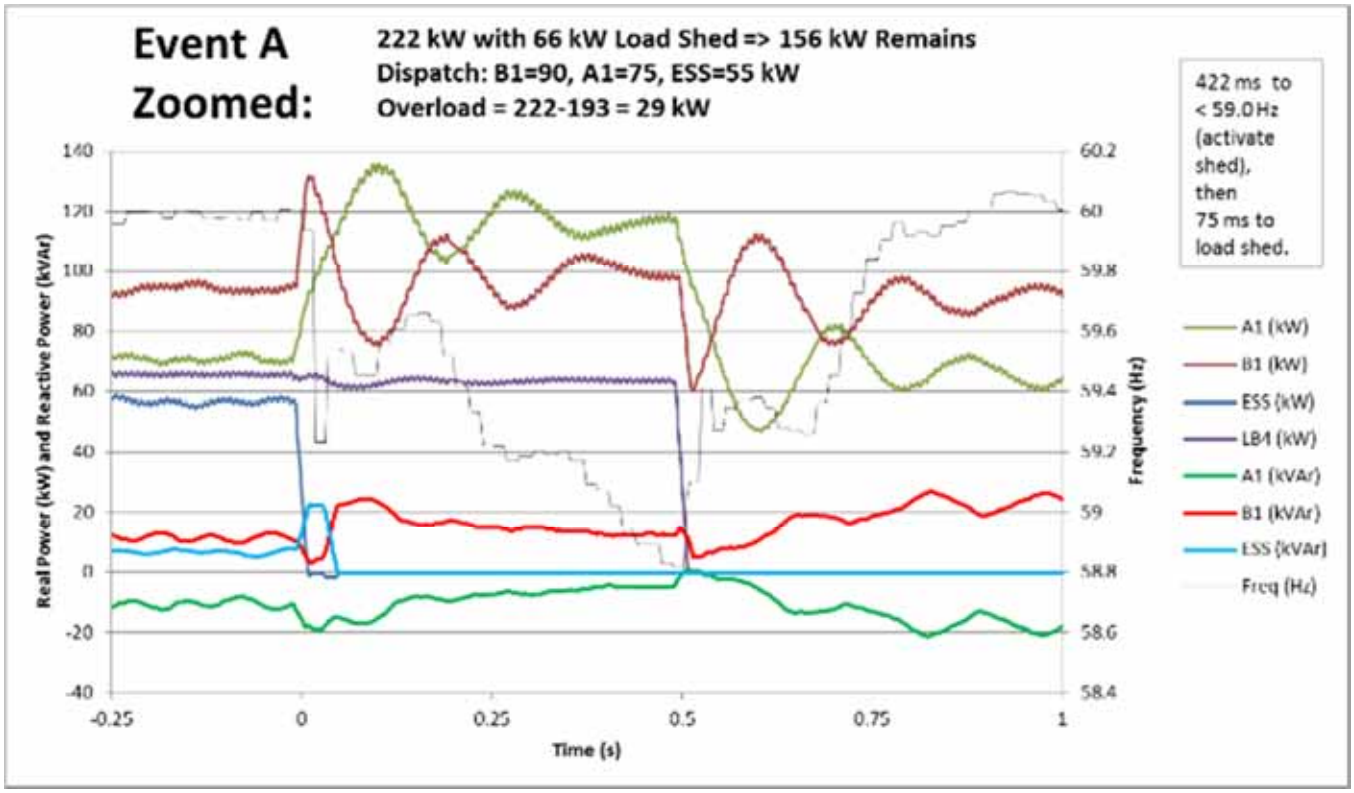

Figure 12: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event A Graph Zoomed, Real & Reactive Power and Frequency

Figure 13 through Figure 24 show the voltage and current results of Test Event A.

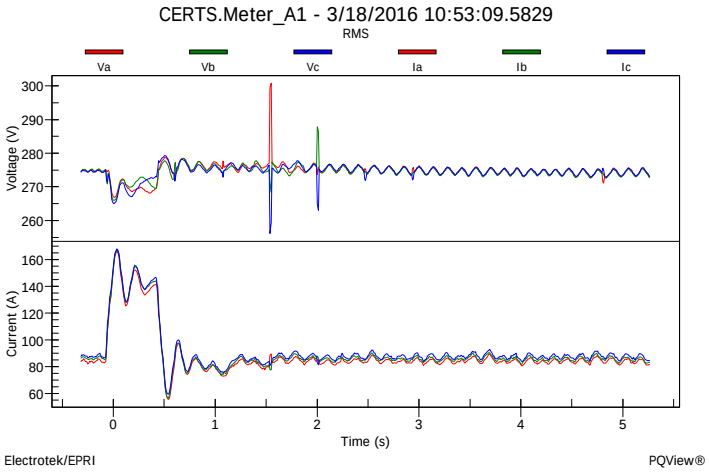

Figure 13: Test Event A: A1 B1 Microgrid Survivability, A1 RMS Voltage & Current

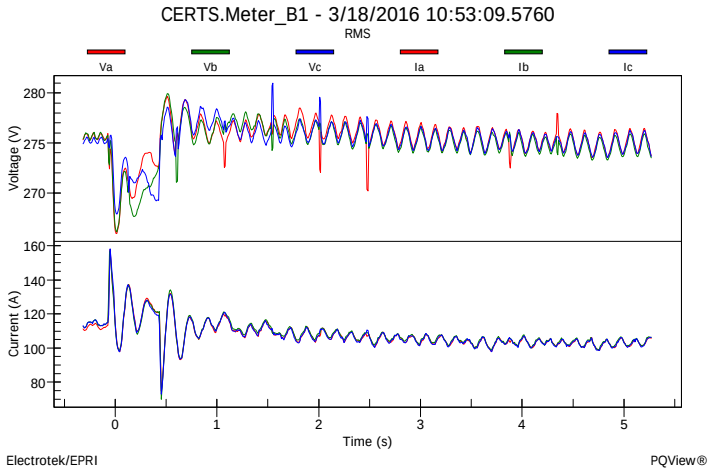

Figure 14: Test Event A: A1 B1 Microgrid Survivability, B1 RMS Voltage & Current

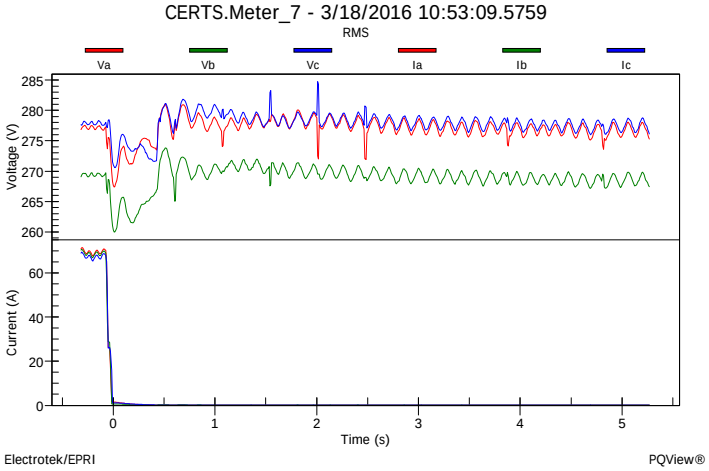

Figure 15: Test Event A: A1 B1 Microgrid Survivability, ESS RMS Voltage & Current

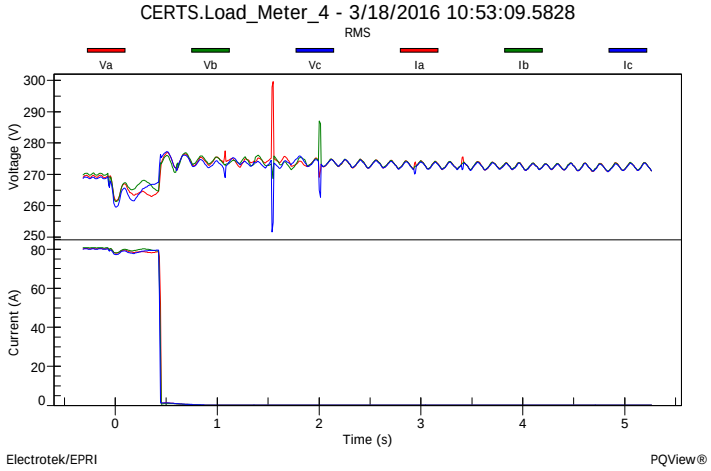

Figure 16: Test Event A: A1 B1 Microgrid Survivability, LB4 RMS Voltage & Current

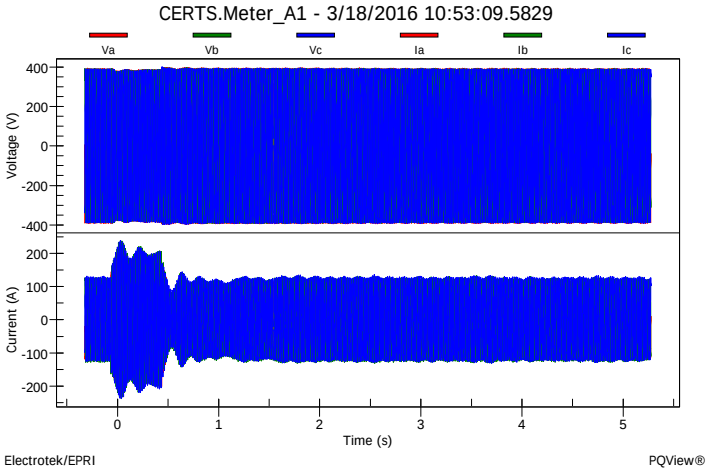

Figure 17: Test Event A: A1 B1 Microgrid Survivability, A1 Waveform Voltage & Current

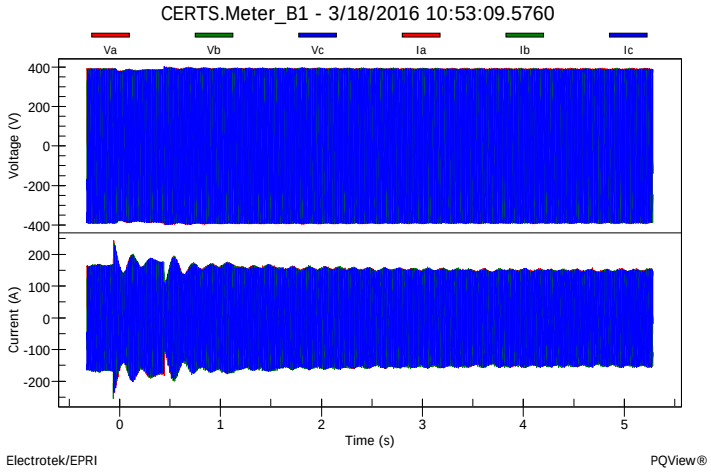

Figure 18: Test Event A: A1 B1 Microgrid Survivability, B1 Waveform Voltage & Current

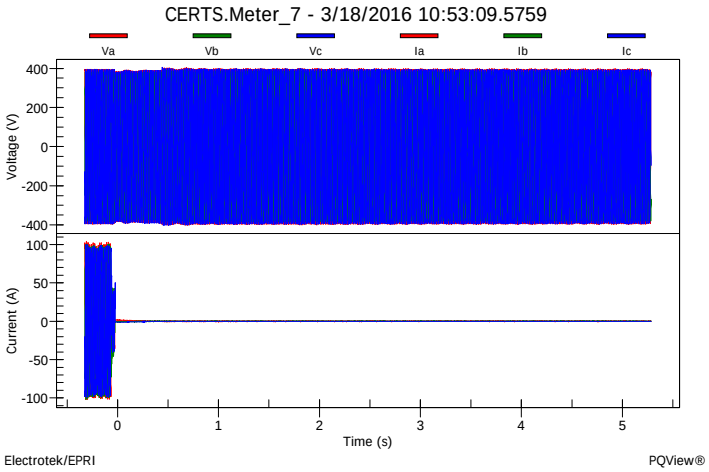

Figure 19: Test Event A: A1 B1 Microgrid Survivability, ESS Waveform Voltage & Current

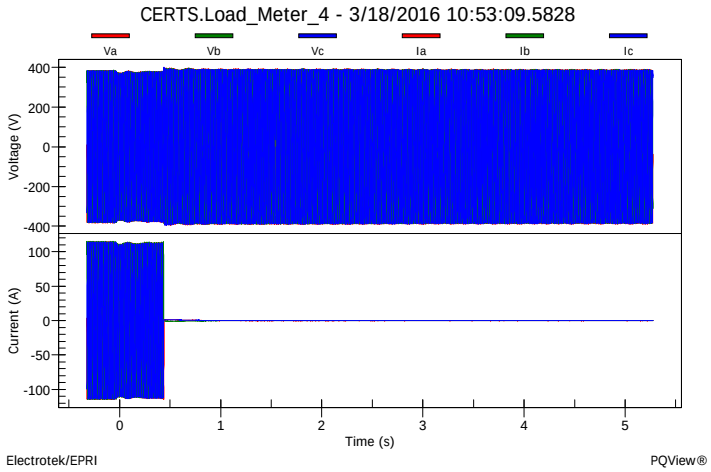

Figure 20: Test Event A: A1 B1 Microgrid Survivability, LB4 Waveform Voltage & Current

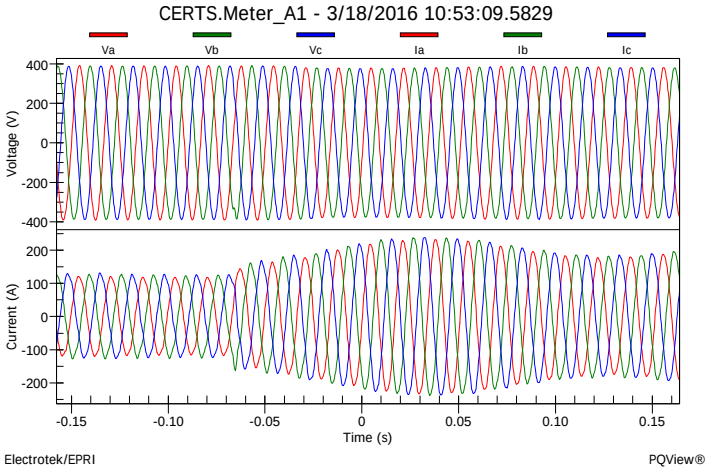

Figure 21: Test Event A: A1 B1 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

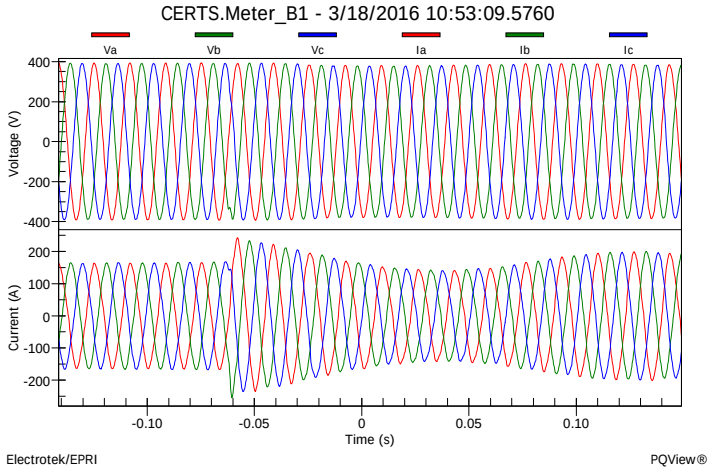

Figure 22: Test Event A: A1 B1 Microgrid Survivability, B1 Waveform (Zoomed) Voltage & Current

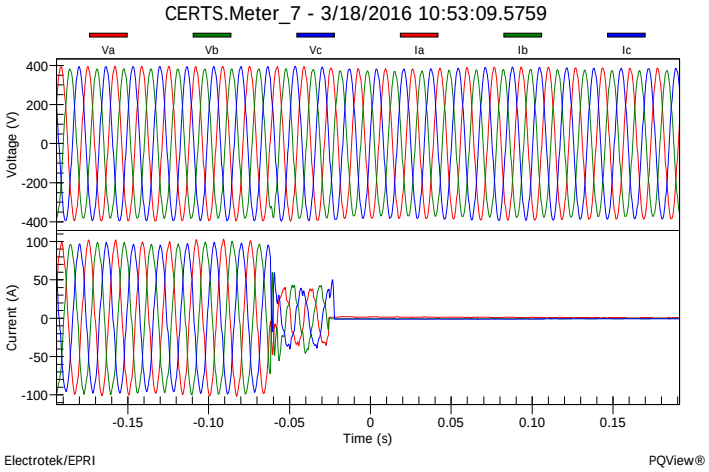

Figure 23: Test Event A: A1 B1 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

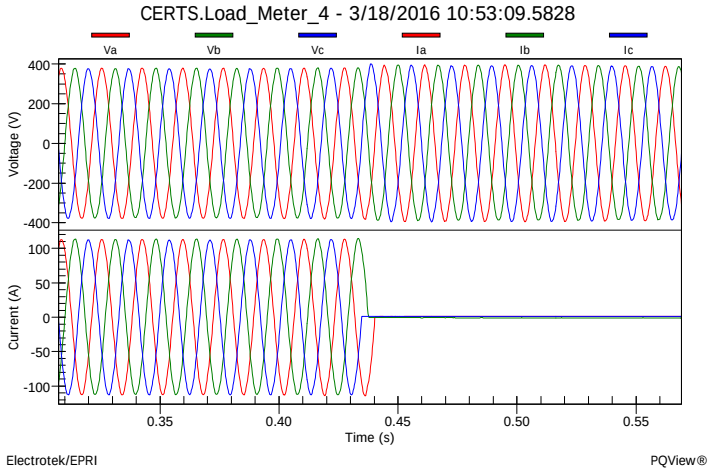

Figure 24: Test Event A: A1 B1 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

Figure 25 and Figure 26 show Test Event D's real and reactive power graphs for DERs A1, B1, and the ESS along with the real power for smart load LB4. Also included are B1's RMS voltage, A1's dc bus voltage, and the microgrid frequency on the secondary axis. Figure 26 shows only the first second after the event begins to focus on the area of the most interest.

At t=0 s the ESS is shut off placing a 58 kW overload on A1 and B1 whose combined capability is 193 kW. The system takes 231 ms to reach the LSF of 59.0 Hz. At t = 297 ms, 66 ms after reaching the LSF, LB4 sheds 65 kW. During this time the system reaches a minimum frequency of 58.88 Hz. Once the load is shed the system returns to a steady-state condition serving 185 kW or 96% of its capability. It is noted that the loss of the ESS which initiates the overload and then the load shed event both result in a transient flow of reactive power flow between the two remaining sources, A1 and B1. It is also noted that there is an approximate 7 Hz oscillation in the real and reactive power from A1 and B1 after the event begins which remains until the system reaches steady-state. At steady-state the oscillation has a frequency of about 14 Hz but with a reduction in magnitude. It is not clear what is responsible for this phenomenon.

At the beginning of the overload B1 supplies more power than A1 for the first 25 ms and by 37 ms B1 has returned to its nominal maximum power of 93 kW and remains approximately at or below that level until the load shed occurs. Thus from 37 ms on, A1 is carrying the bulk of the overload reaching a peak of 155 kW or 155% of its nominal 100 kW. During the overload time A1's dc bus dips to 583 V or 68% of its nominal 860 V. 583 Vdc should only be able to create a 412 Vac rms waveform or 86% of the nominal 480 V. The voltage measured on A1's terminals is 423 Vac or 88% of nominal thus confirming the

significant voltage dip due to A1 being significantly overloaded. After the load is shed A1's dc bus recovers and returns to nominal voltage. The microgrid survives this challenging overload event.

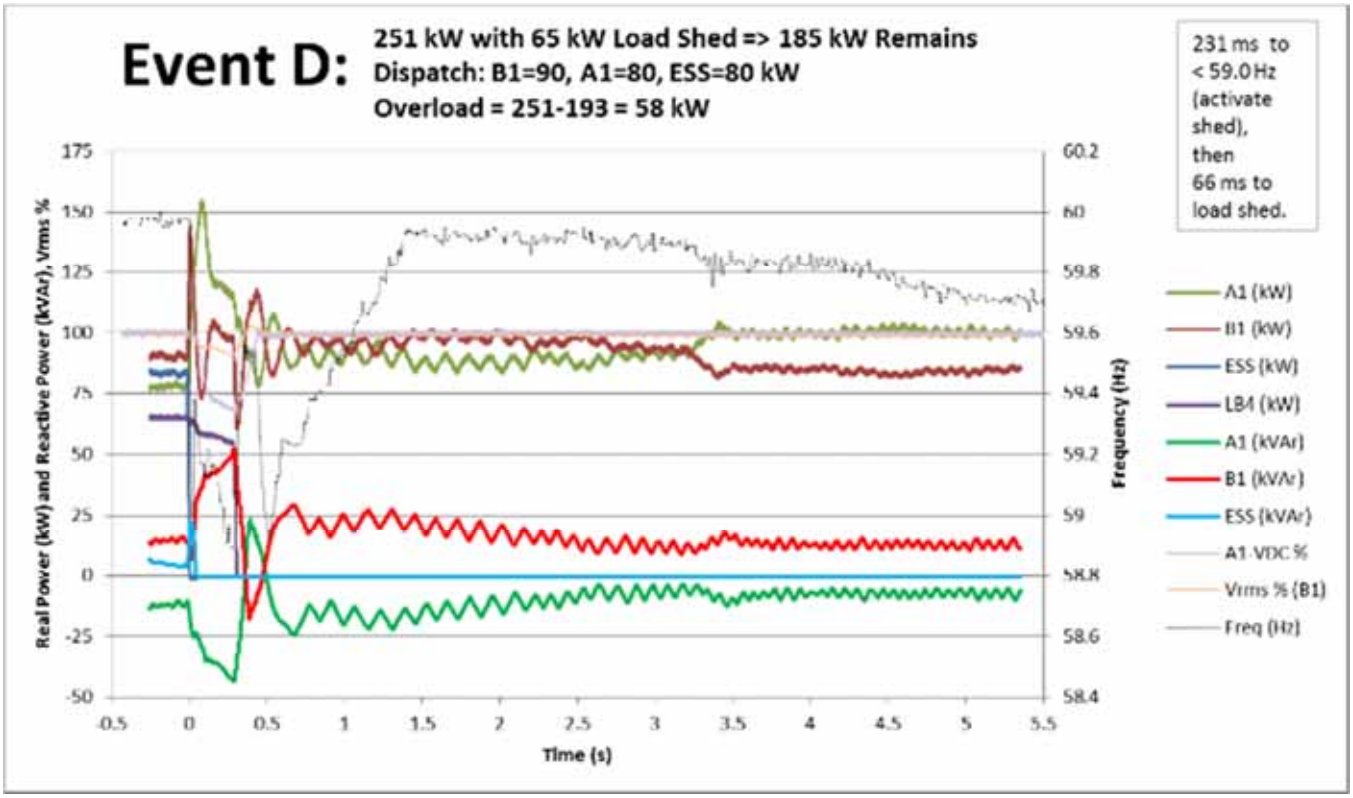

Figure 25: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event D Graph, Real & Reactive Power, Voltage, and Frequency

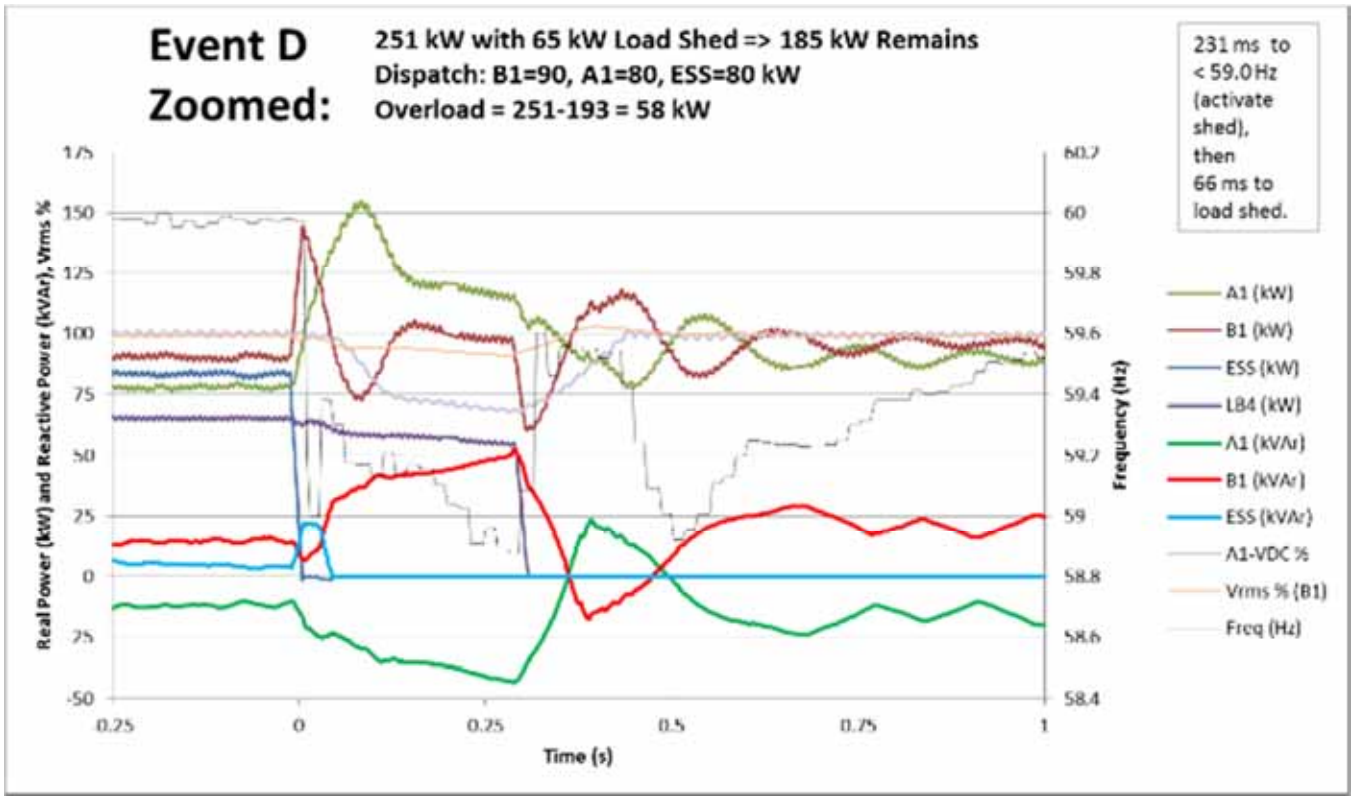

Figure 26: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event D Graph Zoomed, Real & Reactive Power, Voltage, and Frequency

Figure 27 through Figure 38 show the voltage and current results of Test Event D.

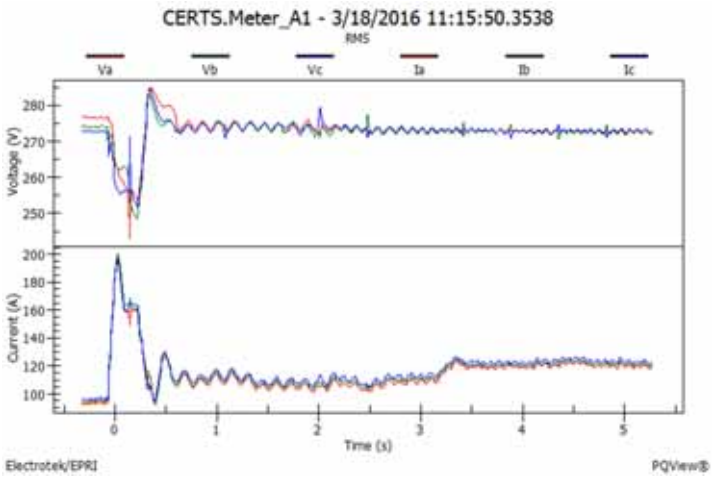

Figure 27: Test Event D: A1 B1 Microgrid Survivability, A1 RMS Voltage & Current

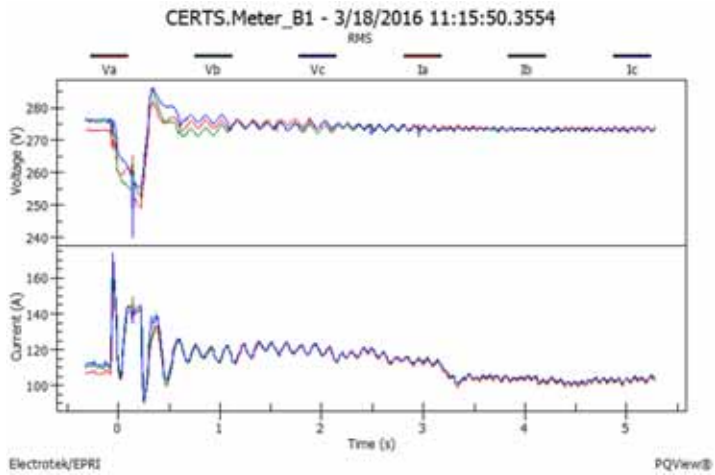

Figure 28: Test Event D: A1 B1 Microgrid Survivability, B1 RMS Voltage & Current

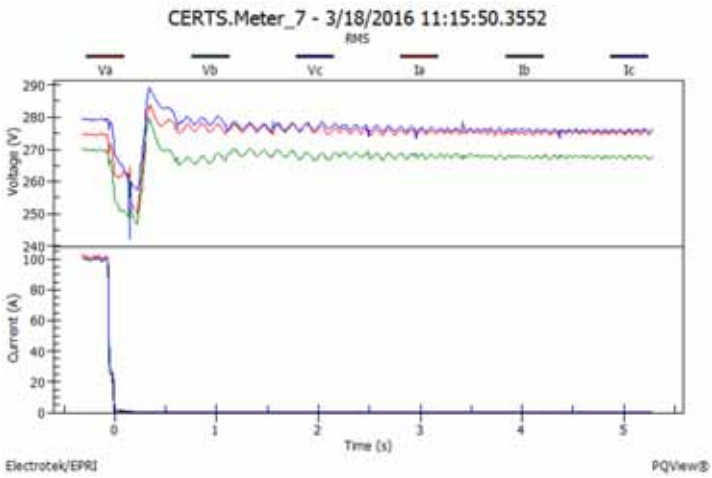

Figure 29: Test Event D: A1 B1 Microgrid Survivability, ESS RMS Voltage & Current

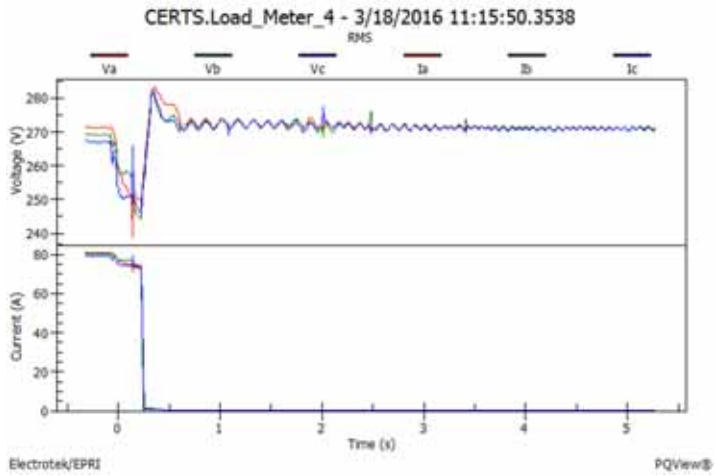

Figure 30: Test Event D: A1 B1 Microgrid Survivability, LB4 RMS Voltage & Current

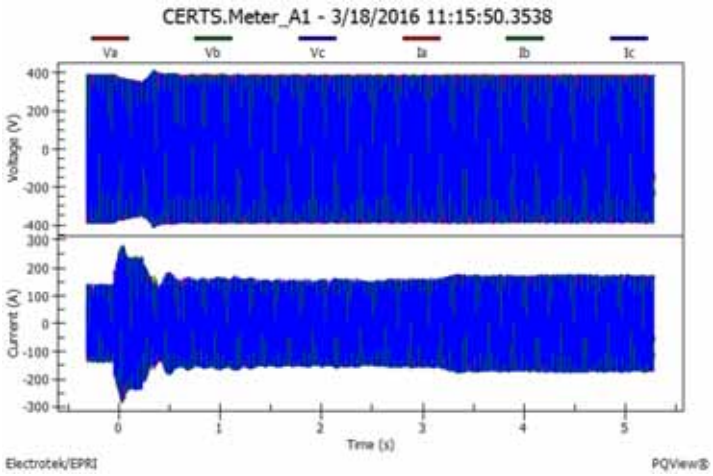

Figure 31: Test Event D: A1 B1 Microgrid Survivability, A1 Waveform Voltage & Current

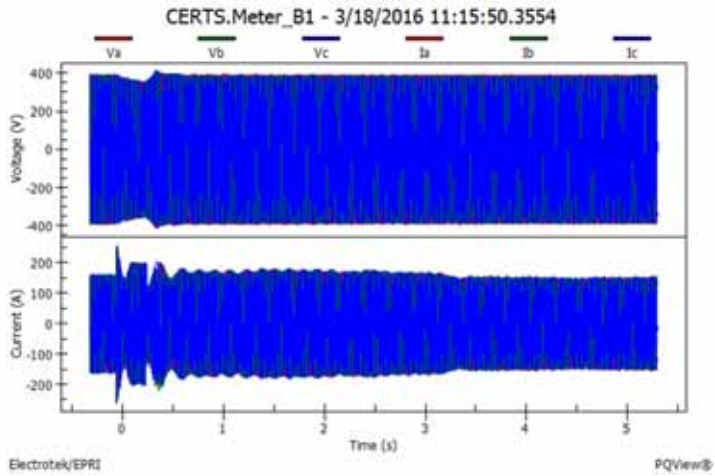

Figure 32: Test Event D: A1 B1 Microgrid Survivability, B1 Waveform Voltage & Current

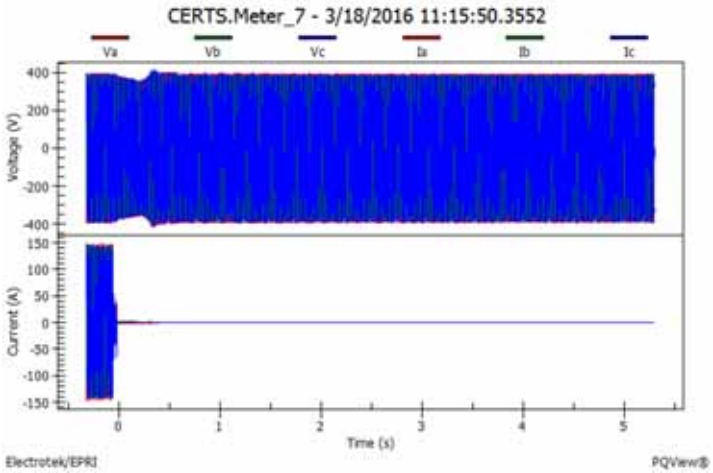

Figure 33: Test Event D: A1 B1 Microgrid Survivability, ESS Waveform Voltage & Current

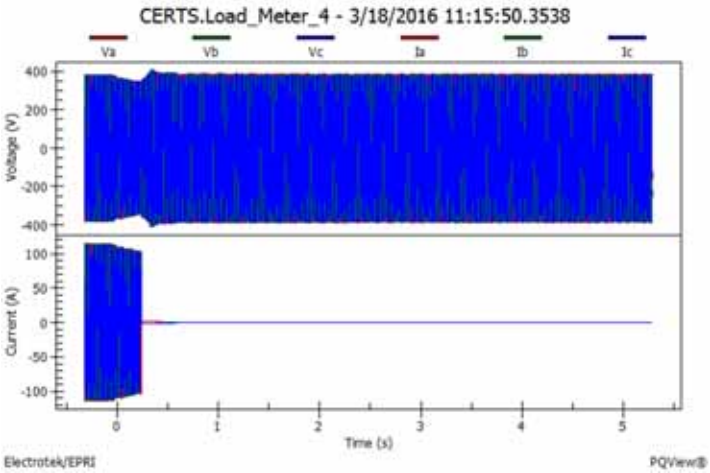

Figure 34: Test Event D: A1 B1 Microgrid Survivability, LB4 Waveform Voltage & Current

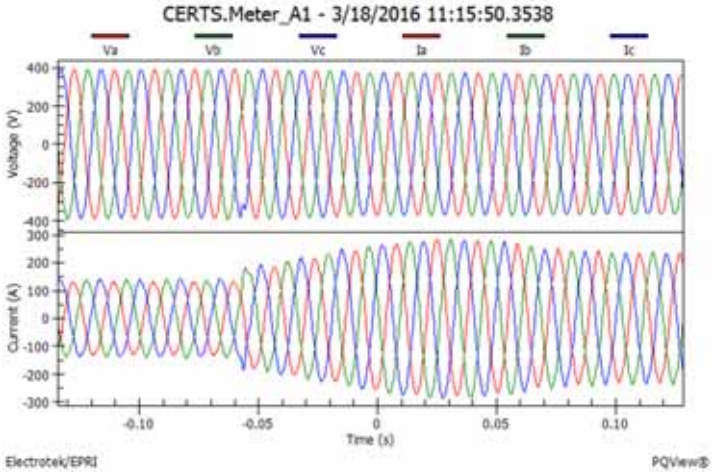

Figure 35: Test Event D: A1 B1 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

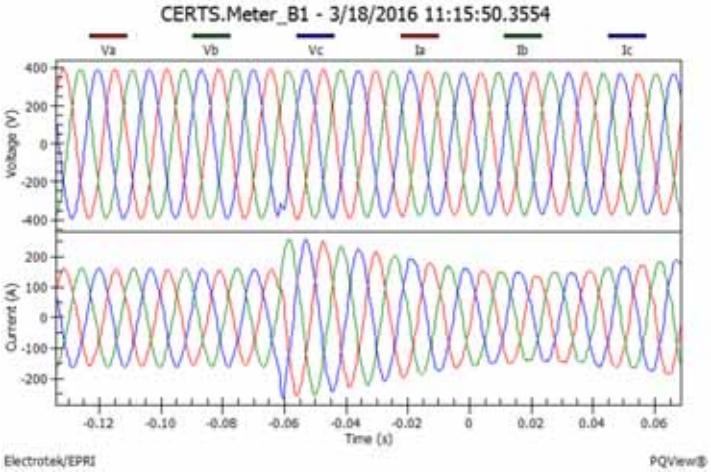

Figure 36: Test Event D: A1 B1 Microgrid Survivability, B1 Waveform (Zoomed) Voltage & Current

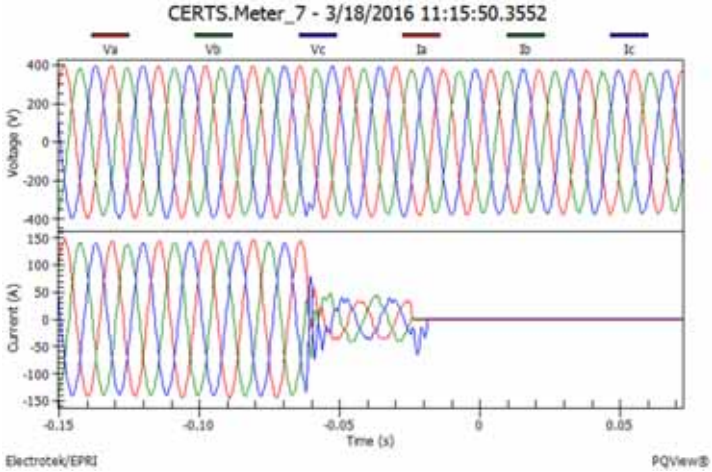

Figure 37: Test Event D: A1 B1 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

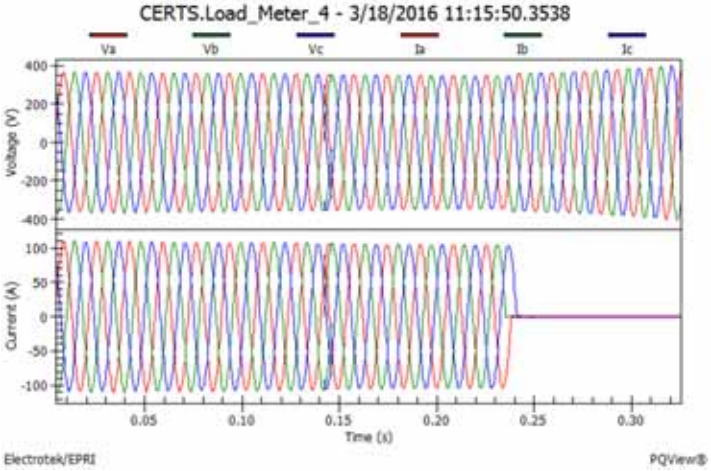

Figure 38: Test Event D: A1 B1 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

Figure 39 and Figure 40 show Test Event E's real and reactive power graphs for DERs A1, B1, and the ESS along with the real power for smart load LB4. Also included are B1's RMS voltage, A1's dc bus voltage, and the microgrid frequency on the secondary axis. Figure 40 shows only the first 3.5 seconds after the event begins to focus on the area of the most interest. Figure 40 also shows the total power output of the three DERs and is labeled "A1+B1+ESS (kW)". Finally, Figure 40 shows two other graphs which represent whether units A1 and B1 have their P_{max} functionality activated which are labeled "A1 P_{max}?" and "B1 P_{max}?" respectively. These graphs are of logic values on/off with on indicated by the elevated signal. These values are calculated based on whether the units output is greater than or equal to its P_{max} setting.

At t=0 s the ESS is shut off placing a 65 kW overload on A1 and B1 whose combined capability is 193 kW. The system takes 222 ms to reach the LSF of 59.0 Hz. At t = 297 ms, 75 ms after reaching the LSF, LB4 sheds 65 kW. During this time the system reaches a minimum frequency of 58.88 Hz.

At t=300 ms A1's dc bus reaches a minimum of 0.66 pu and the microgrid bus voltage a minimum of 0.89 pu. The bus voltage recovers to nominal at t=389 ms and A1's dc bus recovers to nominal at t=480 ms. At this time the DERs are serving the 193 kW load which equals their rated capacity and the frequency is recovering from its minimum and trending upward. It appears that the microgrid will survive this event.

However, at t=1060 ms A1's dc bus voltage begins to decline. At t=1400 ms A1's dc bus voltage reaches 0.77 pu and a large reactive power flow is triggered from B1 to A1. At t=2076 ms A1's dc bus voltage reaches a minimum of 0.64 pu. At t=2500 ms A1 reaches a maximum current of 256 A rms and trips. B1

then attempts to pick up the entire 193 kW load which is not possible and it eventually stalls and the microgrid collapses.

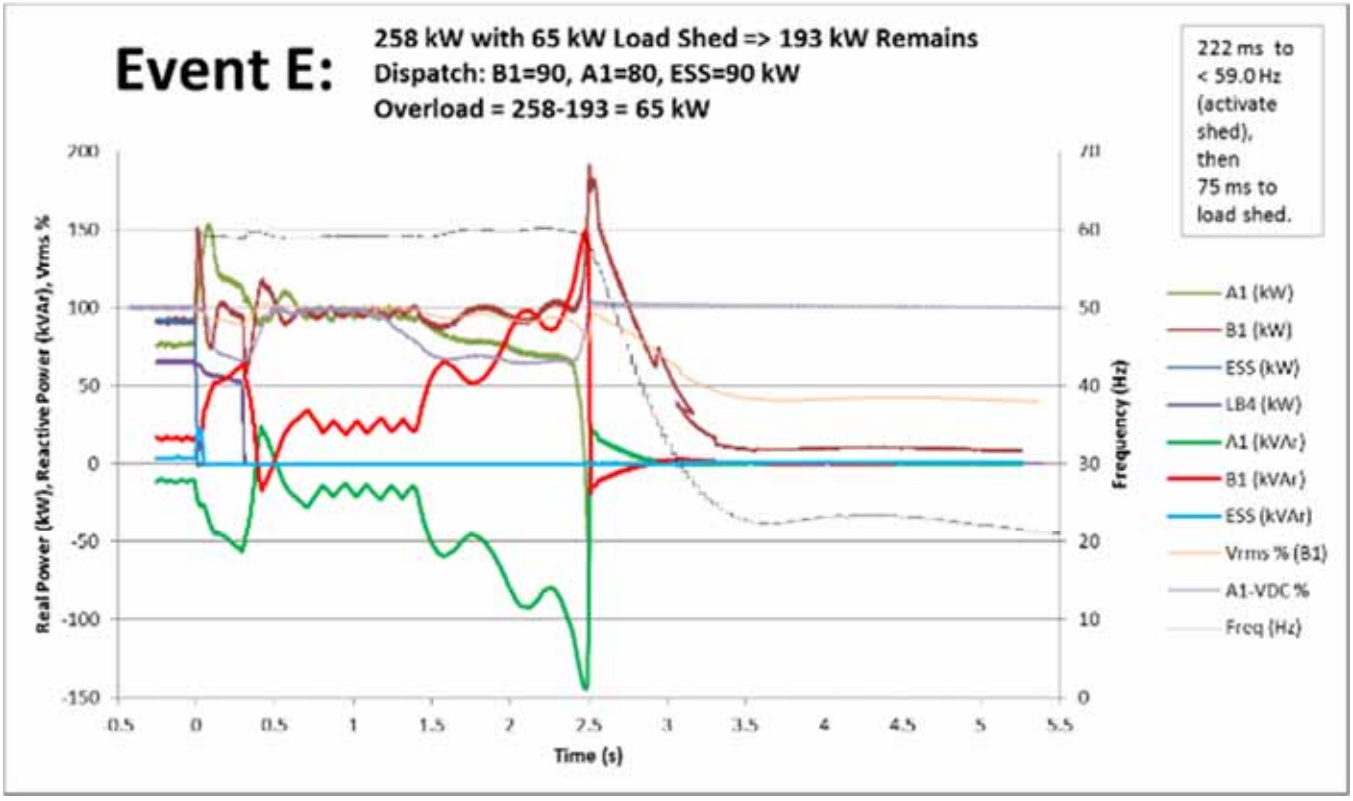

Figure 39: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event E Graph, Real & Reactive Power, Voltage, and Frequency

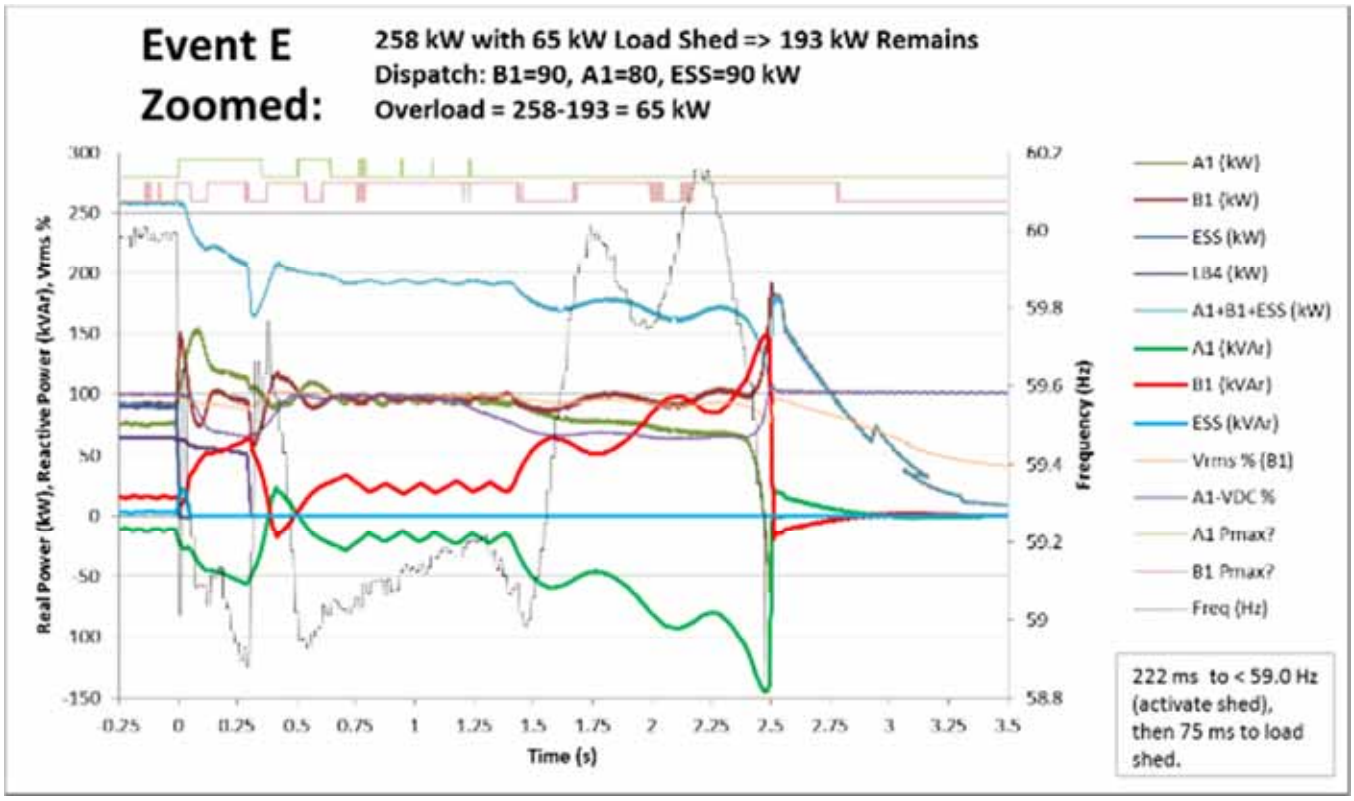

Figure 40: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event E Graph Zoomed, Real & Reactive Power, Voltage, and Frequency

Figure 41 through Figure 52 show the voltage and current results of Test Event E.

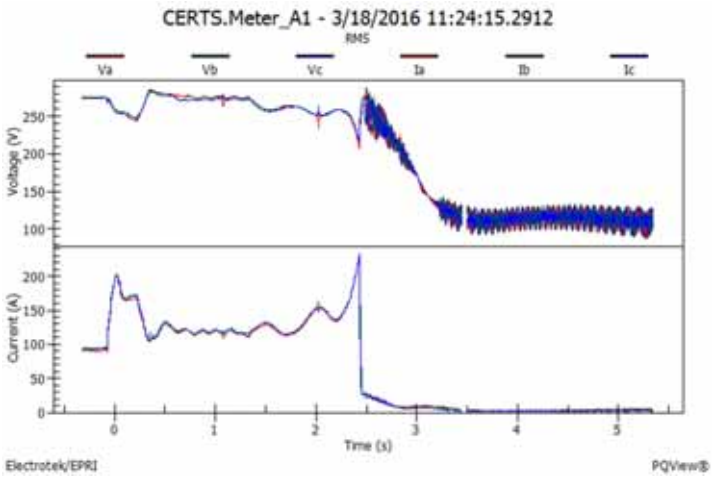

Figure 41: Test Event E: A1 B1 Microgrid Survivability, A1 RMS Voltage & Current

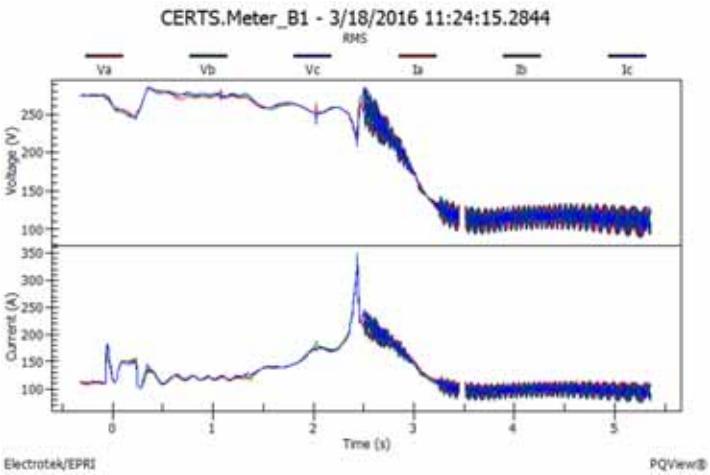

Figure 42: Test Event E: A1 B1 Microgrid Survivability, B1 RMS Voltage & Current

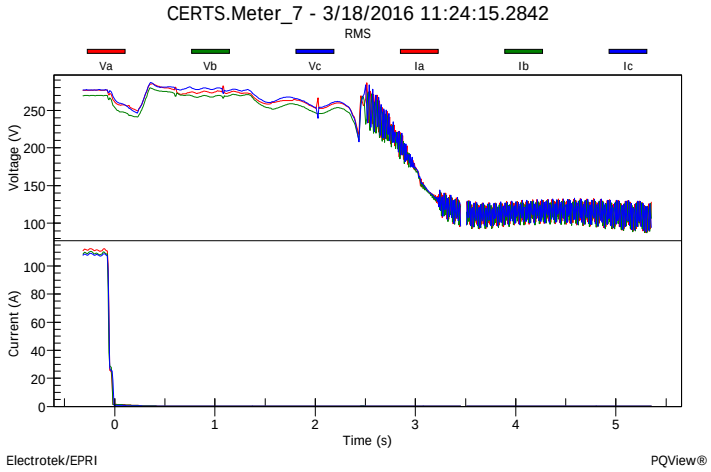

Figure 43: Test Event E: A1 B1 Microgrid Survivability, ESS RMS Voltage & Current

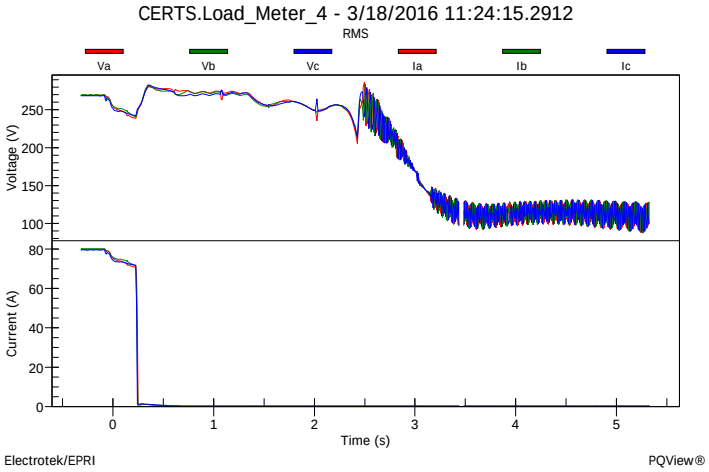

Figure 44: Test Event E: A1 B1 Microgrid Survivability, LB4 RMS Voltage & Current

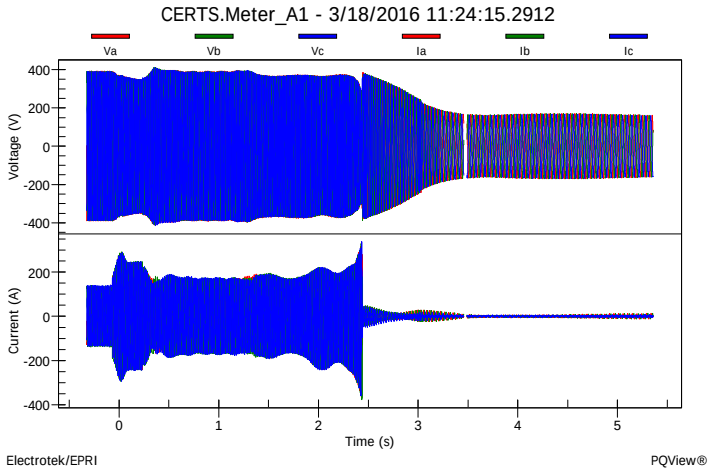

Figure 45: Test Event E: A1 B1 Microgrid Survivability, A1 Waveform Voltage & Current

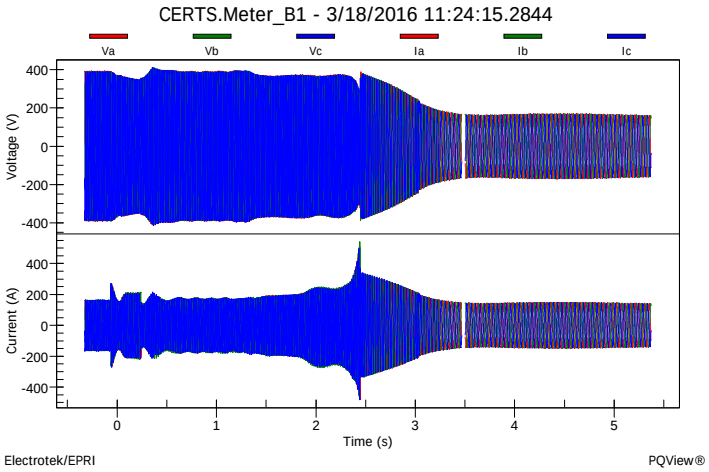

Figure 46: Test Event E: A1 B1 Microgrid Survivability, B1 Waveform Voltage & Current

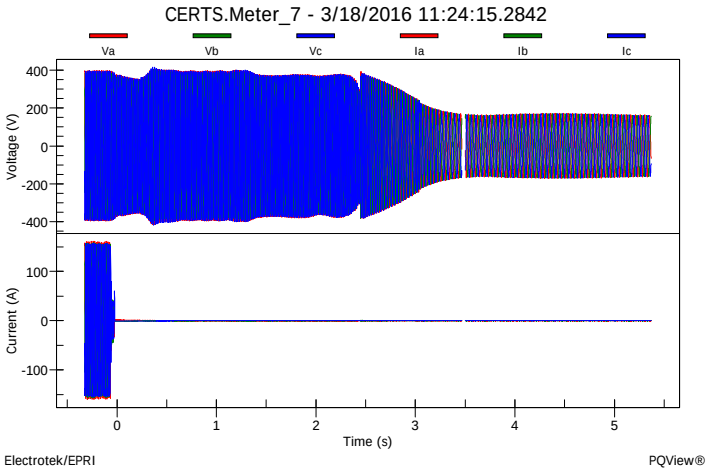

Figure 47: Test Event E: A1 B1 Microgrid Survivability, ESS Waveform Voltage & Current

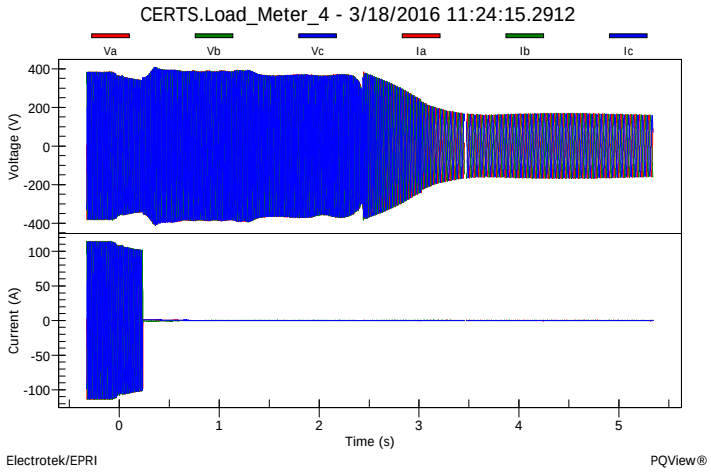

Figure 48: Test Event E: A1 B1 Microgrid Survivability, LB4 Waveform Voltage & Current

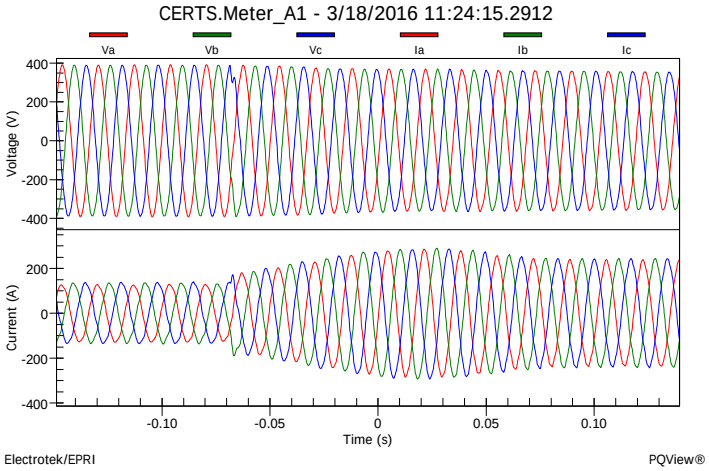

Figure 49: Test Event E: A1 B1 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

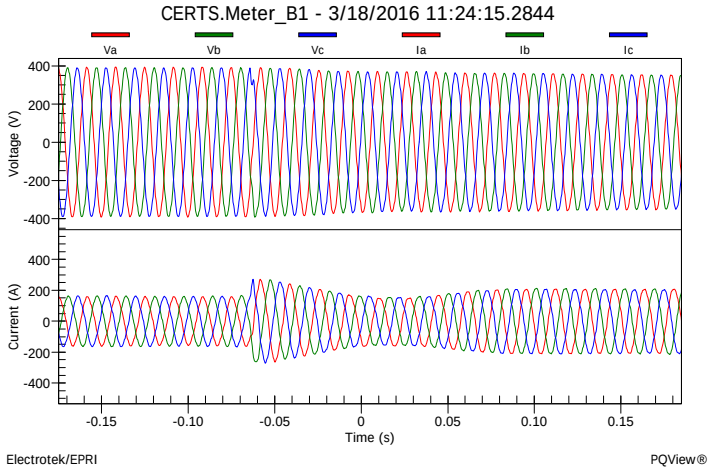

Figure 50: Test Event E: A1 B1 Microgrid Survivability, B1 Waveform (Zoomed) Voltage & Current

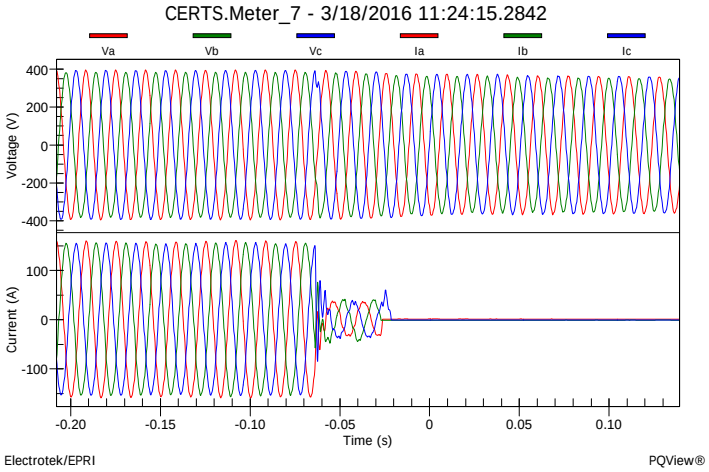

Figure 51: Test Event E: A1 B1 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

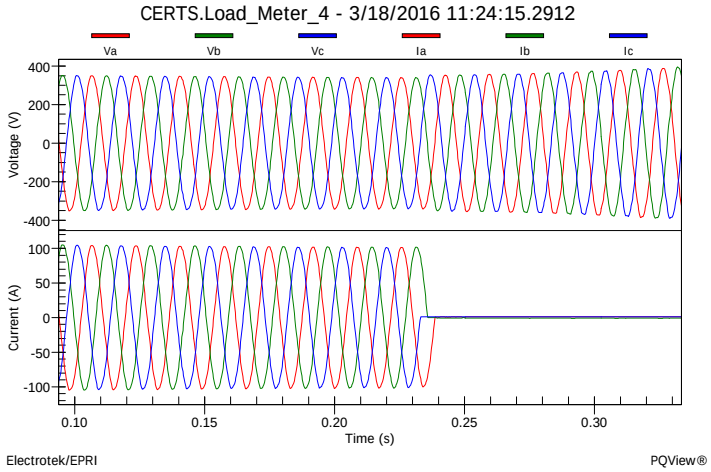

Figure 52: Test Event E: A1 B1 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

Figure 53 and Figure 54 show Test Event G's real and reactive power graphs for DERs A1, B1, and the ESS along with the real power for smart load LB4. Also included are B1's RMS voltage, A1's dc bus voltage, and the microgrid frequency on the secondary axis. Figure 54 shows only the first second after the event begins to focus on the area of the most interest.

At t=0 s the ESS is shut off placing a 77 kW overload on A1 and B1 whose combined capability is 193 kW. This is the largest overload applied to the combination of A1 and B1 as part of these tests. The system takes 79 ms to reach the LSF of 59.0 Hz. At t = 109 ms, 30 ms after reaching the LSF, LB4 sheds 87 kW. During this time the system reaches a minimum frequency of 58.87 Hz. Once the load is shed the system returns to a steady-state condition serving 183 kW or 95% of its capability however it is not quite the steady-state condition that is expected. Given the frequency droop settings and a load of 183 kW, A1 should provide 90 kW and B1 93 kW. During the transient it appears that this is about where the units would settle. At t=1166 ms A1 begins serving more load than B1 and A1 eventually activates its P_{max} controller thereby recruiting B1 to serve more load. Steady-state is reached with A1 serving approximately 97 kW (instead of 90 kW) and B1 serving 86 kW (instead of 93 kW).

It is noted that the loss of the ESS which initiates the overload and then the load shed event both result in a transient flow of reactive power flow between the two remaining sources, A1 and B1. It is also noted that there is an approximate 6.5 Hz oscillation in the real and reactive power from A1 and B1 after the event begins which remains until the system reaches steady-state. At steady-state the oscillation has a frequency of about 9 Hz but with a reduction in magnitude. It is not clear what is responsible for this phenomenon.

During the overload time A1's dc bus dips to 636 V or 74% of its nominal 860 V. 636 Vdc should only be able to create a 450 Vac rms waveform or 94% of the nominal 480 V. The voltage measured on A1's terminals is 450 Vac or 94% of nominal thus confirming the significant voltage dip due to A1 being significantly overloaded. After the load is shed A1's dc bus recovers and returns to nominal voltage. The microgrid survives this challenging overload event.

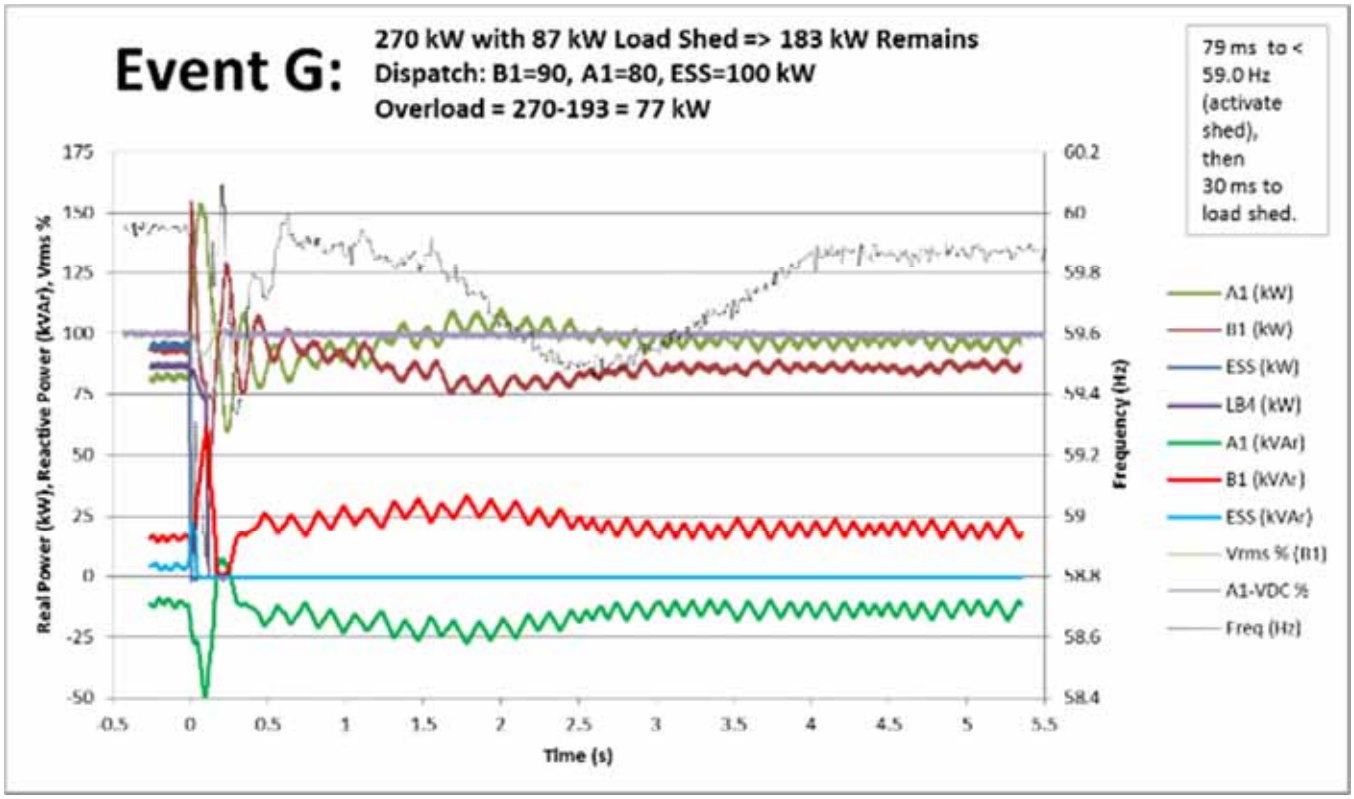

Figure 53: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event G Graph, Real & Reactive Power, Voltage, and Frequency

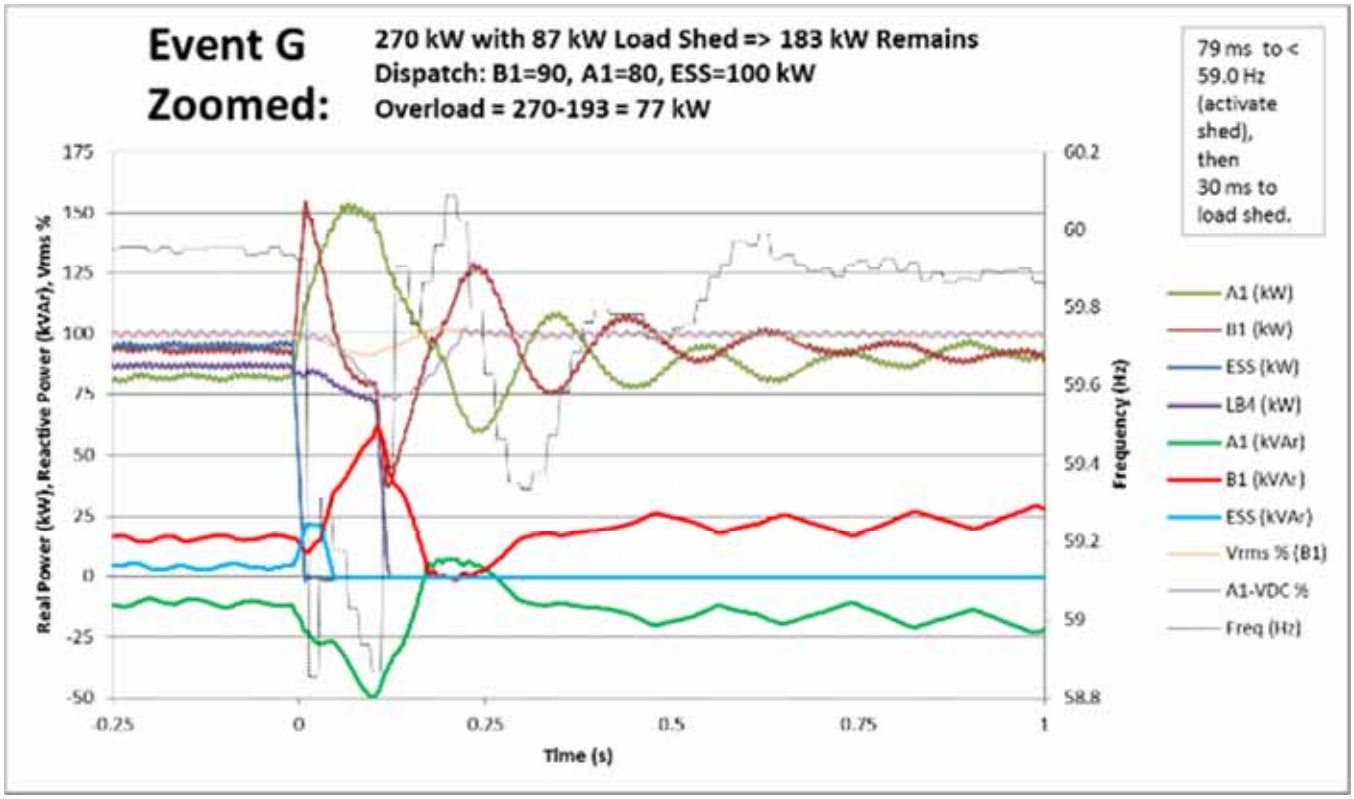

Figure 54: Improved Load Shed Algorithm – A1 B1 Microgrid Survivability Test Event G Graph Zoomed, Real & Reactive Power, Voltage, and Frequency

Figure 55 through Figure 66 show the voltage and current results of Test Event G.

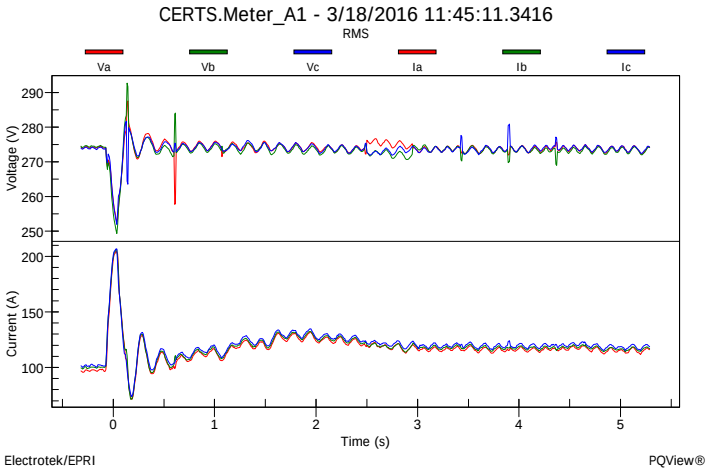

Figure 55: Test Event G: A1 B1 Microgrid Survivability, A1 RMS Voltage & Current

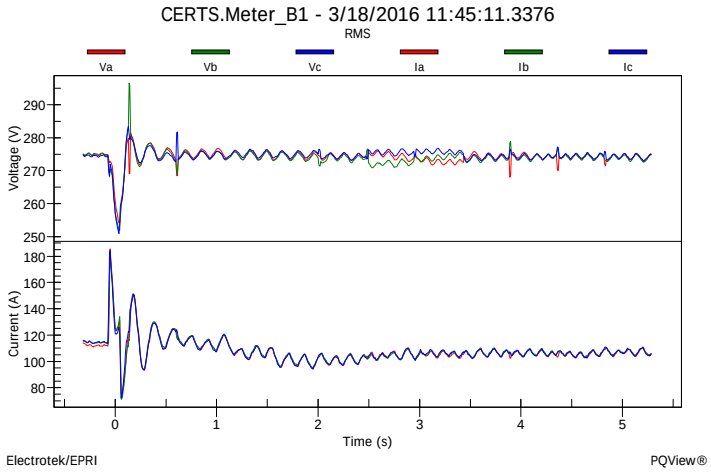

Figure 56: Test Event G: A1 B1 Microgrid Survivability, B1 RMS Voltage & Current

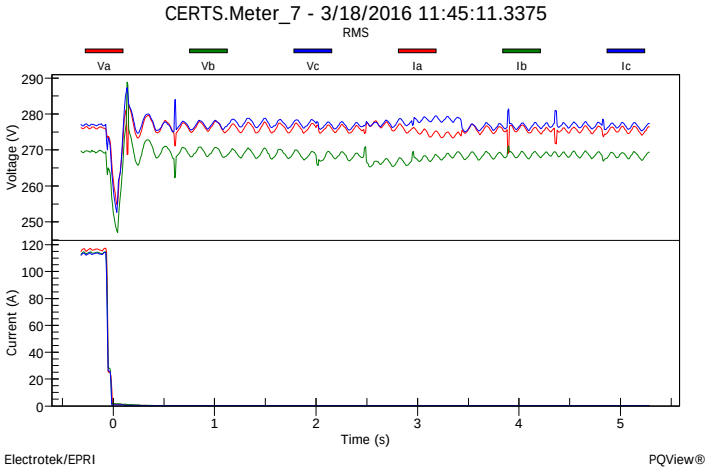

Figure 57: Test Event G: A1 B1 Microgrid Survivability, ESS RMS Voltage & Current

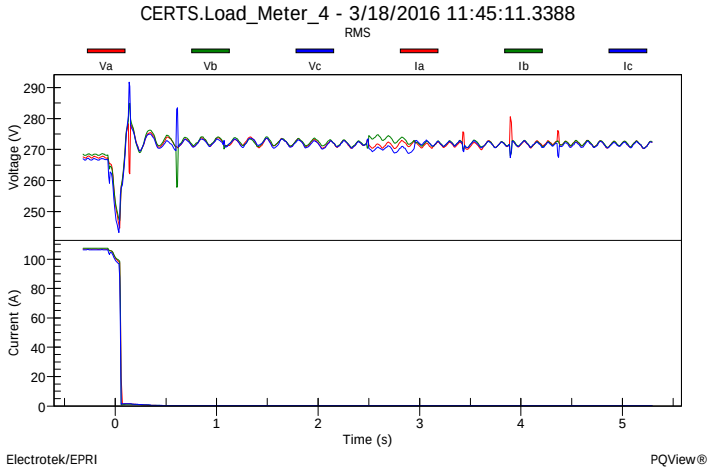

Figure 58: Test Event G: A1 B1 Microgrid Survivability, LB4 RMS Voltage & Current

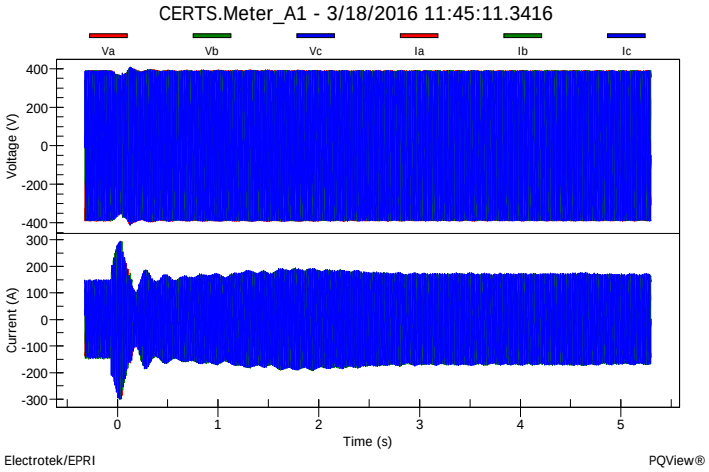

Figure 59: Test Event G: A1 B1 Microgrid Survivability, A1 Waveform Voltage & Current

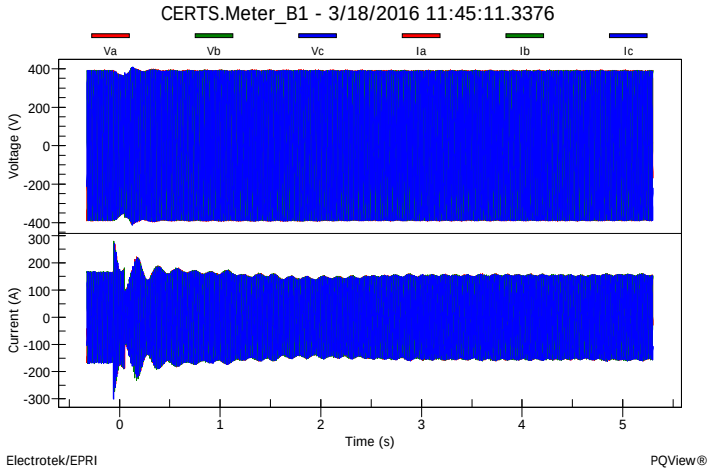

Figure 60: Test Event G: A1 B1 Microgrid Survivability, B1 Waveform Voltage & Current

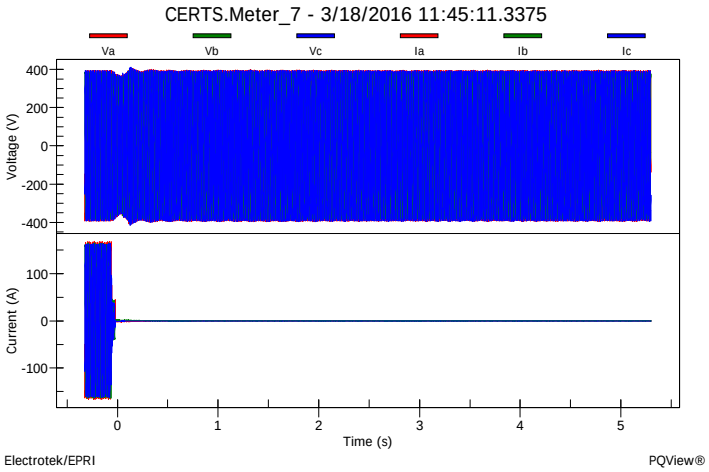

Figure 61: Test Event G: A1 B1 Microgrid Survivability, ESS Waveform Voltage & Current

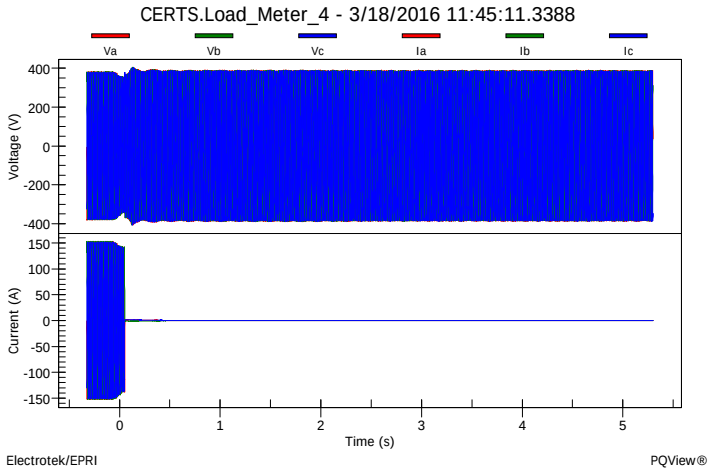

Figure 62: Test Event G: A1 B1 Microgrid Survivability, LB4 Waveform Voltage & Current

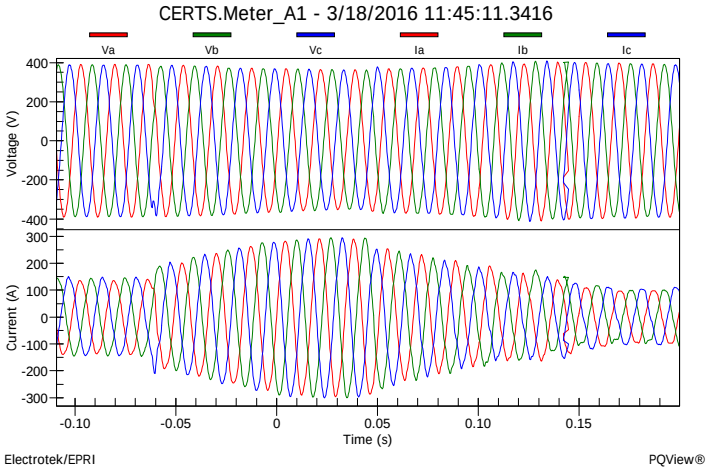

Figure 63: Test Event G: A1 B1 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

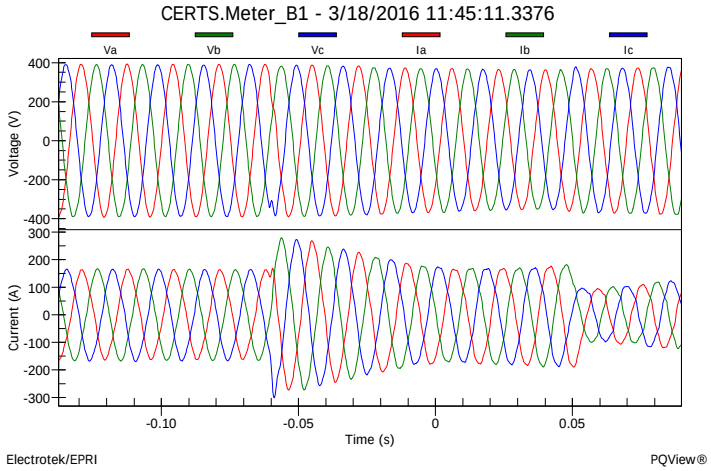

Figure 64: Test Event G: A1 B1 Microgrid Survivability, B1 Waveform (Zoomed) Voltage & Current

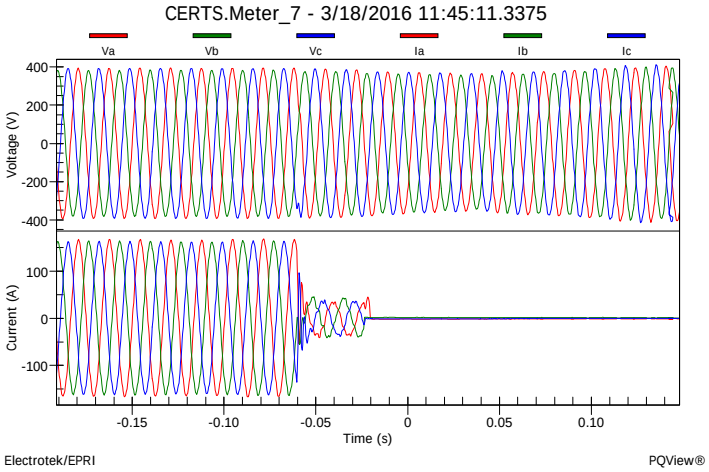

Figure 65: Test Event G: A1 B1 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

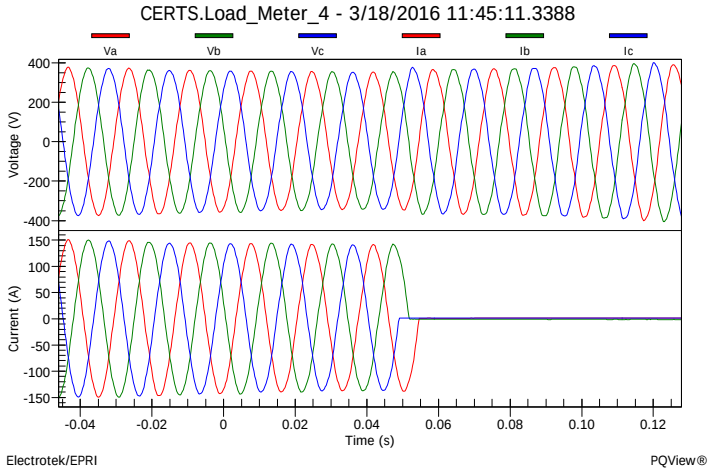

Figure 66: Test Event G: A1 B1 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

6.4 Microgrid Survivability Using Improved Load Shed Algorithm with A1 and A2 as Surviving Units

Performance Goal

Determine whether the improved load shedding algorithm is able to enhance microgrid survivability in an islanded scenario with three DERs active in the microgrid with a subsequent loss of one DER which results in the two surviving DERs becoming overloaded. In this scenario, the question essentially is whether the load shedding algorithm is fast enough to avoid collapse of the microgrid. Compare these tests using A1 and A2 with the tests performed in Section 6.3 above using A1 and B1. In this case A2 has a lower rating of 60 kW compared to 93 kW for B1 and A2 is inverter-connected whereas B1 is a synchronous gen-set.

Description of Procedure

Three DERs, A1, A2, and the ESS, will operate as an island. They will be configured and dispatched according to the values listed in the Test Settings section below. They will serve load from Load Banks 3, 4, and 5 also configured as listed in the Test Settings section below. Initially the load is chosen to match the total real power dispatch values of the three DERs so that the islanded microgrid should have a frequency of approximately 60 Hz. Smart Load Bank 4 is set to shed its entire non-critical load at a frequency of 59.2 Hz with no intentional time delay. 59.2 Hz is used instead of 59.0 Hz for these tests since A2 is hard coded not to let the frequency drop below 59 Hz. Thus a LSF larger than 59.0 Hz is required for the smart load to be able to shed load. The amount of load shed is designed to bring the remaining (critical) load to a value less than the remaining source capabilities thus making it theoretically possible for the microgrid to survive the test event. Test Events E & F are an exception to this in that the load should exceed the capabilities of the remaining sources and result in the collapse of the microgrid.

The ESS will be turned off to simulate a loss of a source. The two remaining sources will become overloaded thus engaging their P_{max} controls which will drive the microgrid frequency down. The non-critical load will shed from LB4. The data acquisition system will record the event based on the trigger of the loss of the ESS.

Test Settings

For these tests the parameters are set as follows:

<u>ESS</u>

Pdispatch = Varies

Frequency Droop = 1%

Real Power-Frequency Droop = -.004 Hz/kW

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)

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

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

A1 (InVerde 100)
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 = -0.01 V_{LN}/kVAr (12% is minimum attainable due to improper voltage control)

A2 (Tecogen Prototype)
Pdispatch = 57 kW
Frequency Droop = 1%
Real Power-Frequency Droop = -.01 Hz/kW
P_{max} = 60 kW
P_{min} = 0 kW
Voltage Set Point = 480 V_{LL}
Voltage Droop = -0.4 V_{LL}/kVAr (5%)

Load Bank 4 – Load Shedding
Non-critical (Shedable) Load = Varies (65 kW or 90 kW)
Load Shedding Frequency = 59.2 Hz
Load Shedding Time Delay = 0 s
Load Shedding Rate = 100 pu/s
Effect is all load will be shed as one block when system frequency drops below 59 Hz with no intended time delay.

During each sequence of tests in Table 8 a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers "Closed"; the microgrid is islanded with the GIS open; load banks are set as close as possible to the prescribed values; reactive load is set to 0 kVAr; and events are triggered based on the transition of the ESS to off.

Test Event	Gen A1 Pdisp (kW)	Gen A2 Pdisp (kW)	ESS Pdisp (kW)	Load Bank 3 (kW)	Load Bank 5 (kW)	SMART Load 4	
						Critical Load (kW)	Non-Critical Load (kW)
A	75	57	55	95	30	0	65
B	80	57	60	95	40	0	65
C	80	57	70	95	50	0	65
D	80	57	80	95	60	0	65

E	80	57	90	95	70	0	65
F	80	57	100	95	80	0	65
G	80	57	100	95	55	0	90

Table 8: Improved Load Shed Algorithm – Microgrid Survivability Test Plan for A1 & A2

Test Events A through D are designed to place an increasing overload condition on the two surviving DERs, A1 and A2, before shedding 65 kW of load thus reducing the total load below the 160 kW capability of A1 and A2 combined. Test Event A starts by placing a total of 190 kW (a 30 kW overload) on the combination of A1 and A2 then sheds 65 kW reducing the total load to 125 kW. Test Event D takes this to a total of 220 kW (a 60 kW overload) on the combination of A1 and A2 then sheds 65 kW reducing the total load to 155 kW.

Test Events E and F continue increasing the overload on A1 and A2 but the load shed of 65 kW reduces the total load remaining to 165 kW and 175 kW respectively which is greater than the 160 kW combined capability of the two units. In these two cases the microgrid is expected to collapse.

Finally, Test Event G places 240 kW (an 80 kW overload) on the combination of A1 and A2 then sheds 90 kW reducing the total load to 150 kW.

Test Results

Table 9 below summarizes the results of using the improved load shedding algorithm to enhance microgrid survivability in an islanded scenario with three DERs (A1, B1, and ESS) active in the microgrid and a subsequent loss of one DER (ESS) which results in the two surviving DERs becoming overloaded. Note that Test Event F was not performed.

Test Event	Real Power (Pre-Event) (kW)				Real Power (Post-Event) (kW)				Load Meter 4 Real Power (kW)		Frequency (Hz)			Time (s)			Pass/Fail
	Genset A1	Genset A2	ESS	Total	Genset A1 Actual	Genset A2 Actual	ESS	Total	Pre-event	Post-event	Pre-event	Minimum Pre-shed	Post-event	Event to < 59.2 Hz	< 59.2 Hz to Load Shed	Event to Load Shed	
A	82.0	57.7	48.2	187.9	70.7	53.1	0.0	123.8	64.8	0.0	59.92	59.08	59.99	0.491	0.048	0.539	Pass
B	76.7	57.6	65.3	199.5	77.2	57.5	0.0	134.7	65.0	0.0	59.98	59.14	59.98	0.364	0.062	0.426	Pass
C	78.0	57.7	74.3	210.1	86.0	58.6	0.0	144.6	65.3	0.0	59.97	59.07	59.93	0.288	0.075	0.363	Pass
D	78.2	58.1	84.0	220.3	98.0	55.9	0.0	153.9	65.0	0.0	59.98	59.12	59.87	0.238	0.087	0.325	Pass
E	77.8	57.9	93.8	229.4	-	-	-	0.0	64.4	0.0	59.98	59.11	0.00	0.188	0.064	0.252	Pass
F	-	-	-	0.0	-	-	-	0.0	-	-	-	-	-	-	-	-	n/a
G	84.1	58.0	94.7	236.8	90.4	58.6	0.0	149.0	87.0	0.0	59.94	59.19	59.90	0.014	0.043	0.057	Pass
													Average =		0.063		

Table 9: Improved Load Shed Algorithm – Microgrid Survivability Test Results for A1 & A2

Analysis

The load shedding algorithm behaves as expected and operates for all test cases. The time it takes for the load shed algorithm to execute a load shed event (<LSF of 59.2 Hz to load shed) ranges from 43 ms to 87 ms with the average equal to 63 ms.

The microgrid survives all events that it is expected to which includes Events A through D and G. Events D and G are particularly difficult since the load shed reduces the microgrid load to approximately 95% of the remaining sources' capability. This indicates that the load shedding algorithm can operate fast enough to allow the microgrid to survive difficult overload conditions. Events E does result in the collapse of the microgrid but this is expected since the remaining load on the microgrid, after the load shed event, exceeds the capability of the remaining sources.

These results are similar to those obtained in the previous section where the remaining DERs in the microgrid were A1 and B1, an inverter-connected and a synchronous gen-set. In this case both DERs, A1 and A2, are inverter-connected. Thus the load shedding algorithm appears to work well for both a homogenous and heterogeneous set of DERs.

Figure 67 and Figure 68 show Test Event A's real and reactive power graphs for DERs A1, A2, and the ESS along with the real power for smart load LB4. Also included are A2's RMS voltage, A1 and A2's dc bus voltage, the microgrid frequency on the secondary axis, and the P_{max} status as ON or OFF at the top of the graph. Figure 68 shows only the first 1.25 seconds after the event begins to focus on the area of the most interest. Both figures show the total power output of the three DERs and is labeled "A1+A2+ESS (kW)". Finally, both figures show two graphs which represent whether units A1 and A2 have their P_{max} functionality activated which are labeled "A1 P_{max}?" and "A2 P_{max}?" respectively. These graphs are of logic values On/Off with "On" indicated by the elevated signal. These values are calculated based on whether the units output is greater than or equal to its P_{max} setting.

At t=0 s the ESS is shut off placing a 28 kW overload on A1 and A2 whose combined capability is 160 kW. The system takes 491 ms to reach the LSF of 59.2 Hz. At t = 539 ms, 48 ms after reaching the LSF, LB4 sheds 65 kW. During this time the system reaches a minimum frequency of 59.08 Hz. At t = 979 ms, 440 ms after the load shed, the system reaches a steady-state frequency of 59.99 Hz.

Initially, A2 responds to the overload more quickly than A1 and picks up more of the load on a per unit basis (A2 real power = 1.45 pu while A1 = 0.96 pu). A1 increases its share of the load and briefly provides more real power on a per unit basis before going into decline. A1 and A2 appear to be divergent at the time the load is shed. At this point A1 and A2 oscillate their share of real power for about 0.5 seconds until steady-state is reached. Note that both A1's and A2's P_{max} is activated during the overload and is then relinquished after the load shed event.

The voltage response on the microgrid remains flat during the event as does the dc bus voltage in both inverters. There is an initial reactive power flow of about 10 kVAr between A1 and A2 at the beginning of the event but this is reduced to near 0 kVAr in the steady-state after the overload is removed.

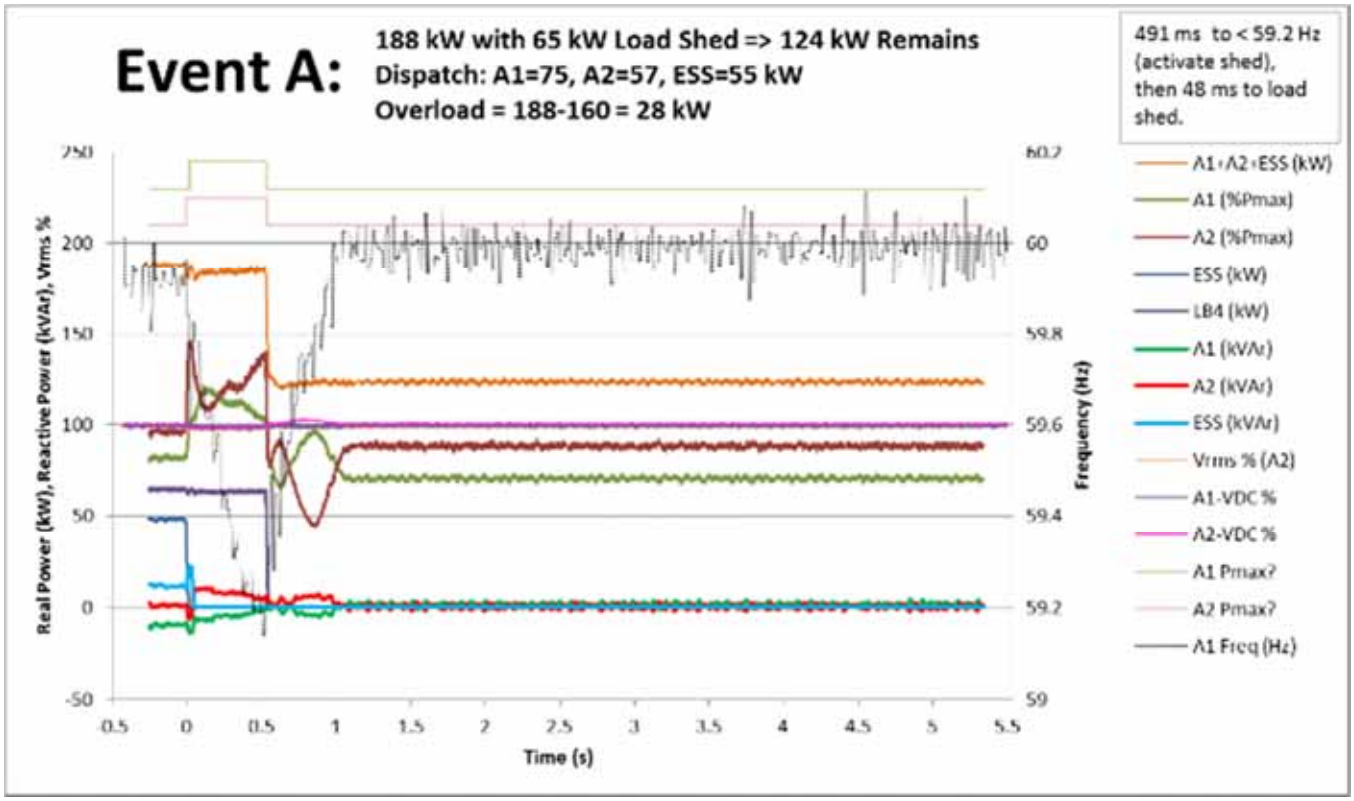

Figure 67: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event A Graph, Real & Reactive Power, Voltage, Frequency, and Pmax Status

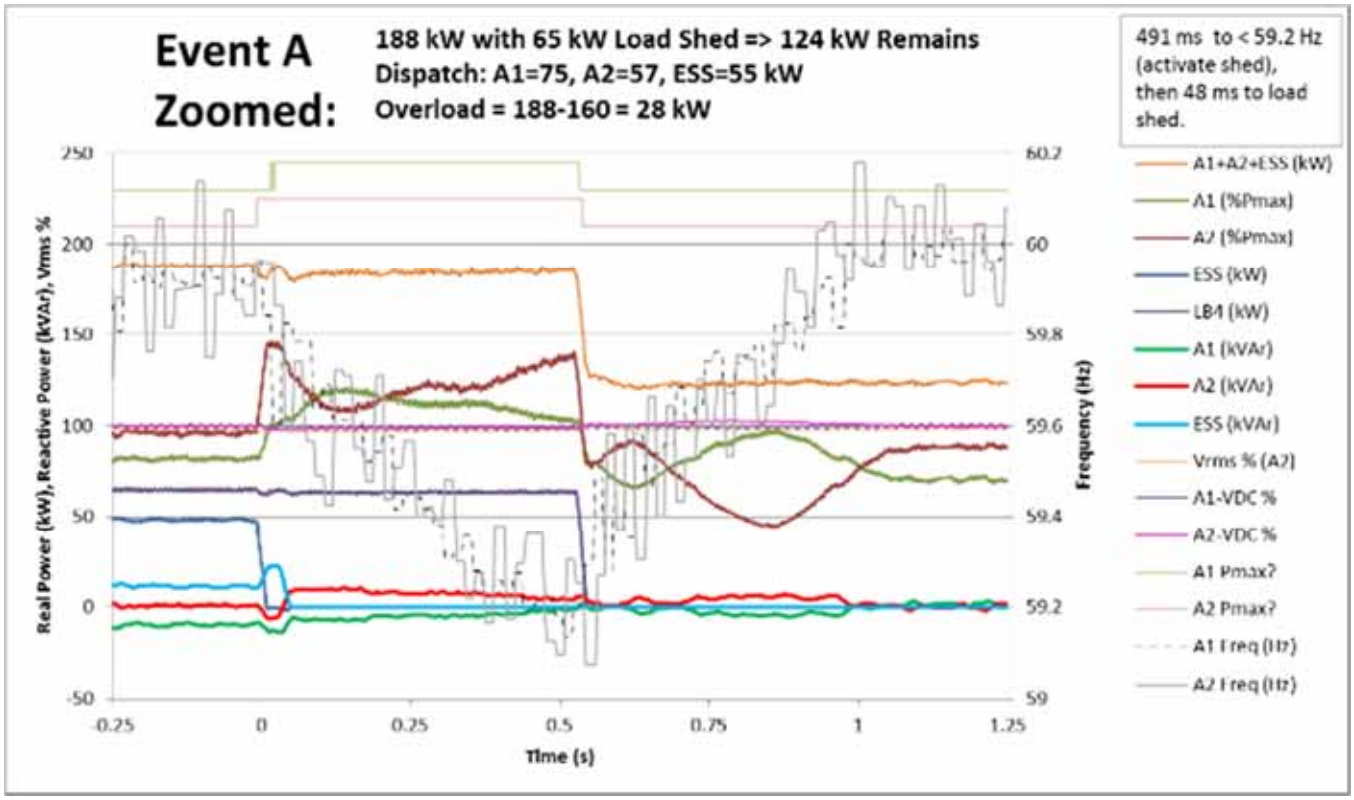

Figure 68: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event A Graph Zoomed, Real & Reactive Power, Voltage, Frequency, and Pmax Status

Figure 69 through Figure 80 show the voltage and current results of Test Event A.

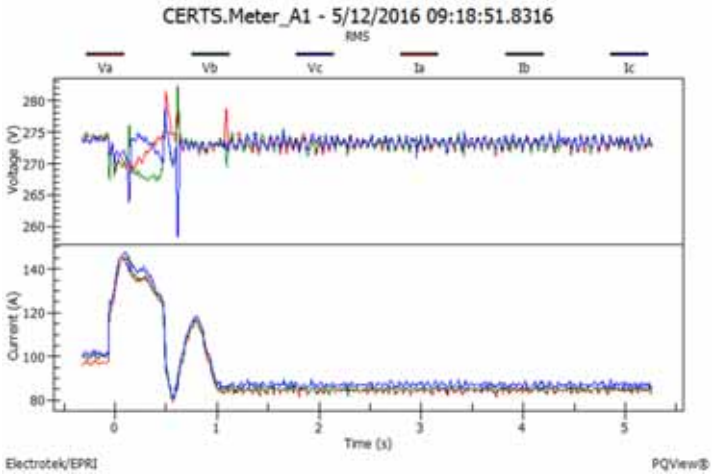

Figure 69: Test Event A: A1 A2 Microgrid Survivability, A1 RMS Voltage & Current

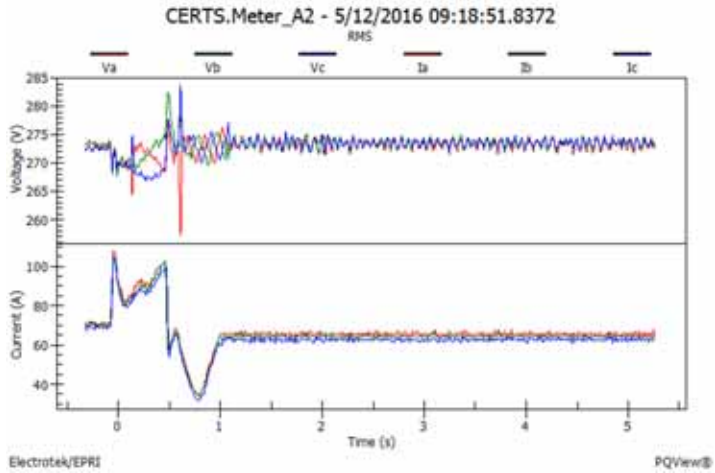

Figure 70: Test Event A: A1 A2 Microgrid Survivability, A2 RMS Voltage & Current

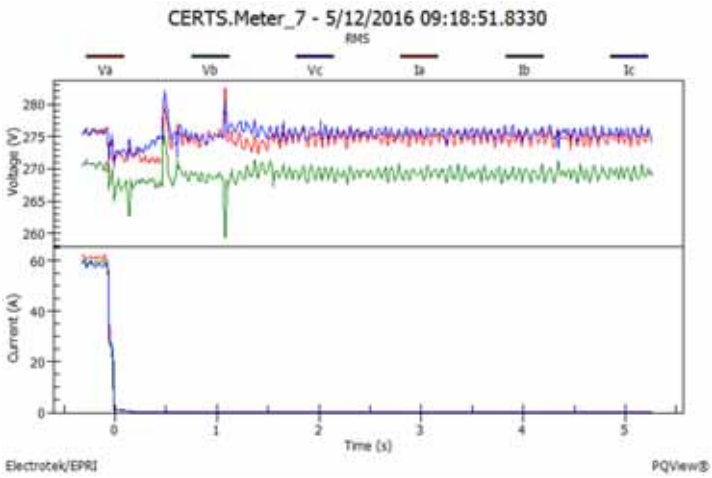

Figure 71: Test Event A: A1 A2 Microgrid Survivability, ESS RMS Voltage & Current

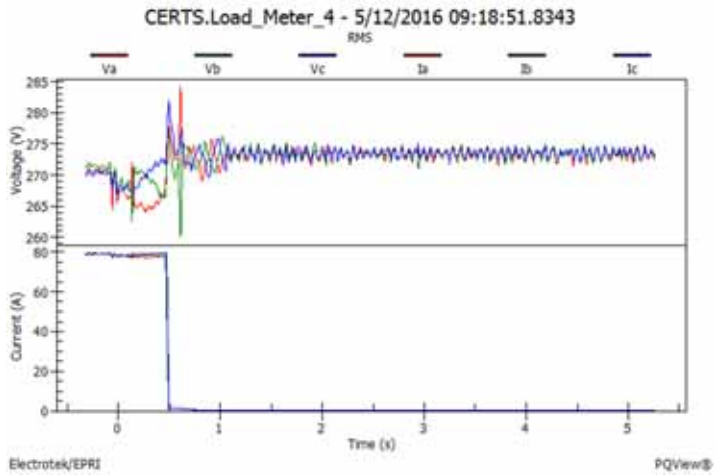

Figure 72: Test Event A: A1 A2 Microgrid Survivability, LB4 RMS Voltage & Current

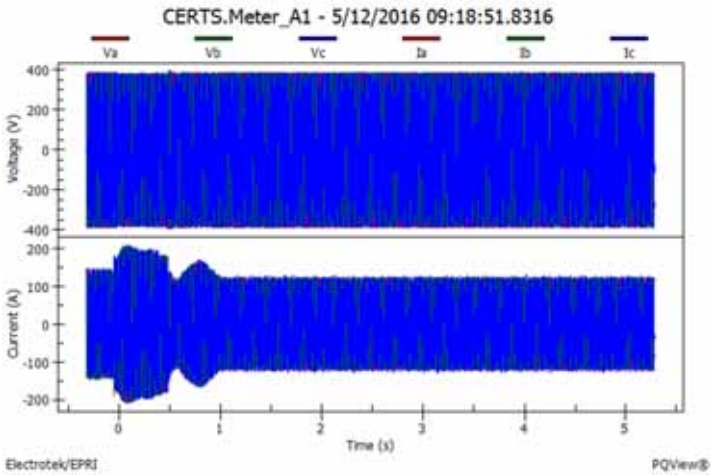

Figure 73: Test Event A: A1 A2 Microgrid Survivability, A1 Waveform Voltage & Current

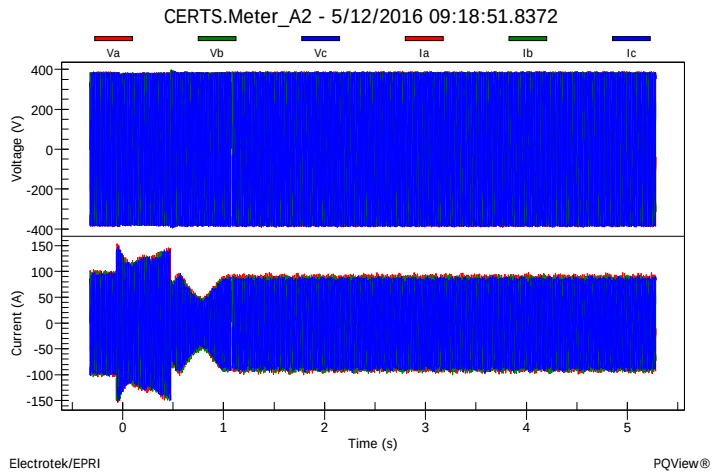

Figure 74: Test Event A: A1 A2 Microgrid Survivability, A2 Waveform Voltage & Current

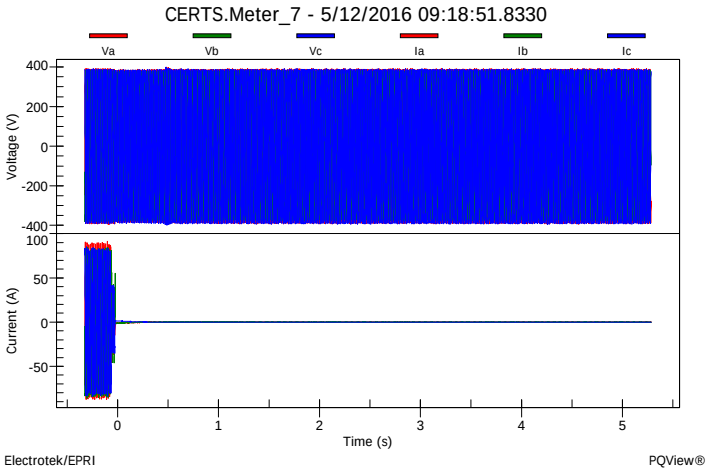

Figure 75: Test Event A: A1 A2 Microgrid Survivability, ESS Waveform Voltage & Current

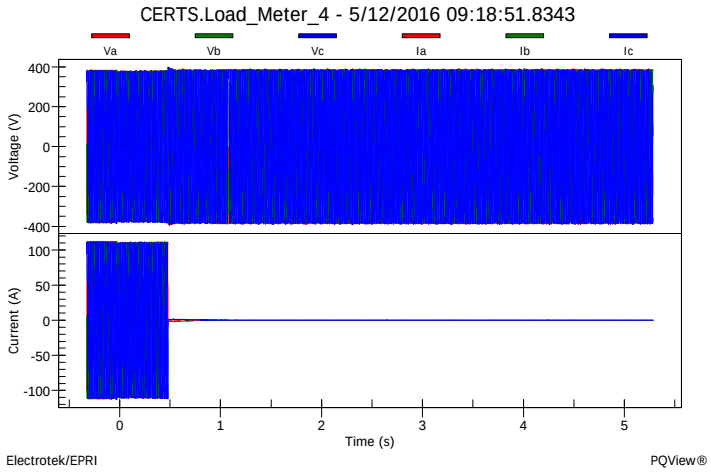

Figure 76: Test Event A: A1 A2 Microgrid Survivability, LB4 Waveform Voltage & Current

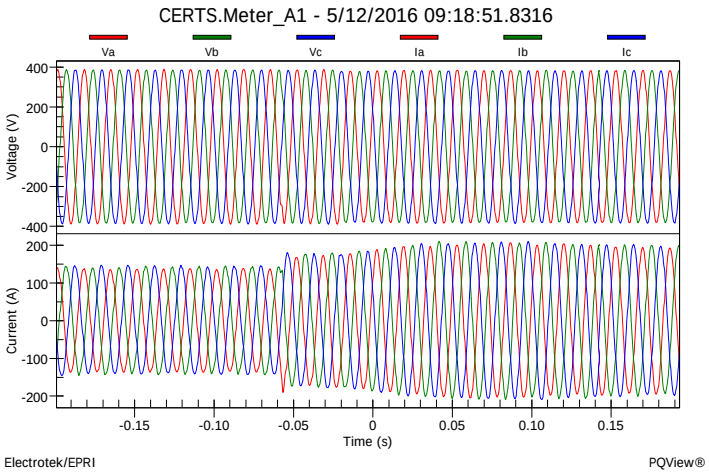

Figure 77: Test Event A: A1 A2 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

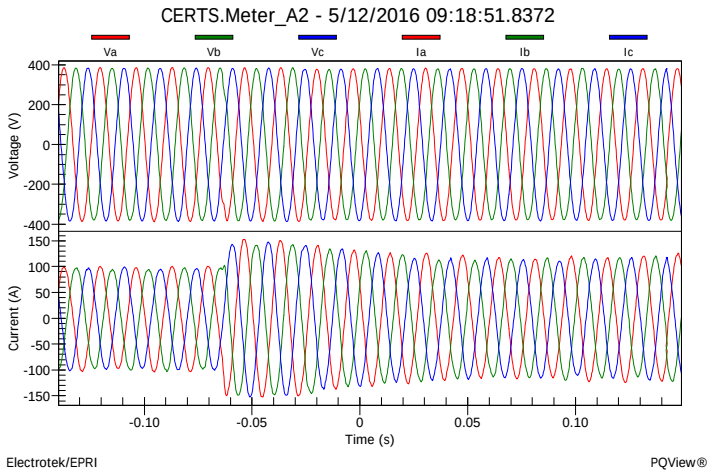

Figure 78: Test Event A: A1 A2 Microgrid Survivability, A2 Waveform (Zoomed) Voltage & Current

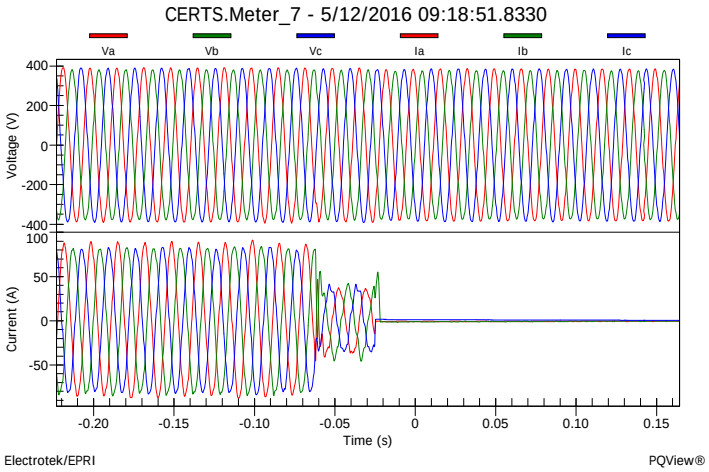

Figure 79: Test Event A: A1 A2 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

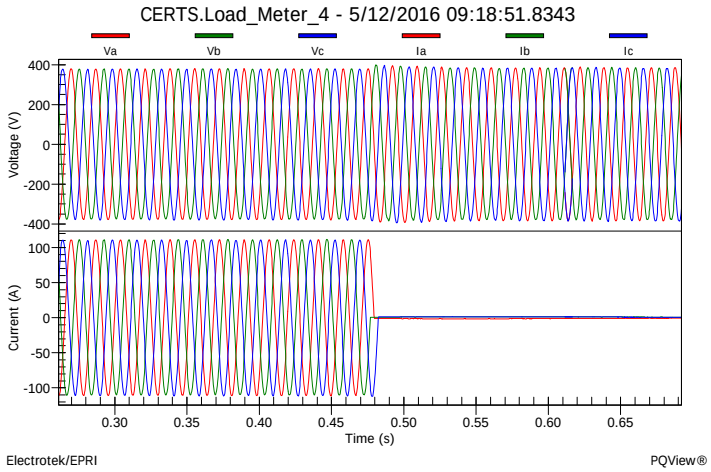

Figure 80: Test Event A: A1 A2 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

Figure 81 and Figure 82 show Test Event D's real and reactive power graphs for DERs A1, A2, and the ESS along with the real power for smart load LB4. Also included are A2's RMS voltage, A1 and A2's dc bus voltage, the microgrid frequency on the secondary axis, and the P_{max} status as ON or OFF at the top of the graph. Figure 82 shows only the first 0.8 seconds after the event begins to focus on the area of the most interest. Both figures show the total power output of the three DERs and is labeled "A1+A2+ESS (kW)". Finally, both figures show two graphs which represent whether units A1 and A2 have their P_{max} functionality activated which are labeled "A1 P_{max}?" and "A2 P_{max}?" respectively. These graphs are of logic values On/Off with "On" indicated by the elevated signal. These values are calculated based on whether the units output is greater than or equal to its P_{max} setting.

At t=0 s the ESS is shut off placing a 60 kW overload on A1 and A2 whose combined capability is 160 kW. The system takes 238 ms to reach the LSF of 59.2 Hz. At t = 325 ms, 87 ms after reaching the LSF, LB4 sheds 65 kW. During this time the system reaches a minimum frequency of 59.12 Hz.

After the load shed occurs the system reaches a quasi-steady-state condition with real power output from A1 at approximately 1.0 pu and from A2 at 0.93 pu. During this time, from t = 0.6 seconds until t = 2.2 seconds, A1's P_{max} functionality is banging on and off. This results in the system frequency being held artificially low at 59.5 Hz. Once A1 reduces its output below its P_{max} value of 100 kW the system reaches steady-state at t = 4.7 seconds with a frequency of 59.87 Hz and real power outputs of 0.97 pu from A1 and 0.98 pu from A2.

Initially, A2 responds to the overload more quickly than A1 and picks up more of the load on a per unit basis (A2 real power = 1.77 pu while A1 = 1.09 pu). A1 increases its share of the load and briefly provides more real power on a per unit basis before going into decline. A1 and A2 appear to be divergent at the time the load is shed. At this point A1 and A2 oscillate their share of real power for about 0.3 seconds until the aforementioned quasi-steady-state is reached. Note that both A1's and A2's P_{max} is activated during the overload.

The voltage response on the microgrid dips to 0.93 pu during the event while the dc bus voltage in A1 dips to 0.84 pu and A2 dips to 0.80 pu. As the voltage dips there is an increasing reactive power flow

between the two sources which peaks at 23 kVAr. After the load shed occurs the reactive power flow is reduced to a steady-state of a few kVAr.

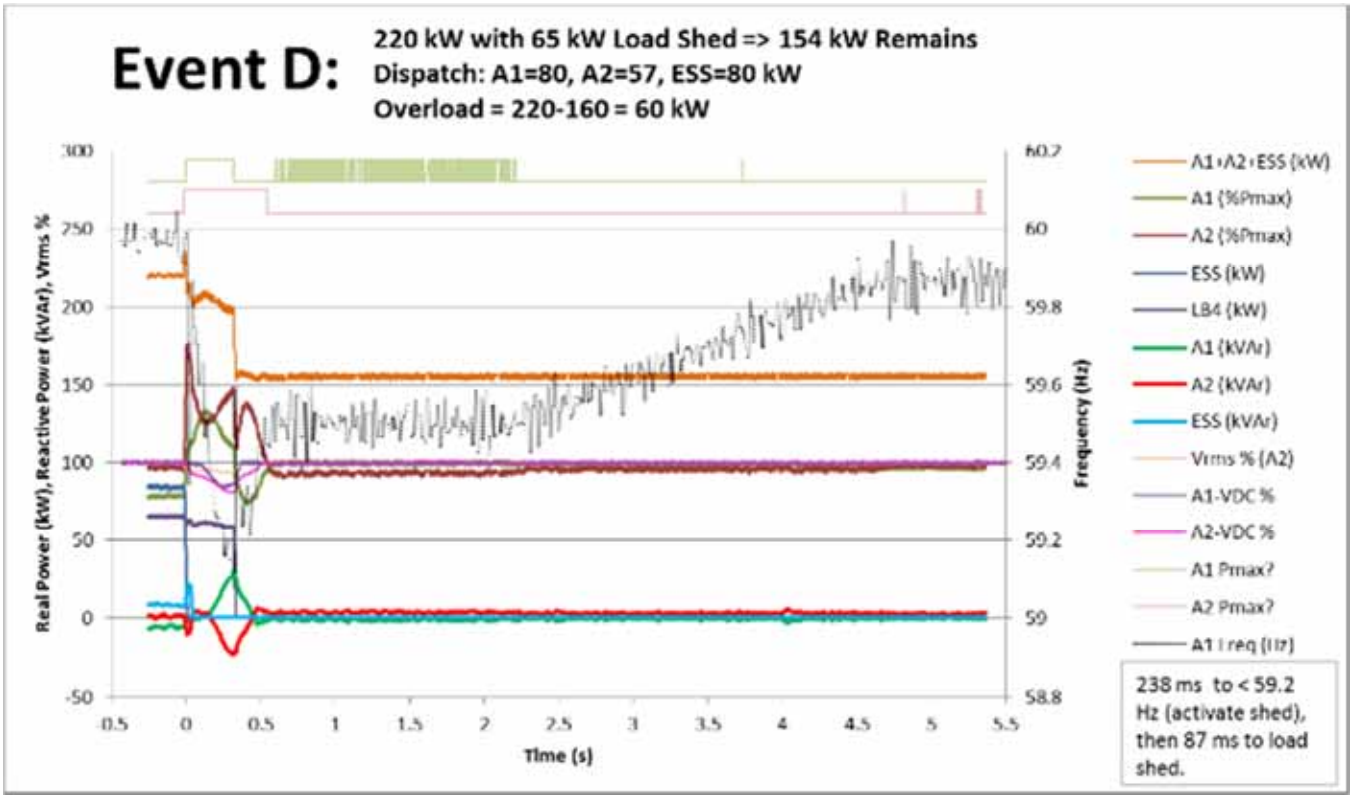

Figure 81: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event D Graph, Real & Reactive Power, Voltage, and Frequency

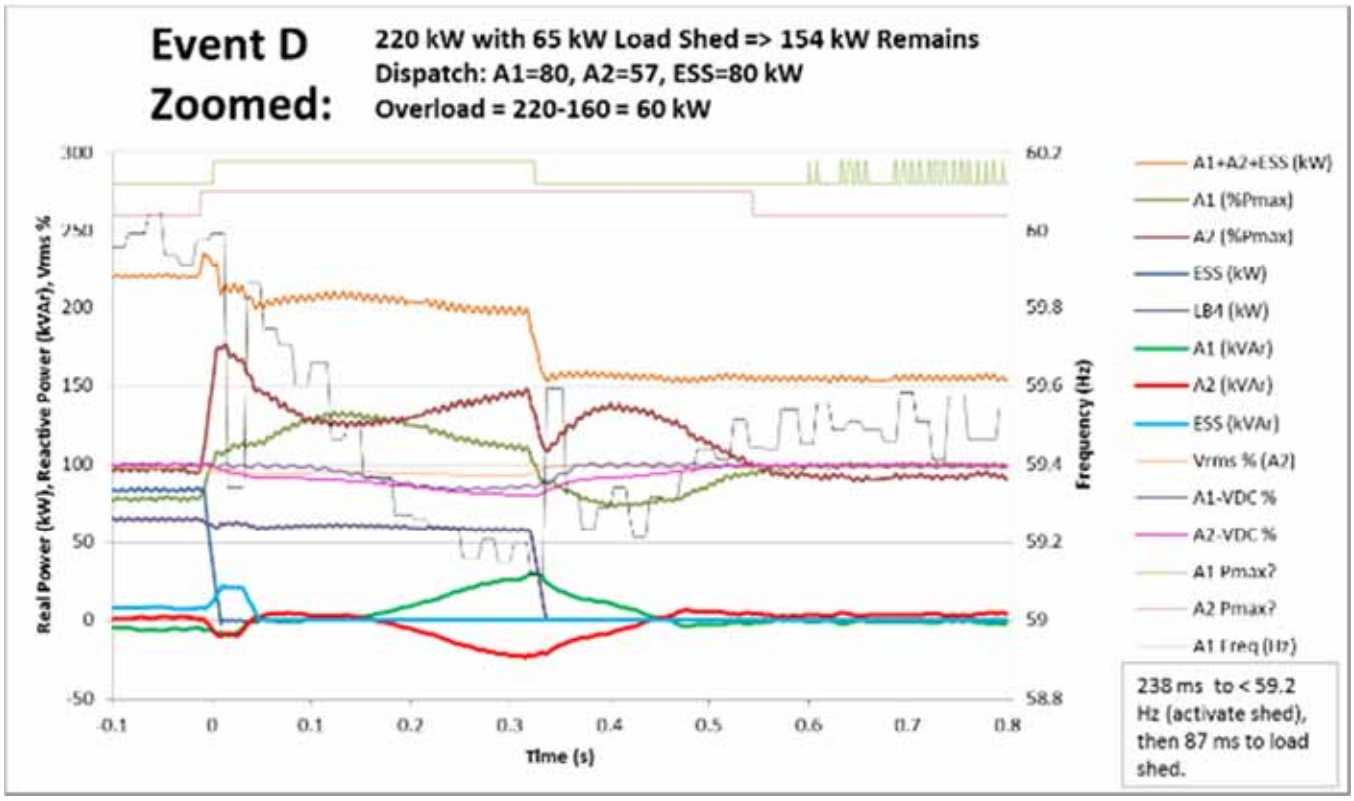

Figure 82: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event D Graph Zoomed, Real & Reactive Power, Voltage, and Frequency

Figure 83 through Figure 94 show the voltage and current results of Test Event D.

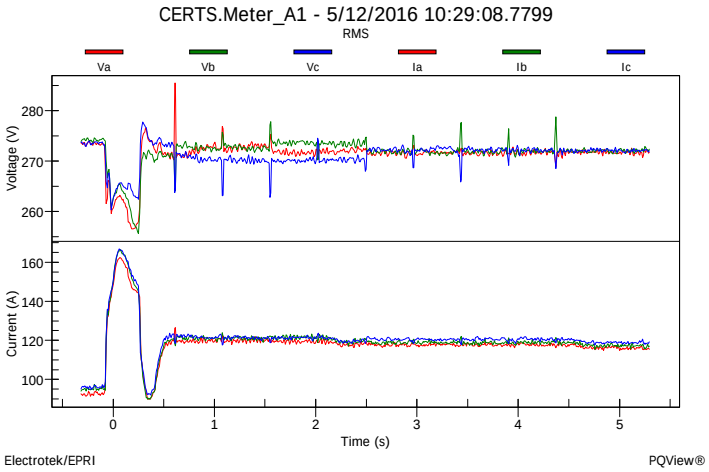

Figure 83: Test Event D: A1 A2 Microgrid Survivability, A1 RMS Voltage & Current

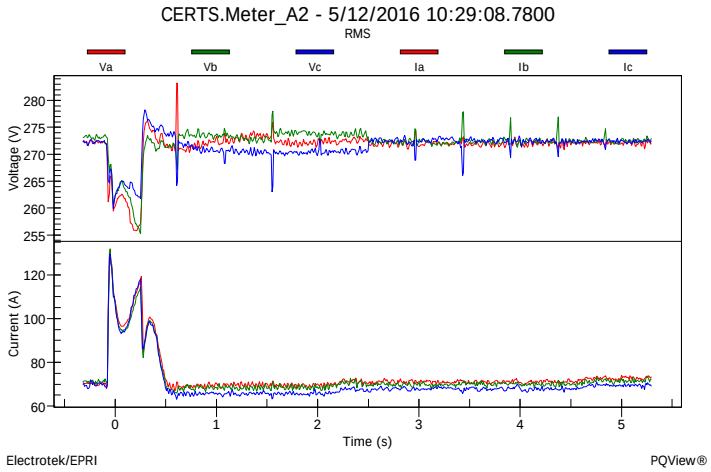

Figure 84: Test Event D: A1 A2 Microgrid Survivability, A2 RMS Voltage & Current

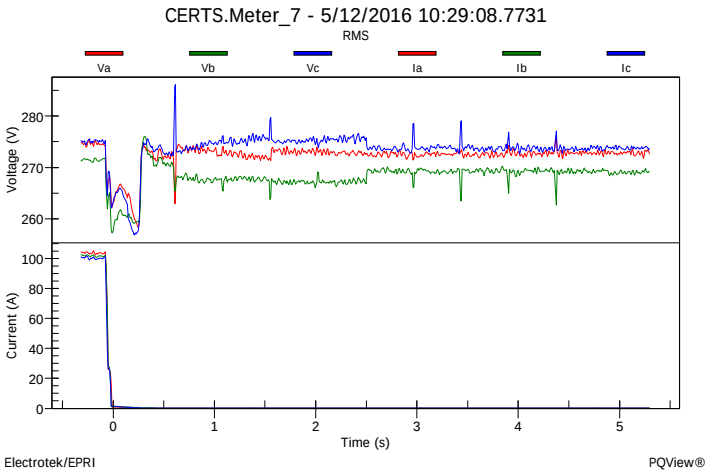

Figure 85: Test Event D: A1 A2 Microgrid Survivability, ESS RMS Voltage & Current

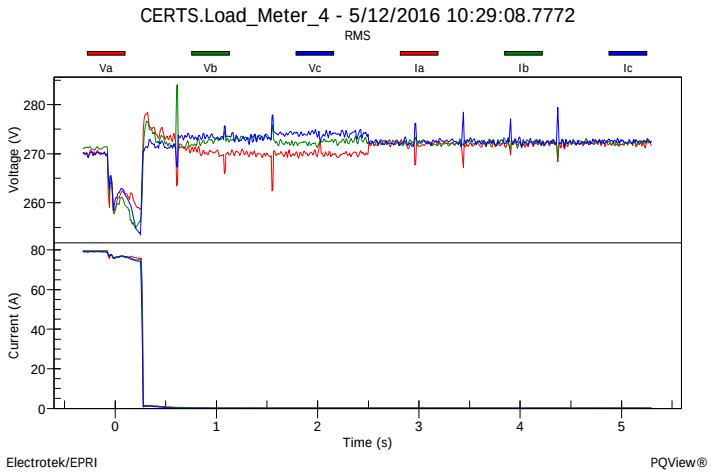

Figure 86: Test Event D: A1 A2 Microgrid Survivability, LB4 RMS Voltage & Current

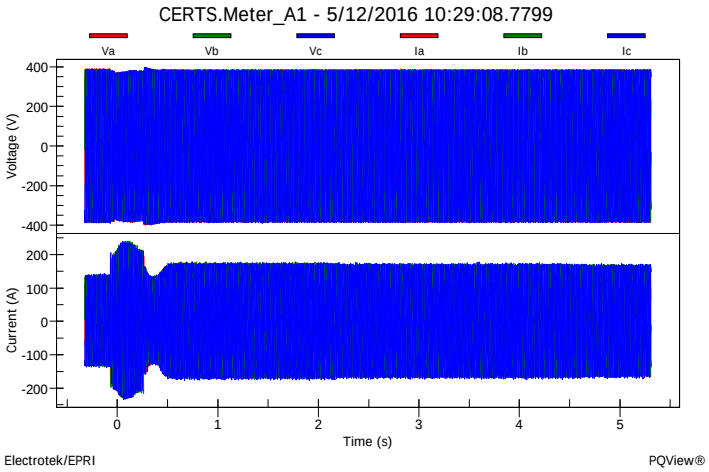

Figure 87: Test Event D: A1 A2 Microgrid Survivability, A1 Waveform Voltage & Current

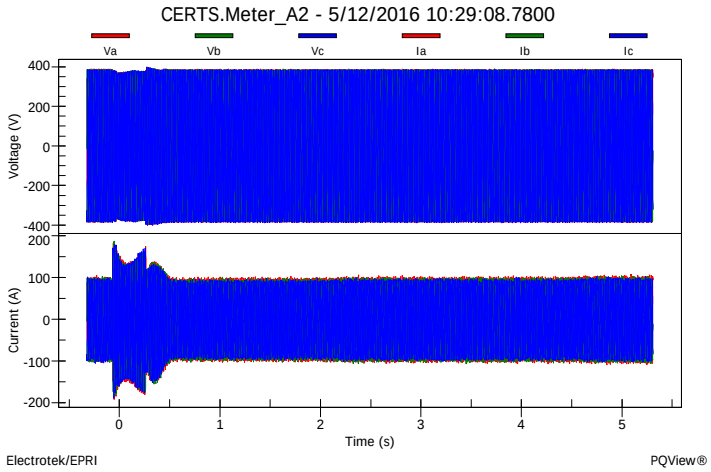

Figure 88: Test Event D: A1 A2 Microgrid Survivability, A2 Waveform Voltage & Current

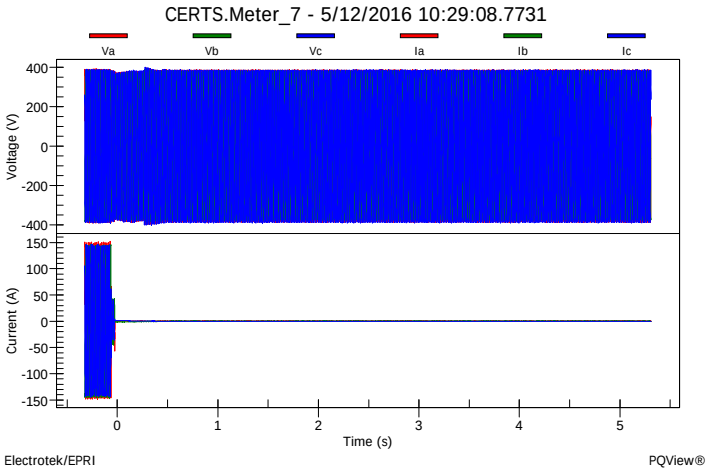

Figure 89: Test Event D: A1 A2 Microgrid Survivability, ESS Waveform Voltage & Current

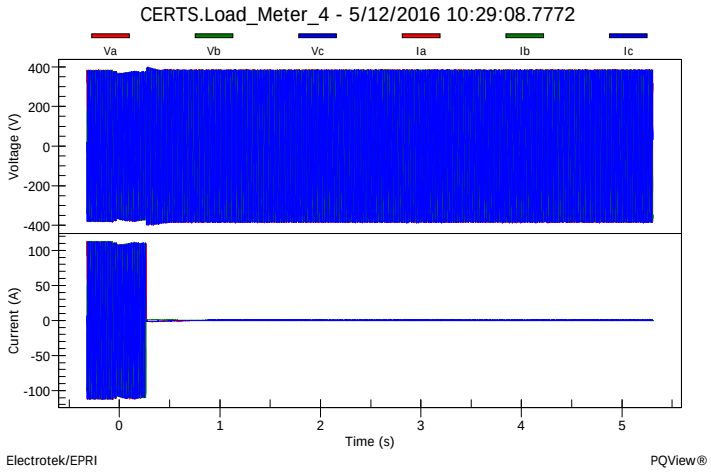

Figure 90: Test Event D: A1 A2 Microgrid Survivability, LB4 Waveform Voltage & Current

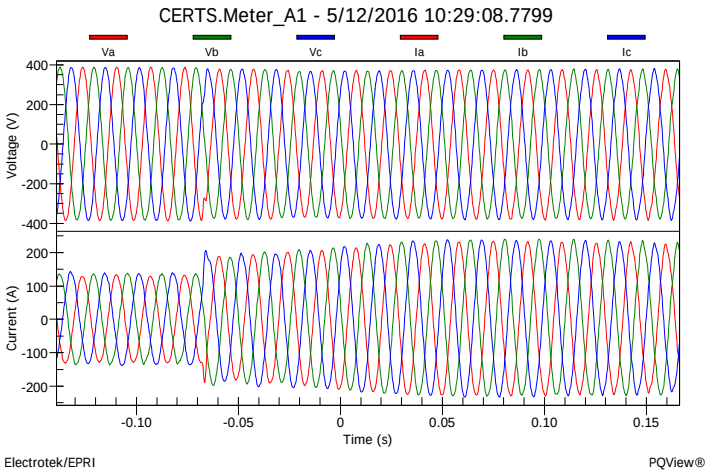

Figure 91: Test Event D: A1 A2 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

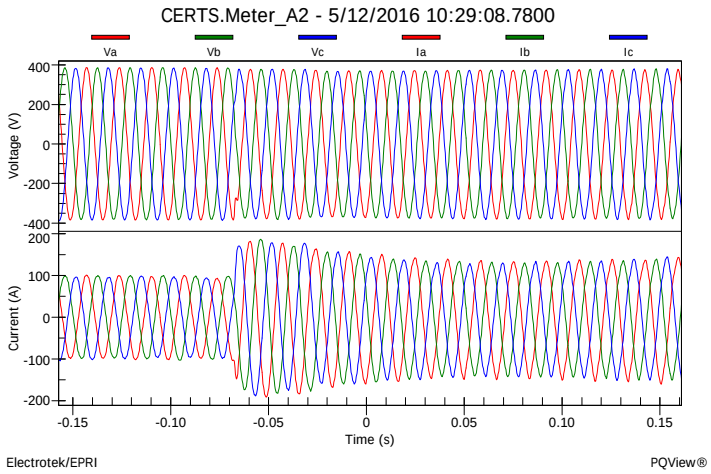

Figure 92: Test Event D: A1 A2 Microgrid Survivability, A2 Waveform (Zoomed) Voltage & Current

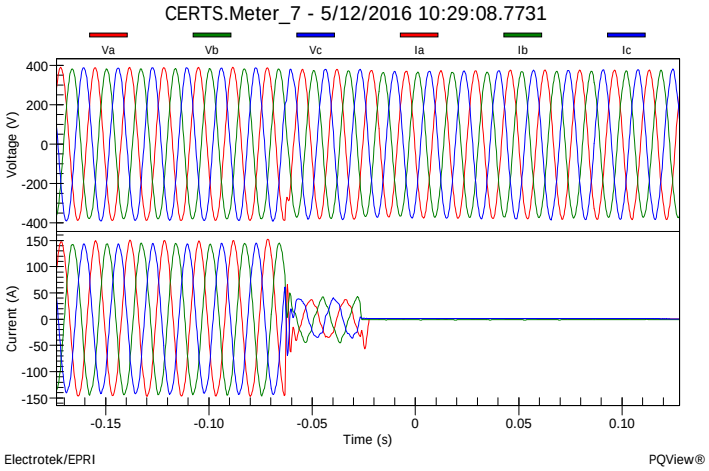

Figure 93: Test Event D: A1 A2 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

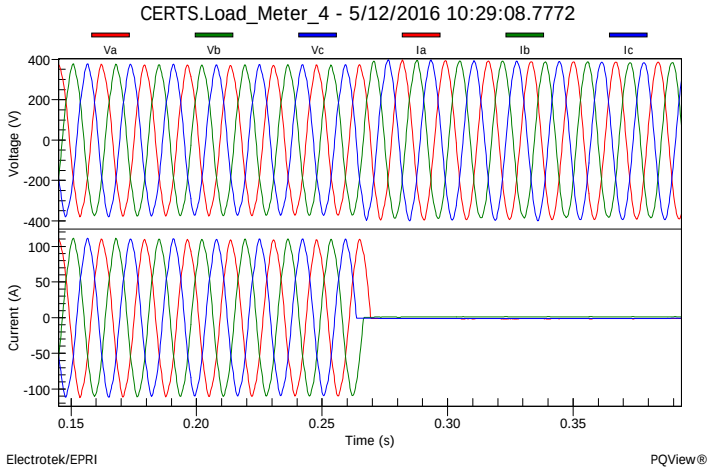

Figure 94: Test Event D: A1 A2 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

Figure 95 through Figure 97 show Test Events E's real and reactive power graphs for DERs A1, A2, and the ESS along with the real power for smart load LB4. Also included are A1's RMS voltage, A1 and A2's dc bus voltage, the microgrid frequency on the secondary axis, and the P_{max} status as ON or OFF at the top of the graph. Figure 96 shows the first 0.6 seconds after the event begins while Figure 97 shows time from 1 second to 4 seconds after the event begins to focus on the areas of the most interest. All figures show the total power output of the three DERs and is labeled "A1+A2+ESS (kW)". Finally, both figures show two graphs which represent whether units A1 and A2 have their P_{max} functionality activated which are labeled "A1 P_{max}?" and "A2 P_{max}?" respectively. These graphs are of logic values On/Off with "On" indicated by the elevated signal. These values are calculated based on whether the units output is greater than or equal to its P_{max} setting.

At t=0 s the ESS is shut off placing a 64 kW overload on A1 and A2 whose combined capability is 160 kW. The system takes 188 ms to reach the LSF of 59.2 Hz. At t = 252 ms, 64 ms after reaching the LSF, LB4 sheds 64 kW. During this time the system reaches a minimum frequency of 59.11 Hz.

At t=240 ms A1 and A2's dc busses reach a minimum of approximately 0.8 pu and A1's ac voltage dips to 0.92 pu. A1's ac voltage recovers to nominal at t=276 ms. A1's dc bus recovers to nominal at t=331 ms while A2's dc bus doesn't recover until t = 450 ms. At this time the DERs are serving the 165 kW load which exceeds their rated capacity of 160 kW by 3%, however the frequency is recovering from its minimum and trending upward. It appears that the microgrid will survive this event.

However, at t=1.06 s A2's dc bus voltage begins to decline. At t=1.6 s A2's dc bus voltage reaches 0.92 pu and a large reactive power flow is triggered from A1 to A2. At t=2.62 s A2's dc bus voltage has completely collapsed reaching 0.005 pu while A2's current peaked at 247 A RMS or 3.42 pu and its

voltage dipped to 122 V RMS or 0.44 pu. At t=2.95 s A2 trips. A1 then attempts to pick up the entire 229 kW load which is not possible and it eventually trips and the microgrid collapses.

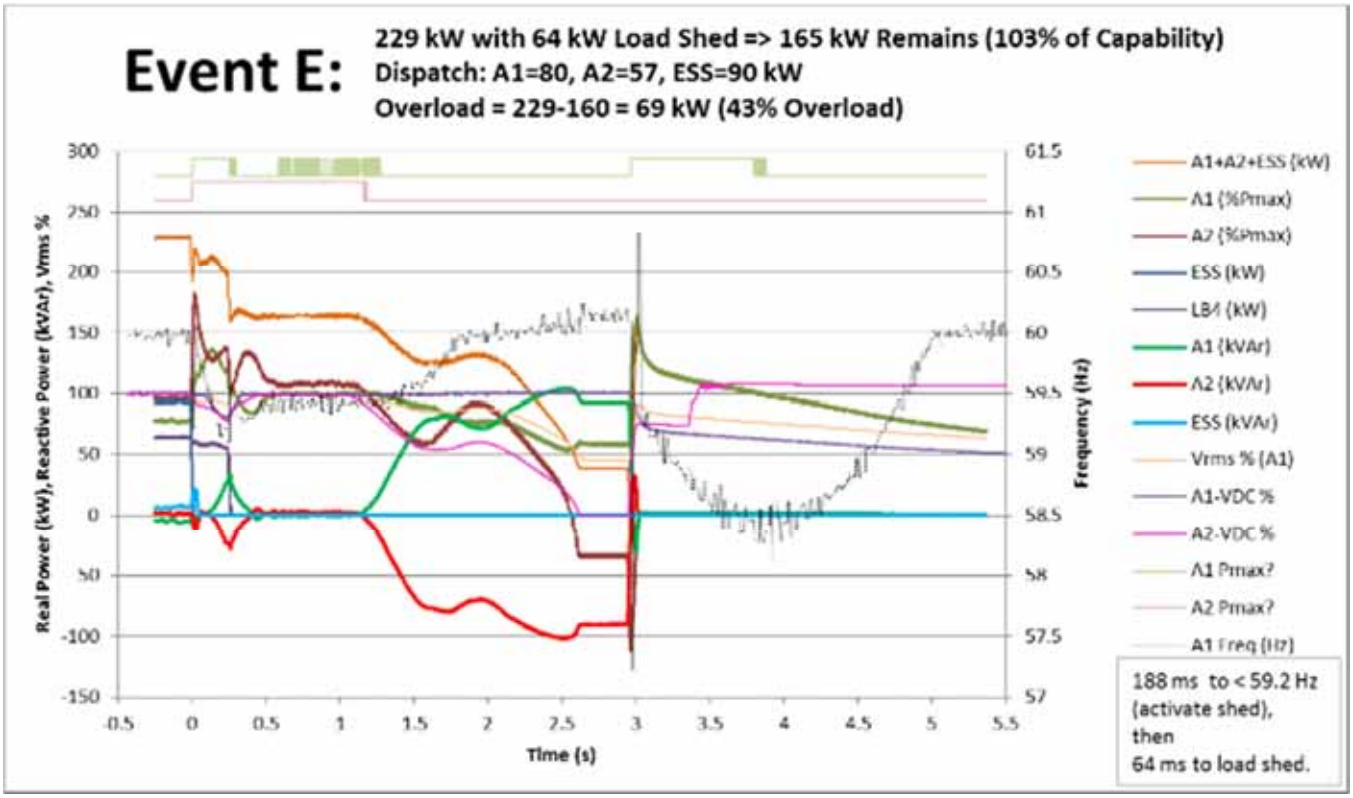

Figure 95: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event E Graph, Real & Reactive Power, Voltage, and Frequency

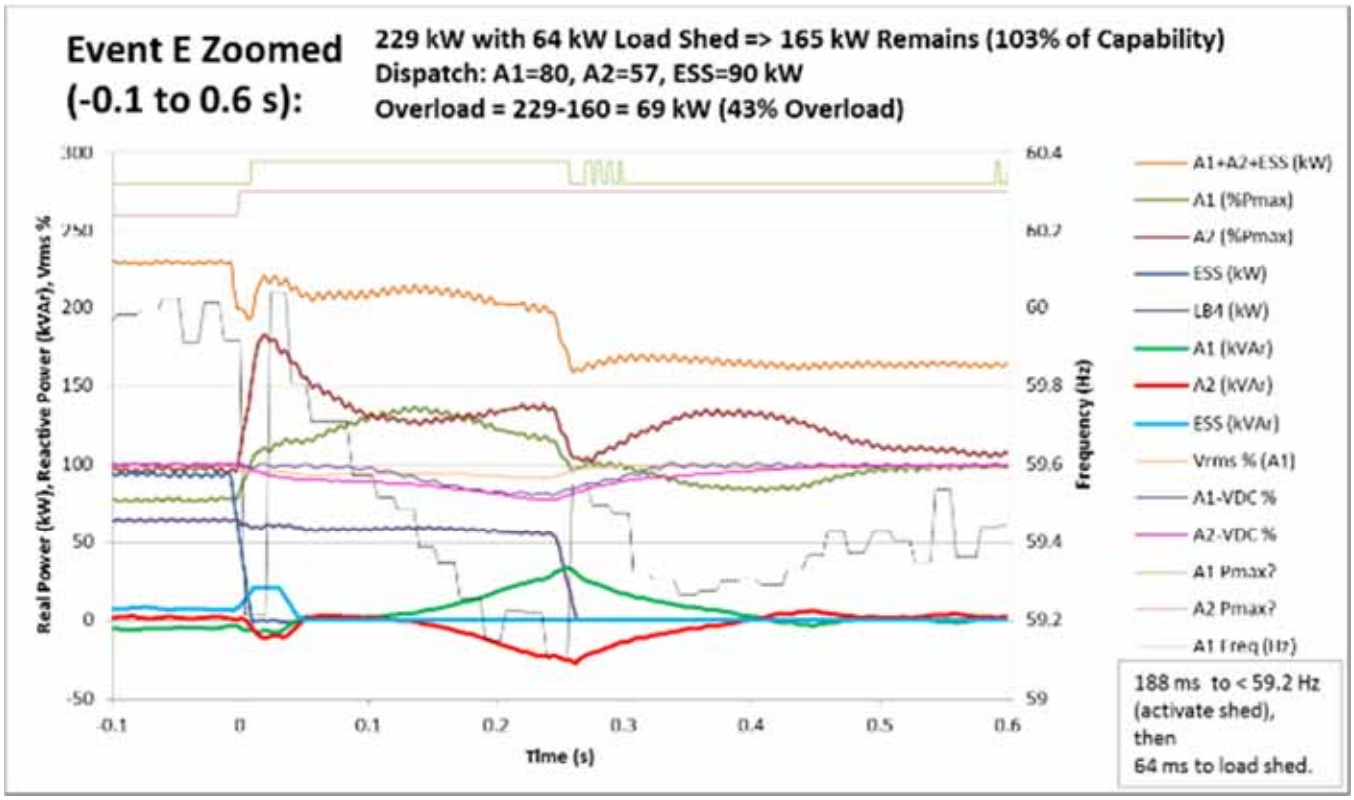

Figure 96: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event E Graph Zoomed (-0.1 to 0.6 s), Real & Reactive Power, Voltage, and Frequency

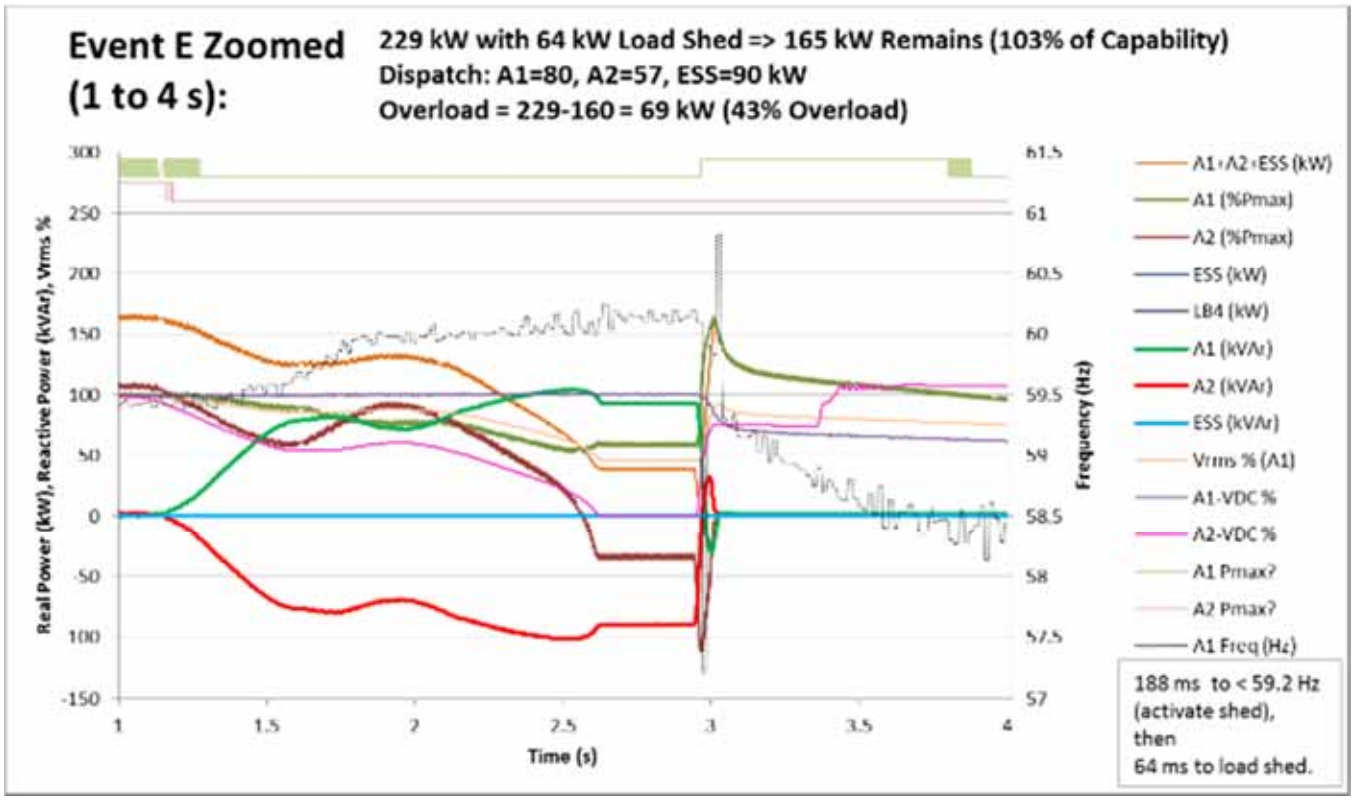

Figure 97: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event E Graph Zoomed (1 to 4 s), Real & Reactive Power, Voltage, and Frequency

Figure 98 through Figure 109 show the voltage and current results of Test Event E.

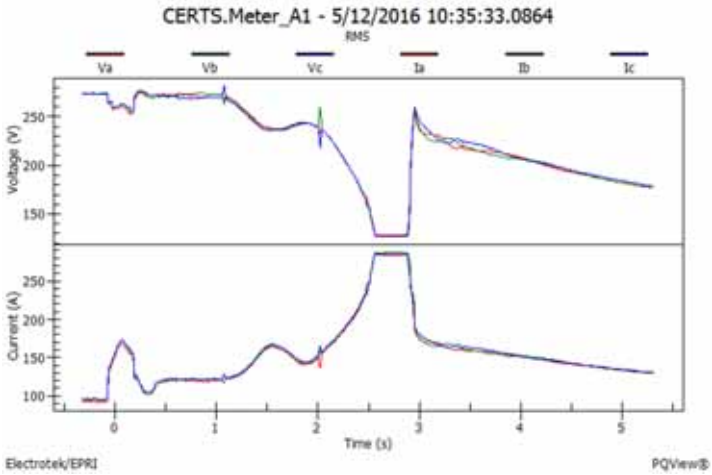

Figure 98: Test Event E: A1 A2 Microgrid Survivability, A1 RMS Voltage & Current

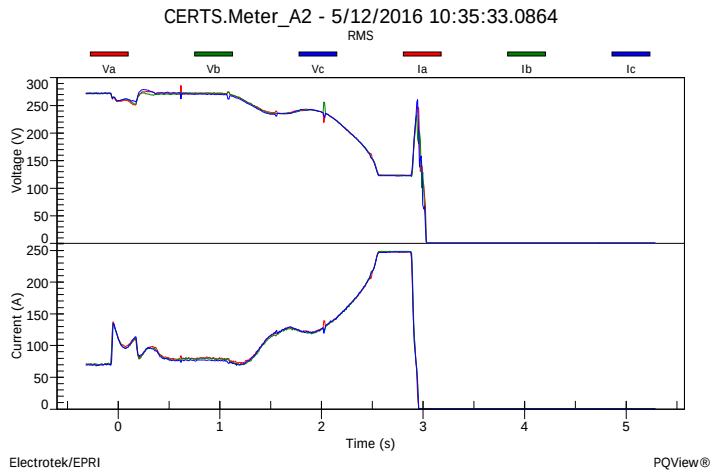

Figure 99: Test Event E: A1 A2 Microgrid Survivability, A2 RMS Voltage & Current

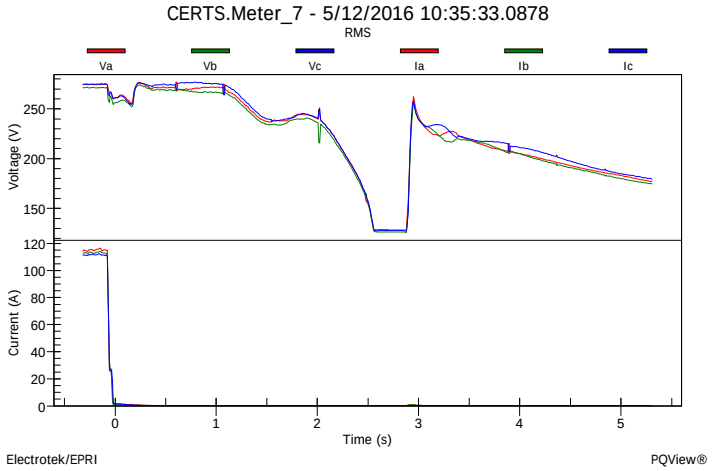

Figure 100: Test Event E: A1 A2 Microgrid Survivability, ESS RMS Voltage & Current

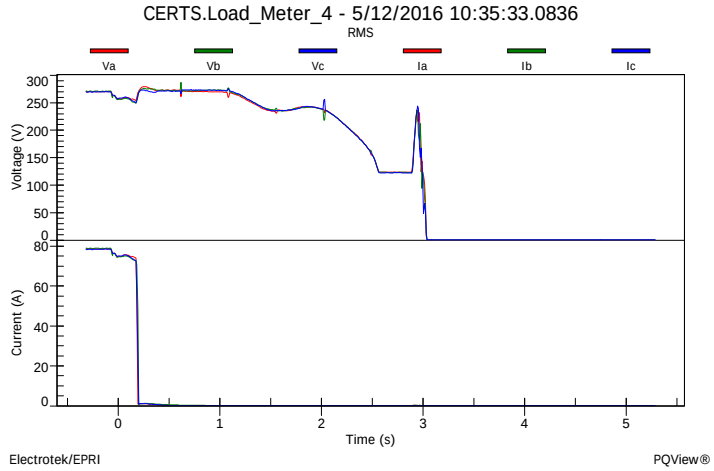

Figure 101: Test Event E: A1 A2 Microgrid Survivability, LB4 RMS Voltage & Current

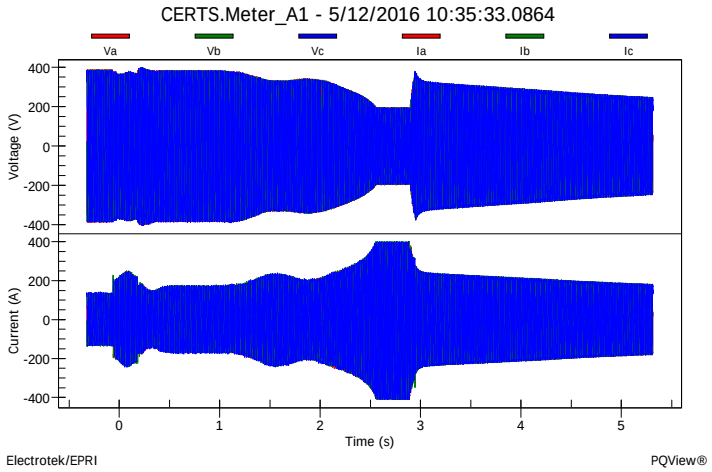

Figure 102: Test Event E: A1 A2 Microgrid Survivability, A1 Waveform Voltage & Current

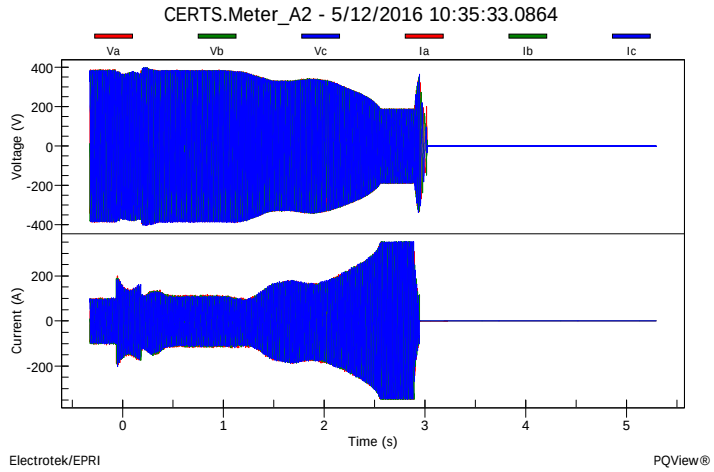

Figure 103: Test Event E: A1 A2 Microgrid Survivability, A2 Waveform Voltage & Current

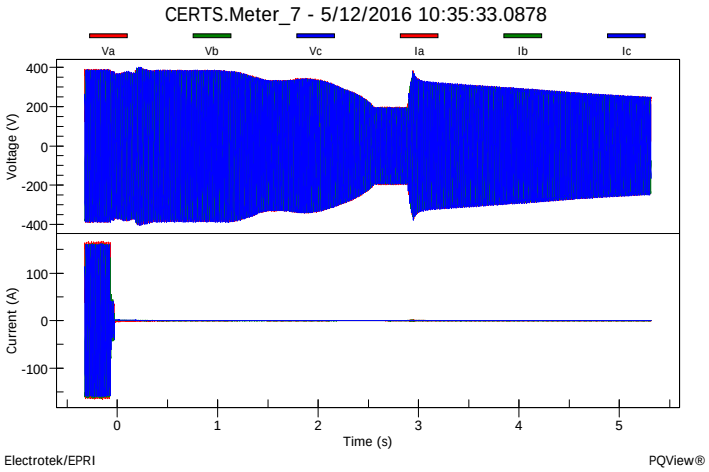

Figure 104: Test Event E: A1 A2 Microgrid Survivability, ESS Waveform Voltage & Current

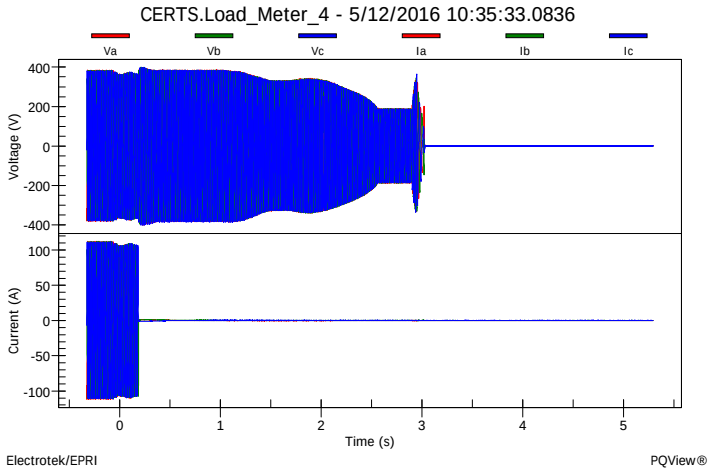

Figure 105: Test Event E: A1 A2 Microgrid Survivability, LB4 Waveform Voltage & Current

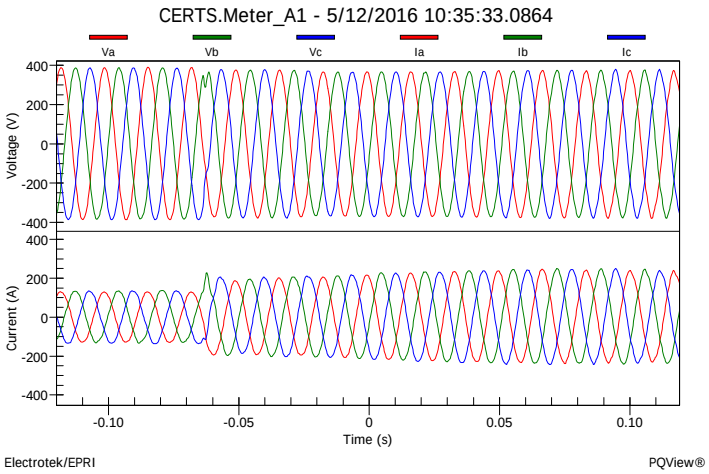

Figure 106: Test Event E: A1 A2 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

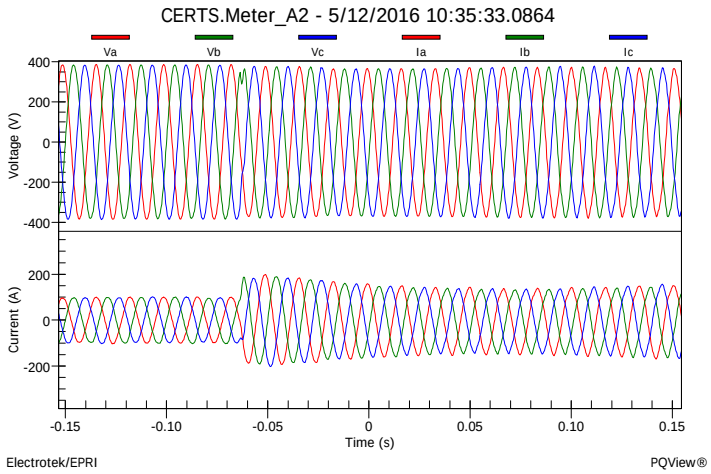

Figure 107: Test Event E: A1 A2 Microgrid Survivability, A2 Waveform (Zoomed) Voltage & Current

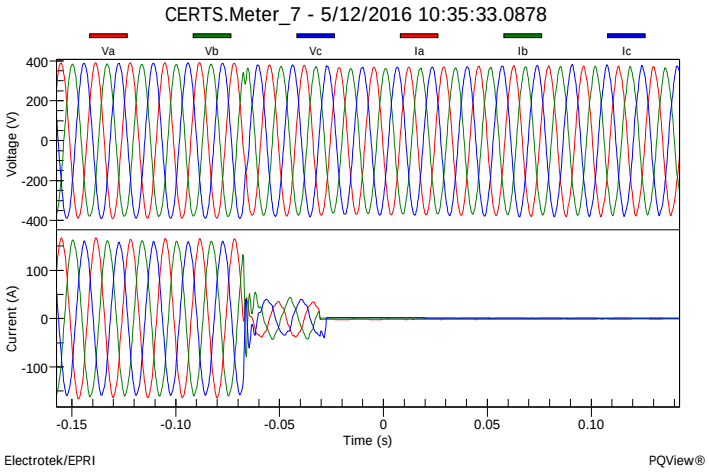

Figure 108: Test Event E: A1 A2 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

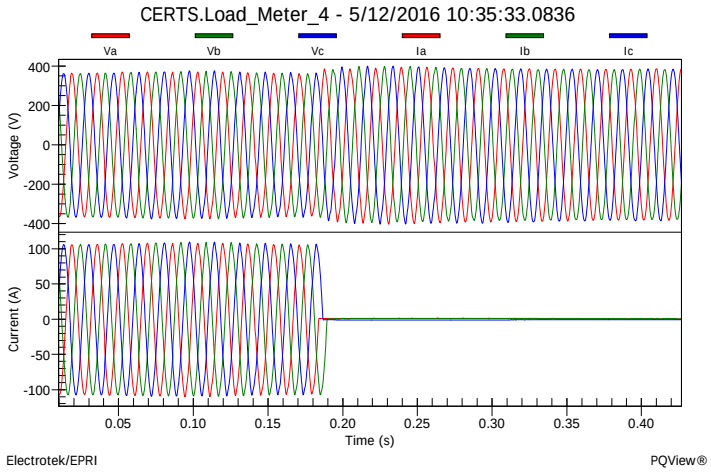

Figure 109: Test Event E: A1 A2 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

Figure 110 and Figure 111 show Test Events G's real and reactive power graphs for DERs A1, B1, and the ESS along with the real power for smart load LB4. Also included are B1's RMS voltage, A1's dc bus voltage, and the microgrid frequency on the secondary axis. Figure 54 shows only the first 0.2 s after the event begins to focus on the area of the most interest.

At t=0 s the ESS is shut off placing a 77 kW overload on A1 and A2 whose combined capability is 160 kW. This is the largest overload applied to the combination of A1 and A2 as part of these tests. The system takes 44 ms to reach the LSF of 59.2 Hz. At t = 57 ms, 13 ms after reaching the LSF, LB4 sheds 87 kW. During this time the system reaches a minimum frequency of 59.19 Hz. At t = 600 ms, 543 ms after the load is shed, the system returns to a steady-state condition serving 150 kW or 94% of its capability.

It is noted that the loss of the ESS which initiates the overload results in a transient flow of reactive power of 20 kVAr from the ESS to A1 and A2. Then the load shed event results in a transient flow of reactive power flow of 10 kVAr between the two remaining sources, A1 and A2.

With A1 and A2, both inverter-connected sources, there is no oscillation in the real and reactive power as there was with A1 and B1.

During the overload time A1's dc bus dips to 0.97 pu while A2's dc bus dips to 0.91 pu. A2's terminal voltage dips to 0.94 pu ac RMS. After the load is shed A1 and A2's dc bus recovers and returns to nominal voltage at about t = 70 ms. The microgrid survives this challenging overload event.

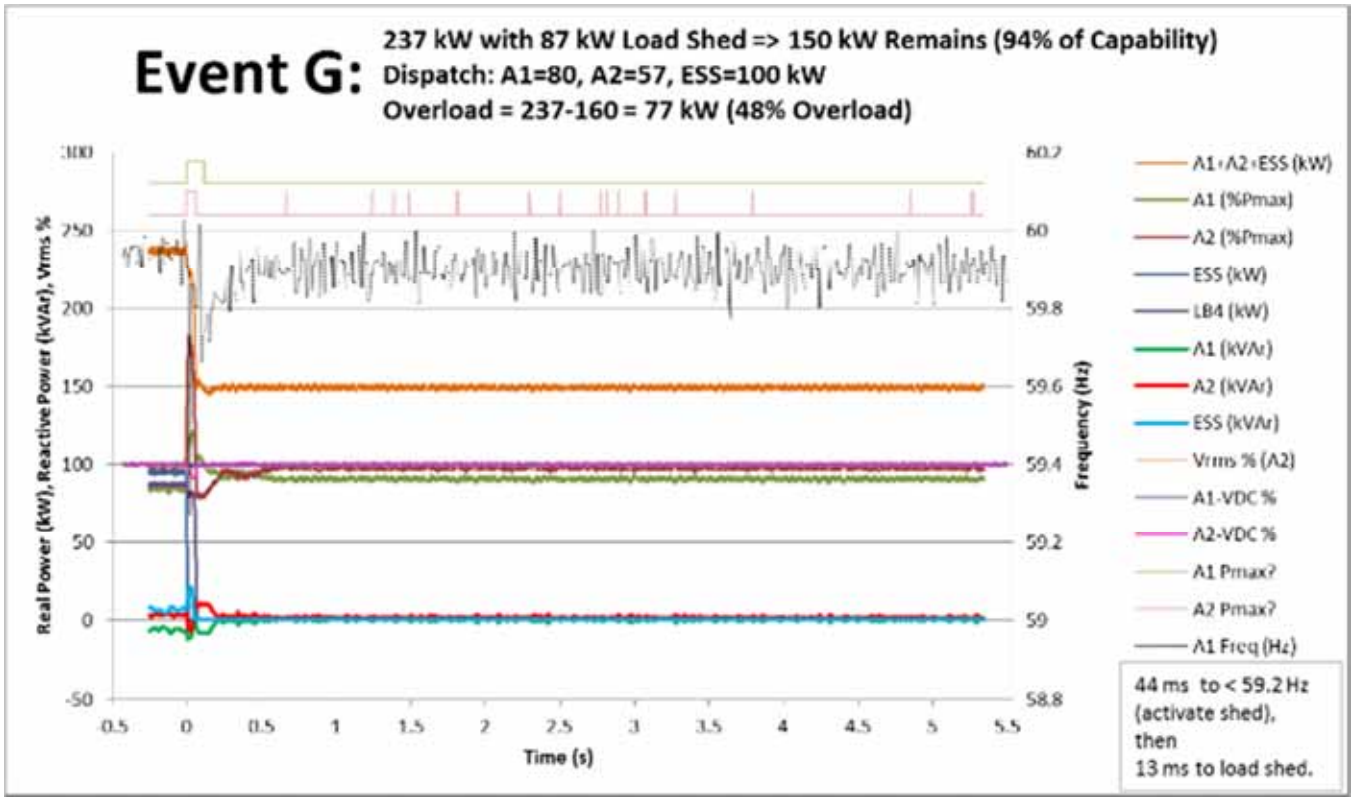

Figure 110: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event G Graph, Real & Reactive Power, Voltage, and Frequency

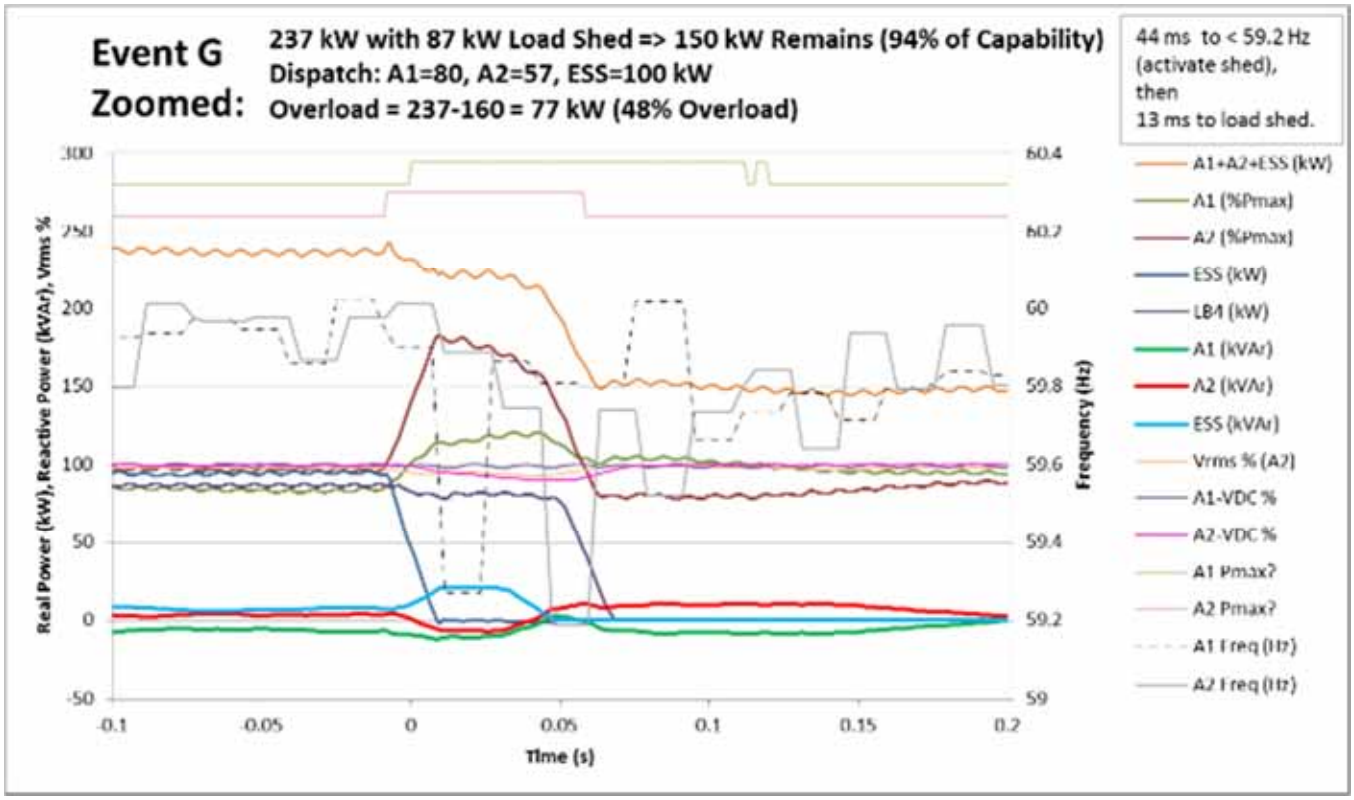

Figure 111: Improved Load Shed Algorithm – A1 A2 Microgrid Survivability Test Event G Graph Zoomed, Real & Reactive Power, Voltage, and Frequency

Figure 112 through Figure 123 show the voltage and current results of Test Event G.

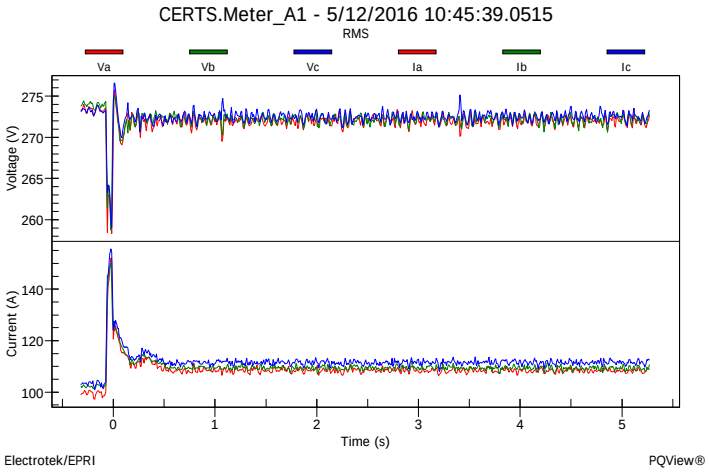

Figure 112: Test Event G: A1 A2 Microgrid Survivability, A1 RMS Voltage & Current

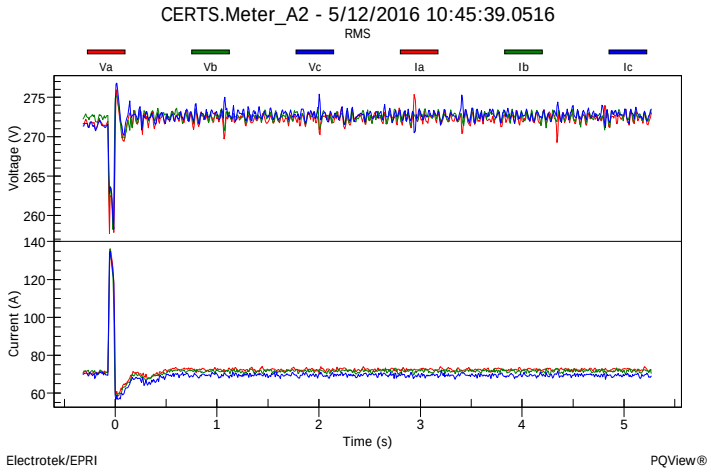

Figure 113: Test Event G: A1 A2 Microgrid Survivability, A2 RMS Voltage & Current

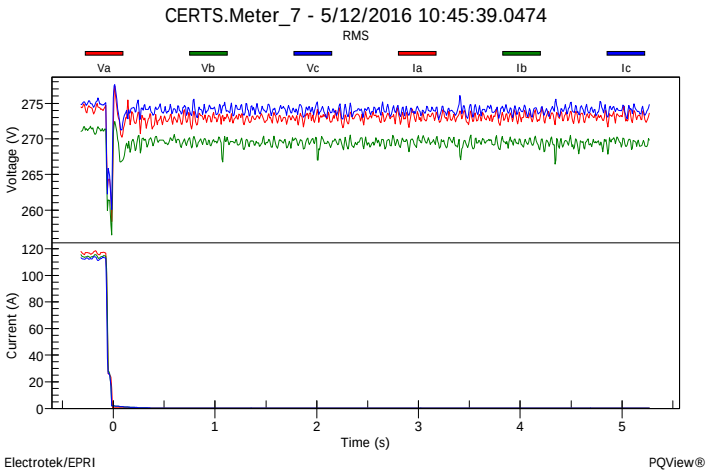

Figure 114: Test Event G: A1 A2 Microgrid Survivability, ESS RMS Voltage & Current

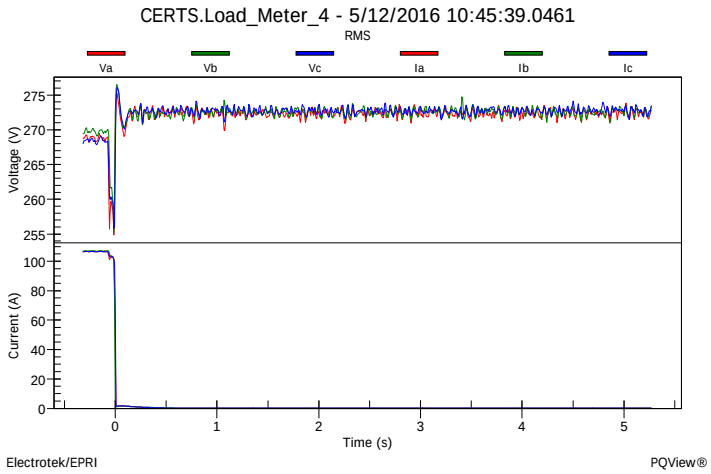

Figure 115: Test Event G: A1 A2 Microgrid Survivability, LB4 RMS Voltage & Current

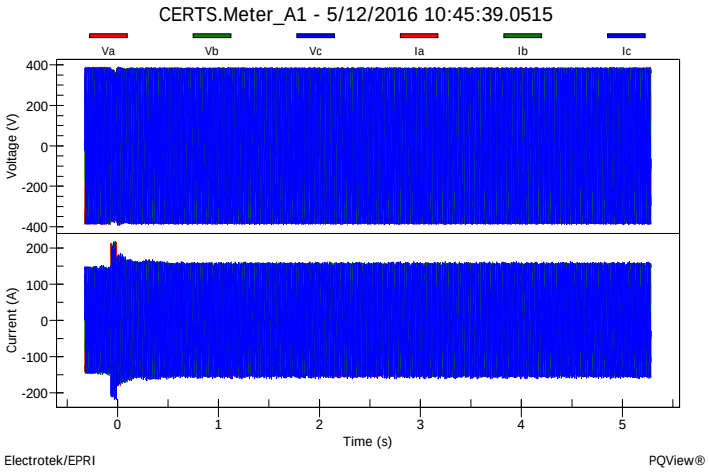

Figure 116: Test Event G: A1 A2 Microgrid Survivability, A1 Waveform Voltage & Current

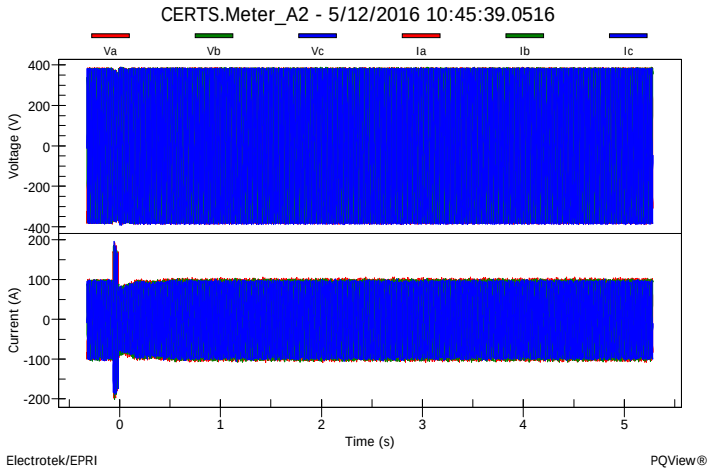

Figure 117: Test Event G: A1 A2 Microgrid Survivability, A2 Waveform Voltage & Current

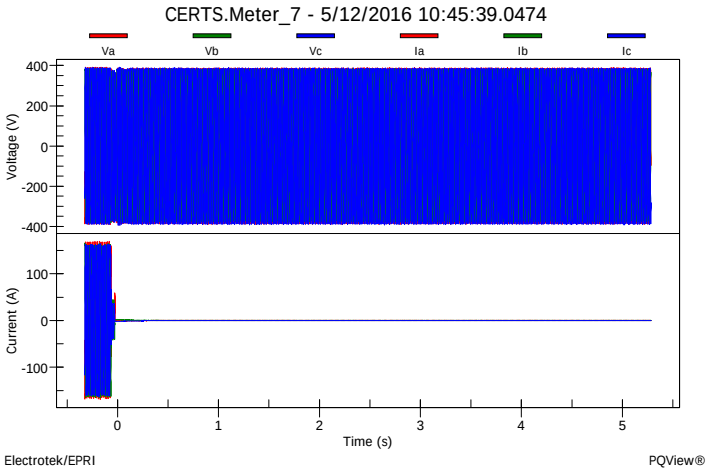

Figure 118: Test Event G: A1 A2 Microgrid Survivability, ESS Waveform Voltage & Current

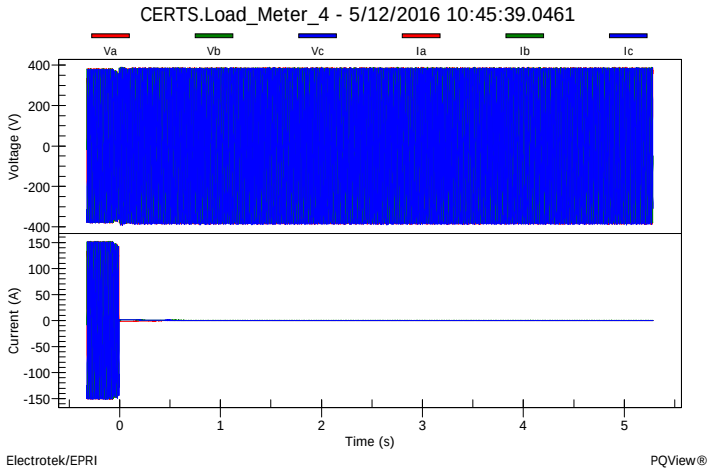

Figure 119: Test Event G: A1 A2 Microgrid Survivability, LB4 Waveform Voltage & Current

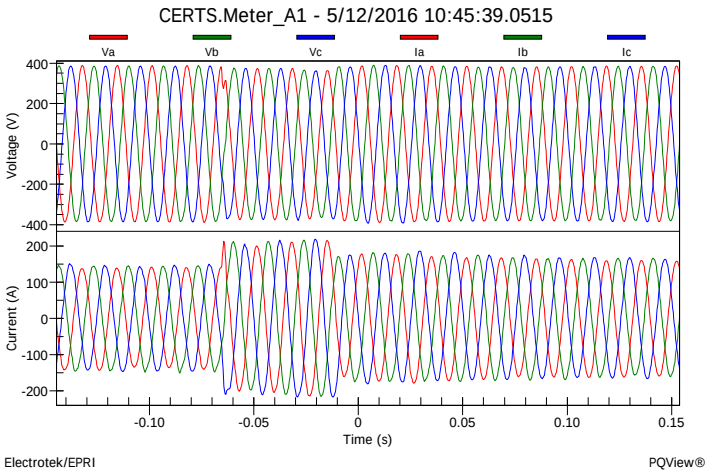

Figure 120: Test Event G: A1 A2 Microgrid Survivability, A1 Waveform (Zoomed) Voltage & Current

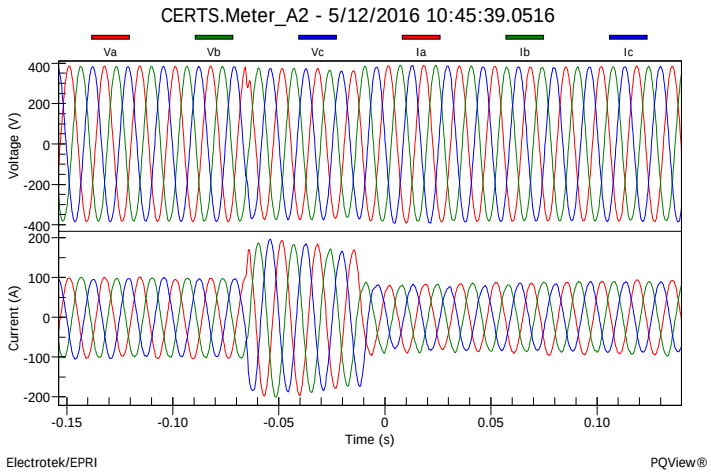

Figure 121: Test Event G: A1 A2 Microgrid Survivability, A2 Waveform (Zoomed) Voltage & Current

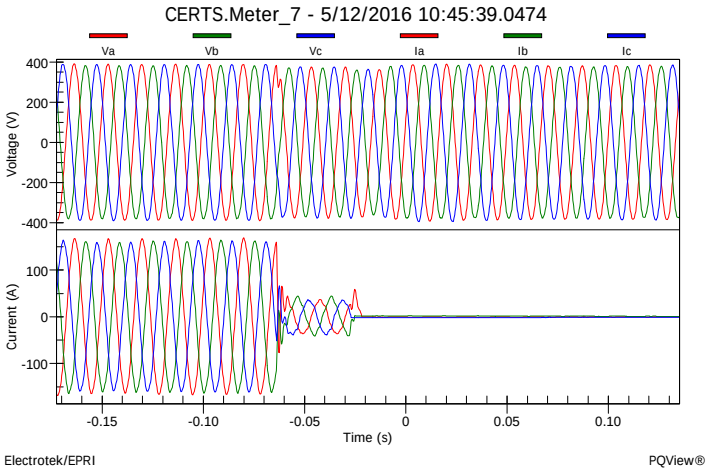

Figure 122: Test Event G: A1 A2 Microgrid Survivability, ESS Waveform (Zoomed) Voltage & Current

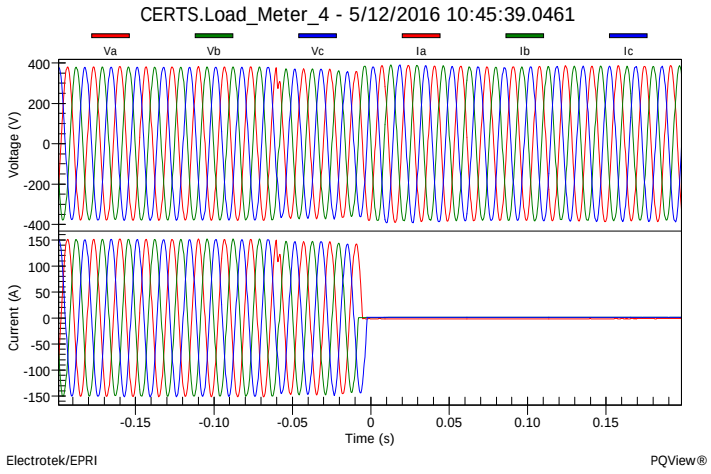

Figure 123: Test Event G: A1 A2 Microgrid Survivability, LB4 Waveform (Zoomed) Voltage & Current

6.5 Envelope of Survivability for Individual DERs

Performance Goal

Determine whether individual DERs have an envelope of survivability such that a smart load could be used to shed load just in time to allow the single DER microgrid to survive. The theory being that the Load Shed Time Delay (LTSD) used to save an overloaded DER would be longer for a unit that is slightly overloaded and would decrease as the unit's overload is increased. Furthermore, that the relationship might be similar to the time-current characteristics curves used in common overcurrent protective devices such as relays, reclosers, and fuses.

If the above is true, it might be possible to determine a load shedding algorithm for a heterogeneous multi-DER microgrid if the envelope of survivability information is known for each individual DER. It is recognized that this is likely a complex task given that the envelope of survivability for the multi-DER microgrid will depend on a number of factors such as: dispatch value of each DER; initial load of each DER; the system's transient response to an overload; the amount of load that can be shed; and the way in which the load can be shed such as all at once or in a multi-step fashion. Finally, to perform this utilizing the CERTS concept of autonomous controllers, each smart load in the microgrid would have to be able to determine the load shedding characteristics to apply to any overload condition without knowledge of how the other controllers in the microgrid are configured or what the load conditions are in the microgrid at the time of the event. Of course, the load shedding algorithm could be applied outside of the CERTS controllers and instead embedded as part of a microgrid controller.

Description of Procedure

The following procedure is used individually on each DER.

1. One DER will be connected to the microgrid and the microgrid is initially connected to the utility system.
2. The DER is dispatched to 80% of its P_{max}.
3. LB3 is set to the dispatch value of the DER, i.e. 80% of its P_{max}.
4. The shedable load on LB4 and LB5 is set to create the desired overload condition. Initially the total load of all load banks is set at 110% of P_{max}. This will be increased by 10% (or as desired) in subsequent iterations until the DER does not survive or the maximum shedable load is reached. Choose a LSTD to see if the DER survives the overload. The LSTD will be adjusted to determine the maximum possible LSTD for each shedable load value that results in the DER surviving the overload.
5. Open the GIS to island the microgrid and apply the overload condition to the DER.
6. Repeat steps 1 to 5 above, adjusting the LSTD in step 4 as necessary to determine the maximum LSTD that results in the DER surviving 5 tests with a given shedable load without any failures. Repeat the test one more time to capture the oscillography for the event.
7. Increment the shedable load by 10% of P_{max} (or as desired) and repeat steps 1 to 6 until load shedding does not allow the unit to survive or the maximum possible load shedding value is reached.

Test Settings

For these tests the parameters are set as follows:

<u>B1 (Sync Gen)</u>

Pdispatch = 75 kW

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%)

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

Pdispatch = 80 kW

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 = -0.01 V_{LN}/kVAr (12% is minimum attainable due to improper voltage control)

<u>A2 (Tecogen Prototype)</u>

Pdispatch = 48 kW

Frequency Droop = 1%

Real Power-Frequency Droop = -.01 Hz/kW

P_{max} = 60 kW

P_{min} = 0 kW

Voltage Set Point = 480 V_{LL}

Voltage Droop = -0.4 V_{LL}/kVAr (5%)

<u>ESS</u>

Pdispatch = 80 kW

Frequency Droop = 1%

Real Power-Frequency Droop = -.004 Hz/kW

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)

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

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

<u>Load Bank 4 and Load Bank 5 – Load Shedding</u>

Non-critical (Shedable) Load = Varies

Load Shedding Frequency = 59.2 Hz

Load Shedding Time Delay = Varies

Load Shedding Rate = 100 pu/s

Effect is all load will be shed as one block when system frequency drops below 59.2 Hz.

During each sequence of tests a weak grid connection with L11 in the circuit is maintained; all zone and load bank circuit breakers "Closed"; the microgrid is grid-connected with the GIS closed; reactive load is set to 0 kVAr; and events are triggered based on the transition of the GIS to open.

Test Results

Table 10 through Table 13 summarize the results for the envelope of survivability tests for each DER: B1, A1, A2, and the ESS respectively. The maximum Load Shed Time Delay (LSTD) and Total Load Shed Time is determined for each overload event.

Test Event	B1 Real Power (kW)					B1 Current (A)		Time to Load Shed Freq (ms)	Load Shed Time Delay (ms)	Load Shed Execution Time (ms)	Total Load Shed Time (ms)	Pass/ Fail	# of LB's Shedding
	Pre-Event	Load Peak	Load Peak %	Expected Load Peak %	Post-Event	Load Peak	Load Peak %						
1A	74.5	102.5	110%	107%	65.7	121.0	108%	56	3400	107	3563	Pass	1
2A	73.9	111.3	120%	116%	70.8	132.0	118%	56	2500	44	2600	Pass	1
3A	78.5	128.7	138%	135%	68.5	153.3	137%	14	1700	95	1809	Pass	1
4A	73.7	145.3	156%	154%	65.1	172.8	154%	5	1200	155	1360	Pass	1
5A	79.7	164.2	177%	179%	72.2	197.9	177%	19	1000	59	1078	Pass	2
6A	76.7	178.2	192%	194%	70.6	215.6	193%	7	800	110	917	Pass	2
7A	76.8	192.4	207%	212%	80.4	235.5	210%	7	600	107	714	Pass	2
8A	78.5	204.7	220%	228%	73.5	257.5	230%	8	600	82	690	Pass	2
9A	80.0	221.3	238%	252%	74.9	277.0	248%	13	500	136	649	Pass	2
10A	77.6	229.0	246%	263%	73.2	288.5	258%	1	500	158	659	Pass	2

Notes
1. B1 survived the maximum shedable load that could be applied (LB4 + LB5) of 190 kW nameplate (151 kW actual).

Table 10: B1 Envelope of Survivability Test Results

Test Event	A1 Real Power (kW)					A1 Current (A)		Time to Load Shed Freq (ms)	Load Shed Time Delay (ms)	Load Shed Execution Time (ms)	Total Load Shed Time (ms)	Pass/ Fail	# of LB's Shedding
	Pre-Event	Load Peak	Load Peak %	Expected Load Peak %	Post-Event	Load Peak	Load Peak %						
1A	73.58	106.85	107%	107%	78.01	132.7	110%	957	200	90	1247	Pass	1
2A	70.22	117.33	117%	120%	77.56	144.9	120%	381	300	70	751	Pass	1
3A	71.29	135.51	136%	142%	77.95	168.2	140%	146	100	44	290	Pass	1
4A	72	144.47	144%	158%	78.14	185.4	154%	118	300	52	470	Pass	1
5A	74.12	143.76	144%	181%	77.95	196.5	163%	115	100	180	395	Pass	2
6A	79.4	146.45	146%	194%	72.51	210.3	175%	103	300	485	888	Pass	2
7A	78.04	150.78	151%	221%	77.25	226.5	188%	210	50	88	348	Pass	2
8A	77.17	150.91	151%	239%	77.54	235	195%	199	50	61	310	Pass	2
9A	74.1	150.62	151%	243%	77.42	236.8	197%	264	50	227	541	Pass	2

Notes
1. Events 4-6 and 7-9 exhibit constant real power peaks of 144% and 151% respectively even though applied load was increasing. The load current does not exhibit the same behavior.
2. The Time to Load Shed Frequency for Events 7-9 is longer than expected given the pattern from the first 6 events and that this time should decrease with increasing load.
3. Event 6 is an example of having to wait through 2 Load Shed Time Delays since the frequency recovers above the LSF after the first load shed occurs.

Table 11: A1 Envelope of Survivability Test Results

Test Event	A2 Real Power (kW)					A2 Current (A)		Time to Load Shed Freq (ms)	Load Shed Time Delay (ms)	Load Shed Execution Time (ms)	Total Load Shed Time (ms)	Pass/ Fail	# of LB's Shedding
	Pre-Event	Load Peak	Load Peak %	Expected Load Peak %	Post-Event	Load Peak	Load Peak %						
1A		< 84	< 140%	< 140%					0		n/a	Fail	1
2A	43.63	85.83	143%	143%	48.72	106.1	147%	432	50	69	551	Pass	1
3A	45.33	92.98	155%	162%	48.5	117.3	162%	418	10	69	497	Pass	1
4A	45.02	99.41	166%	181%	48.43	127.1	176%	400	50	84	534	Pass	1
5A	44.14	107.76	180%	200%	48.45	139.9	194%	432	0	94	526	Pass	1
6A	46.4	115.36	192%	225%	48.43	151.8	210%	466	0	45	511	Pass	2
7A	46.29	122.43	204%	246%	48.39	162.8	226%	86	10	482	578	Pass	2
8A		> 125	> 208%						0		n/a	Fail	2

Notes
1. Loads less than 140% resulted in a frequency above the Load Shed Frequency of 59.2 Hz, thus load shedding could not occur.
2. Loads greater than 204% could not be saved by load shedding.
3. A2 has a lower frequency limit of ~59 Hz and it can be difficult to drive the frequency below the LSF of 59.2 Hz as demonstrated in the Time to LSF.
4. Event 7 is an example of having to wait through 2 Load Shed Time Delays since the frequency recovers above the LSF after the first load shed occurs.

Table 12: A2 Envelope of Survivability Test Results

Test Event	ESS Real Power (kW)					ESS Current (A)		Time to Load Shed Freq (ms)	Load Shed Time Delay (ms)	Load Shed Execution Time (ms)	Total Load Shed Time (ms)	Pass/ Fail	# of LB's Shedding
	Pre-Event	Load Peak	Load Peak %	Expected Load Peak %	Post-Event	Load Peak	Load Peak %						
1A	78.9	108.9	109%	107%	80.49	132.4	110%	242	0	54	296	Pass	1
2A	80.7	114.1	114%	113%	n/a	137.1	114%	n/a	0	n/a	n/a	Fail	1

Notes
1. ESS does not exhibit loading characteristics that can benefit from load shedding. It can serve load up to approximately 110 kW (110% of nameplate). Above 110 kW the ESS trips faster than the load shedding routine can operate.

Table 13: ESS Envelope of Survivability Test Results

Analysis

The timing of a load shed event can be given as:

$$t_{LS} = t_{LSF} + t_{Sample} + t_{LSTD} + t_{Execute}$$

Where:

t_{LS} = Time from the beginning of the event to the load shed.

t_{LSF} = Time to reach the Load Shed Frequency. 59.2 Hz in these tests.

t_{Sample} = Sampling time for the controller to detect that the LSF has been reached. This is typically one to two cycles based on a one cycle sampling period.

t_{LSTD} = A predetermined time delay after the controller determines that the Load Shedding Frequency has been reached which must expire before load shedding occurs.

$t_{Execute}$ = Time for the controller to execute the load shed once the LSTD has been satisfied. Typically 25 ms to 50 ms for our load shed controller.

The graphs in this section will show both the LSTD and the total load shed time (t_{LS}) as a function of peak load experienced by the DER.

Figure 124 shows the results for the synchronous generator-set B1. B1 behaves as expected in that the load shed times are inversely proportional to the load. The graph resembles the inverse time-current characteristics curves used in common overcurrent protective devices such as relays, reclosers, and fuses and thus appears to provide the opportunity to coordinate the load shedding characteristics with those protective devices.

B1 survived the maximum shedable load that could be applied using LB4 and LB5 which is 190 kW combined nameplate or 156 kW actual (taking into account heating of the resistive elements and the

voltage drop to the load). Given that the LSTD used during the maximum overload event was 500 ms, it is likely that B1 could have survived larger overloads with lower LSTDs.

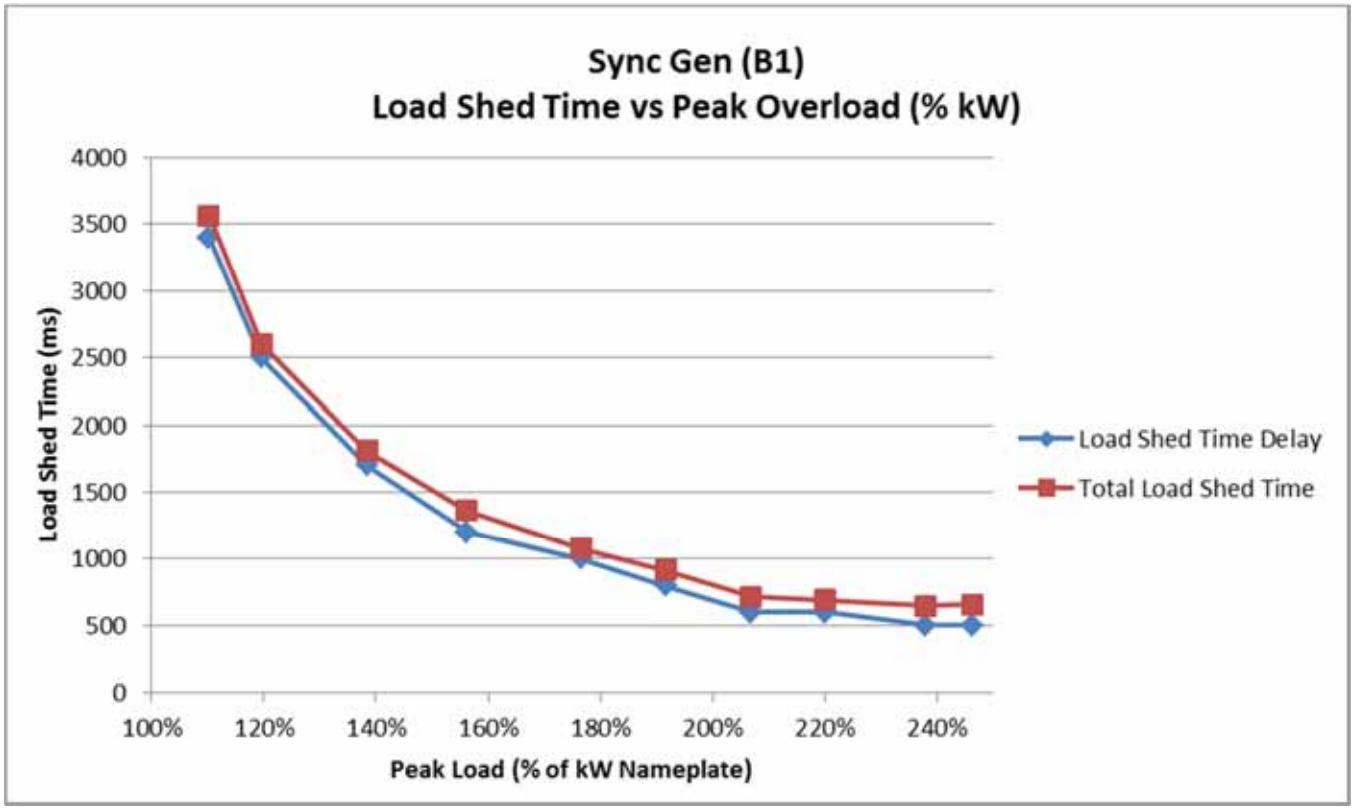

Figure 124: B1 Envelope of Survivability – Load Shed Time vs. Peak Load

Figure 125 shows B1's frequency and current during Event 10A which provides the most severe overload condition. During this event the LSTD = 500 ms and the overload is 136 kW or 146% above its nameplate rating of 93 kW. The overload portion of the event lasts approximately 690 ms during which time B1's P_{max} functionality drives the frequency down in a linear fashion to 27 Hz. At t = 610 ms LB5 sheds 78 kW followed at t = 690 ms by LB4 shedding 78 kW. The frequency recovers to 45 Hz about 1 s

after the shed and to 56 Hz about 8.8 s after the shed event at which time the data recorder's recording time limit is reached. B1 does eventually reach steady-state and survives the event.

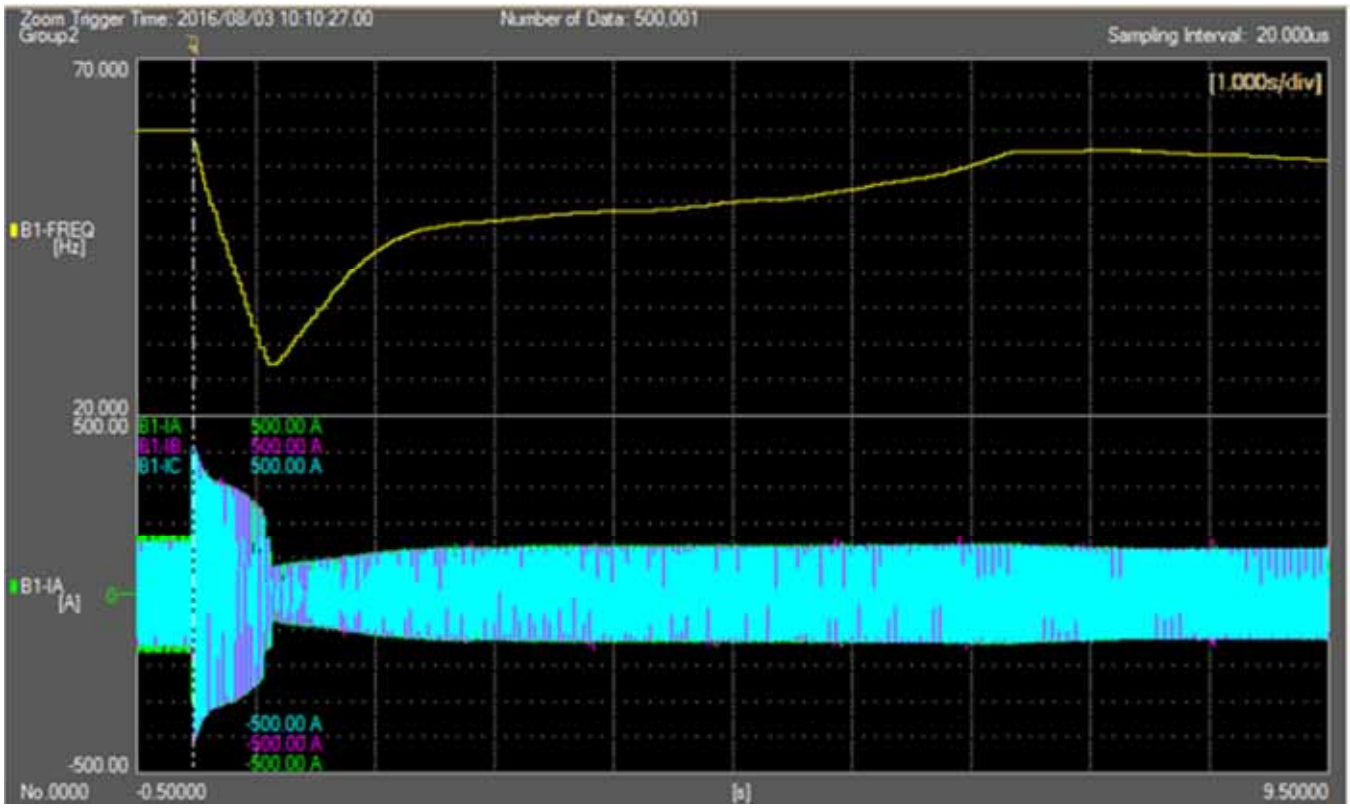

Figure 125: B1 Envelope of Survivability – Frequency and Current Plot (Test Event 10A)

Figure 126 through Figure 129 show B1's voltage, current, and real power response to Test Event 10A, the most difficult overload applied. A severe voltage dip of 48% occurs and the real power output is likewise significantly reduced far below the applied load. After the shed event the voltage, current, and real power return to the appropriate steady-state condition.

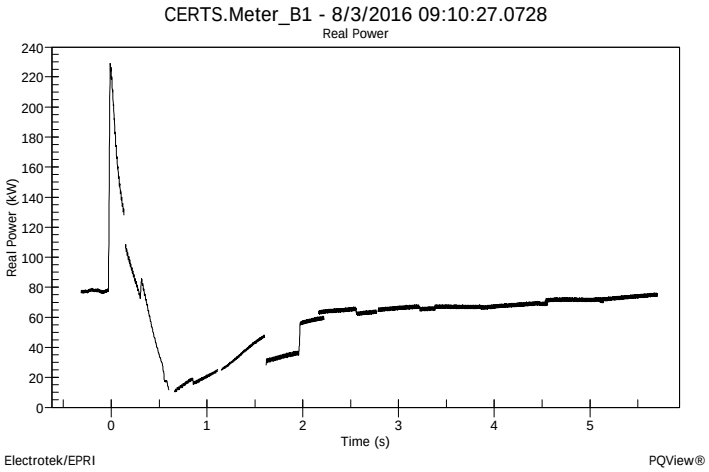

Figure 126: B1 Envelope of Survivability – Real Power (Test Event 10A)

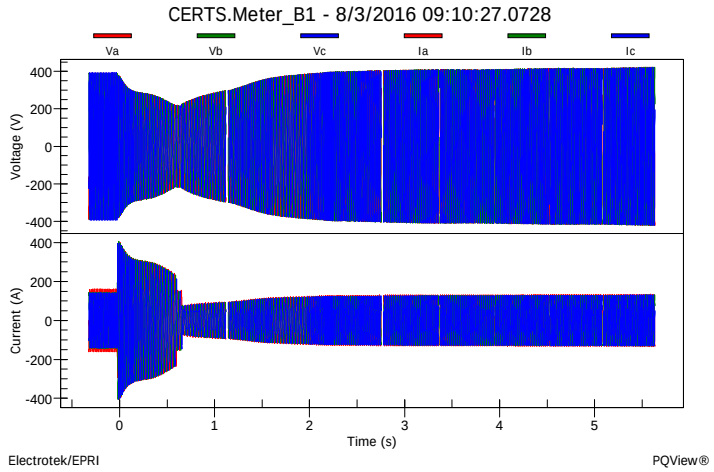

Figure 127: B1 Envelope of Survivability – Waveform Voltage & Current (Test Event 10A)

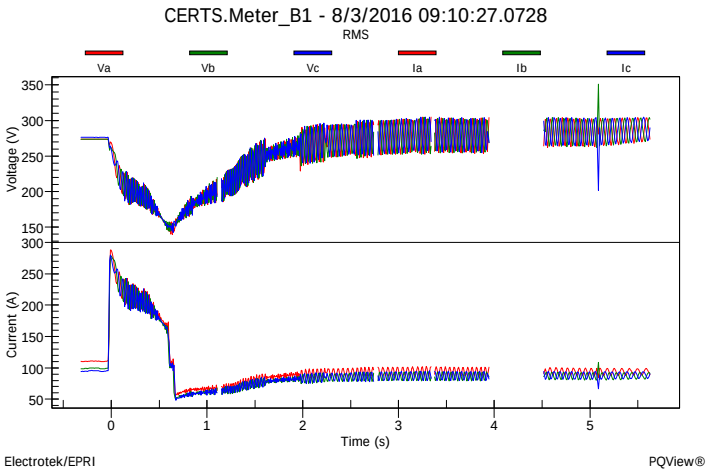

Figure 128: B1 Envelope of Survivability – RMS Voltage & Current (Test Event 10A)

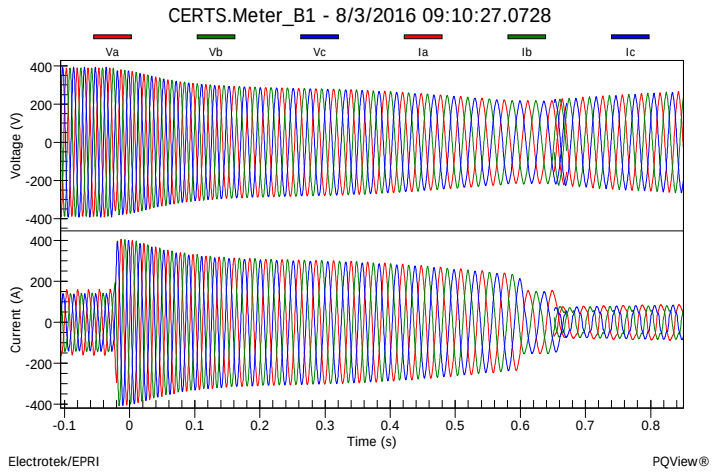

Figure 129: B1 Envelope of Survivability – Waveform (Zoomed) Voltage & Current (Test Event 10A)

Figure 130 shows the results for the Tecogen InVerde inverter-connected DER, A1. A1 does not exhibit a clear inverse relationship between the load shed times and the amount of load. This would suggest it would be difficult to coordinate the load shedding characteristics of A1 with typical protective devices. However, as described below, there are some adjustments that could be made to A1 or the load shedding scheme that could allow A1 to be compatible with a protection scheme.

There are several behaviors that should be noted that are part of this set of tests. First, the peak real power load experienced at the beginning of events 4A to 6A and 7A to 9A are constant at about 144% and 151% of nameplate respectively even though the applied load is being increased from 158% to

243%. It is interesting that the current during these six events does continuously increase from 154% to 197%. This is shown in Table 10 in the previous section (page 83). Since the current does continue to increase with increased load, it would serve as a better indicator of the degree to which the unit is overloaded. It is not clear why the peak real power exhibits this near constant value for events 4A through 9A but it may be worth noting that DER A2, a similar unit to A1 and a proto-type for A1, does not exhibit the same behavior.

Second, the "Time to Load Shed Frequency" which is the time it takes the system to reach the LSF of 59.2 Hz, decreases from event 1A, 957 ms, through 6A, 103 ms, as one might expect but then increases to between 199 ms and 264 ms for the last three events 7A to 9A. This is also shown in Table 10.

Third, the "Time to Load Shed Frequency" is much longer for A1 than it is for B1 for similar overload events. In fact, B1 reached the LSF in the range of 1 ms to 56 ms whereas A1 took between 103 ms and 957 ms. This is the result of A1's P_{max} controller being less aggressive at driving the frequency down than B1. It's possible that an adjustment to A1's P_{max} controller could result in A1's load shedding behavior becoming compatible with coordination of protective devices.

Fourth, the LSTD (Load Shed Time Delay) which results in saving the DER is expected to decrease as the overload is increased. For A1, it does not show a decreasing pattern but rather bounces around between 50 ms and 300 ms.

Finally, when more than one smart load bank is used to create an overload condition it is possible that after one load bank sheds its load that the frequency of the microgrid can recover above the LSF thus resetting the load shed routine and LSTDs on any other smart load banks that remain active. This is observed in Test Event 6A and can easily be seen in Figure 131: A1 Envelope of Survivability – Frequency and Current Plot (Test Event 6A). At t = 103 ms the frequency drops below the LSF of 59.2 Hz. 364 ms later, at t = 467 ms, LB4 sheds its 80 kW. 25 ms later, at t = 492 ms, the frequency recovers above the LSF of 59.2 Hz and LB5 resets it LSTD as it has not yet shed its load. 395 ms later, at t = 887 ms, LB5 sheds its 40 kW. In this case LB5 has to effectively wait through two series of LSTDs. This condition could be avoided by using a direct transfer trip scheme to trip all non-critical load once any non-critical load has decided to trip. Whether or not to use a direct transfer trip scheme would depend on various engineering considerations such as whether the load shed timing is attempting to coordinate with protective devices and whether there is sufficient transient reserve margin in the system to support the extended overload condition.

A1 survived the maximum shedable load that could be applied using LB4 and LB5 which is 190 kW combined nameplate or 166 kW actual (taking into account heating of the resistive elements and the voltage drop to the load). Given that the LSTD used during the maximum overload event was 50 ms, it is likely that A1 could have survived some larger overloads with lower LSTDs.

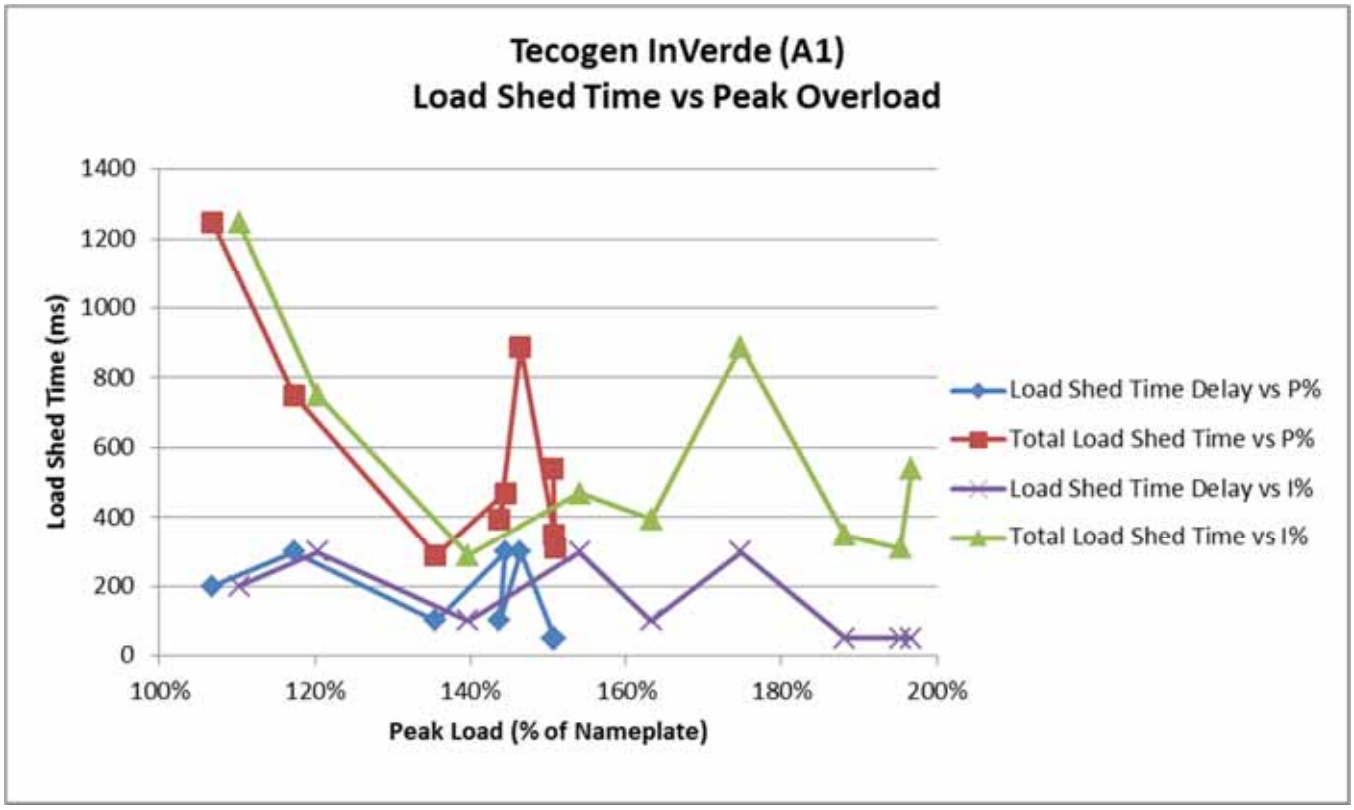

Figure 130: A1 Envelope of Survivability – Load Shed Time vs. Peak Load

Figure 131 shows A1's frequency and current during Event 6A which provides a moderate overload condition. During this event the LSTD = 300 ms and the overload is 146 kW or 146% above its nameplate rating of 100 kW. This event is an example of a case where one load bank's LSTD can reset before shedding load and then go through another LSTD before performing the shed. This event is

described in more detail in a previous paragraph. The final load shed occurs at t = 887 ms and the system reaches steady-state at approximately 1300 ms.

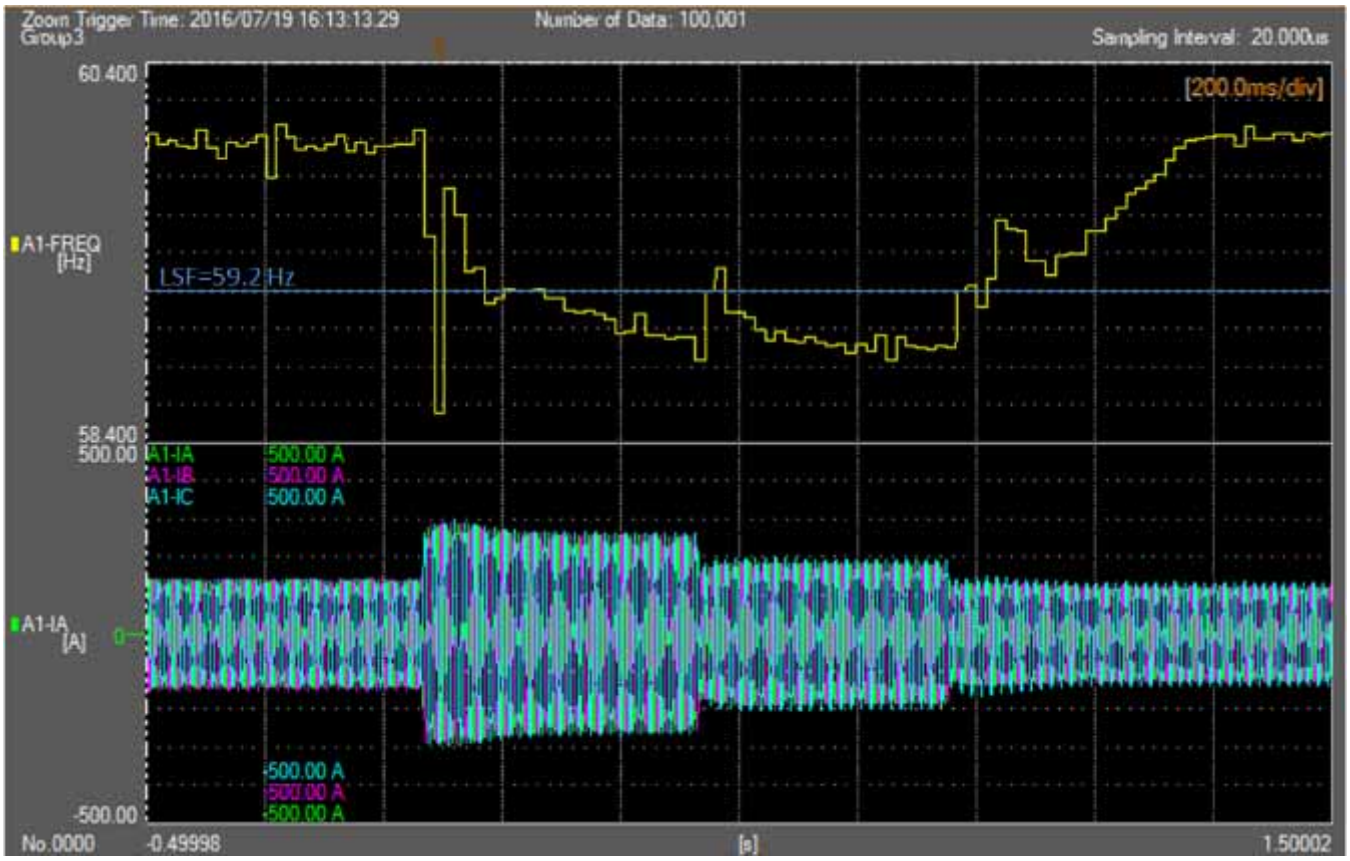

Figure 131: A1 Envelope of Survivability – Frequency and Current Plot (Test Event 6A)

Figure 132 through Figure 135 show A1's voltage, current, and real power response to Test Event 6A, in which a moderate overload is applied. A severe voltage dip of 27% occurs and the real power output is likewise significantly reduced. After the shed event the voltage, current, and real power return to the appropriate steady-state condition.

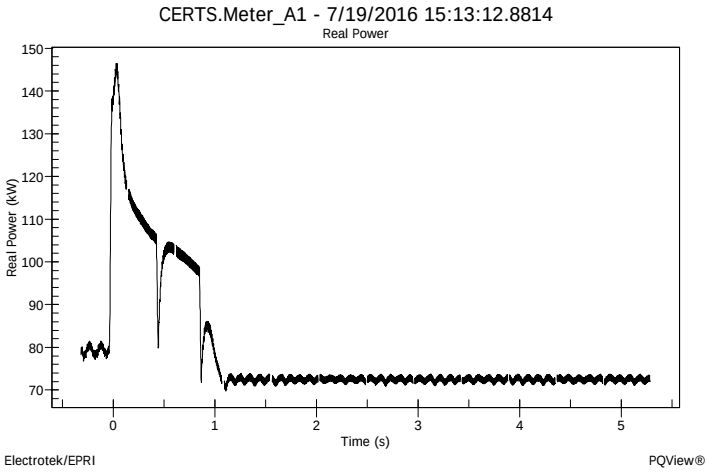

Figure 132: A1 Envelope of Survivability – Real Power (Test Event 6A)

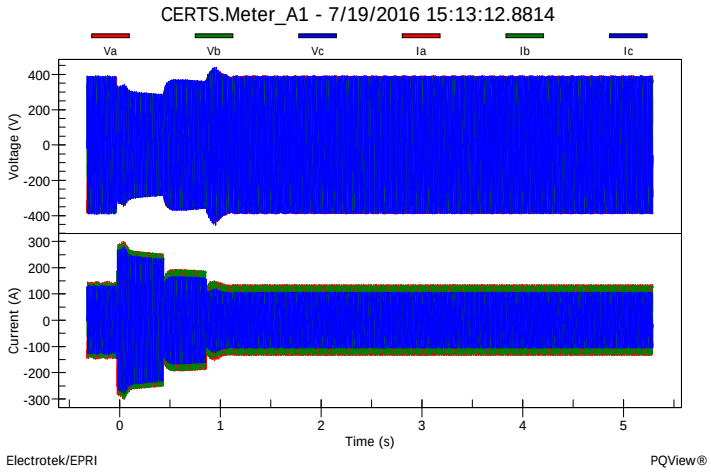

Figure 133: A1 Envelope of Survivability – Waveform Voltage & Current (Test Event 6A)

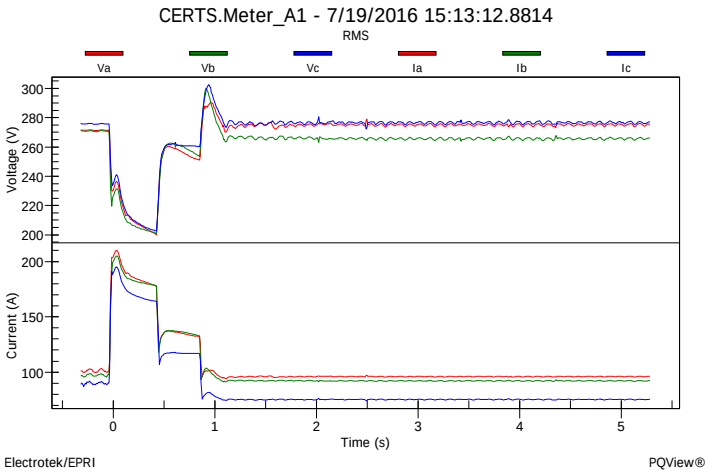

Figure 134: A1 Envelope of Survivability – RMS Voltage & Current (Test Event 6A)

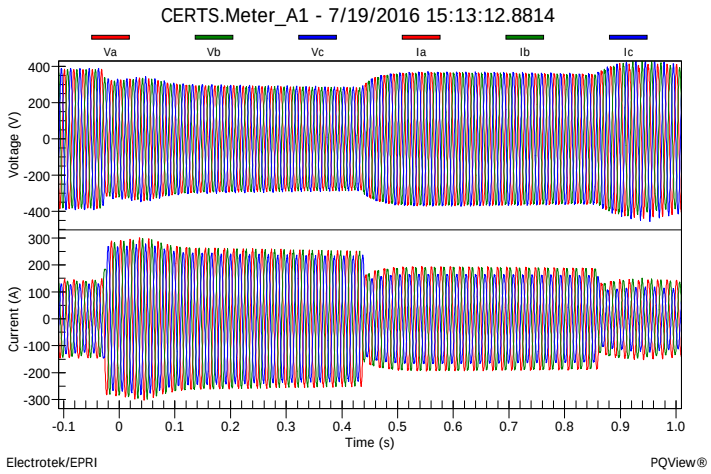

Figure 135: A1 Envelope of Survivability – Waveform (Zoomed) Voltage & Current (Test Event 6A)

Figure 136 shows the results for the Tecogen proto-type inverter-connected DER, A2. A2 does not exhibit a clear inverse relationship between the load shed times and the amount of load. In fact the total load shed time curve is rather flat and better resembles a definite time relay. This would suggest it would be difficult to coordinate the load shedding characteristics of A2 with typical inverse time protective devices.

There are several behaviors that should be noted that are part of this set of tests. First, an overload of less than 40% does not result in a load shedding event and A2 trips due to the overload. A2 is programmed so that its frequency will not go below 59 Hz and this is not user or client configurable. In the cases where the overload was less than 40%, the LSF of 59.2 Hz was not reached for a sufficient amount of time for the smart load to shed load. With the relatively small overload, A2's P_{max} controller

does not have a strong enough response to drive and hold the frequency below 59.2 Hz. This issue would most likely not exist if the controller allowed A2's frequency to go below 59 Hz.

Second, the "Time to Load Shed Frequency" which is the time it takes the system to reach the LSF of 59.2 Hz, is relatively constant with values from 400 ms to 466 ms for the first five successful events, 2A through 6A. Even though Event 7A has a time to load shed frequency of 86 ms, this event is another example of the second load bank having to go through two LSTD cycles because the microgrid frequency returns above the LSF after the first shed event. While LB4 sheds its load first at t = 148 ms, LB5 does not shed its load until 430 ms later at t = 578 ms.

Third, the LSTD (Load Shed Time Delay) which results in saving the DER is expected to decrease as the overload is increased. For A2, it does not show a decreasing pattern but rather bounces around between 0 ms and 50 ms. Part of this may be due to the relatively long and constant time it takes for A2 to reach the LSF of 59.2 Hz.

Finally, A2 could not be saved by load shedding when a load of 260% of its rated 60 kW or 156 kW was applied. Event 8A applied 156 kW to A2. LB4 and LB5 shed load within 58 ms of the event beginning. The frequency recovered but 218 ms later at t = 276 ms A2 tripped.

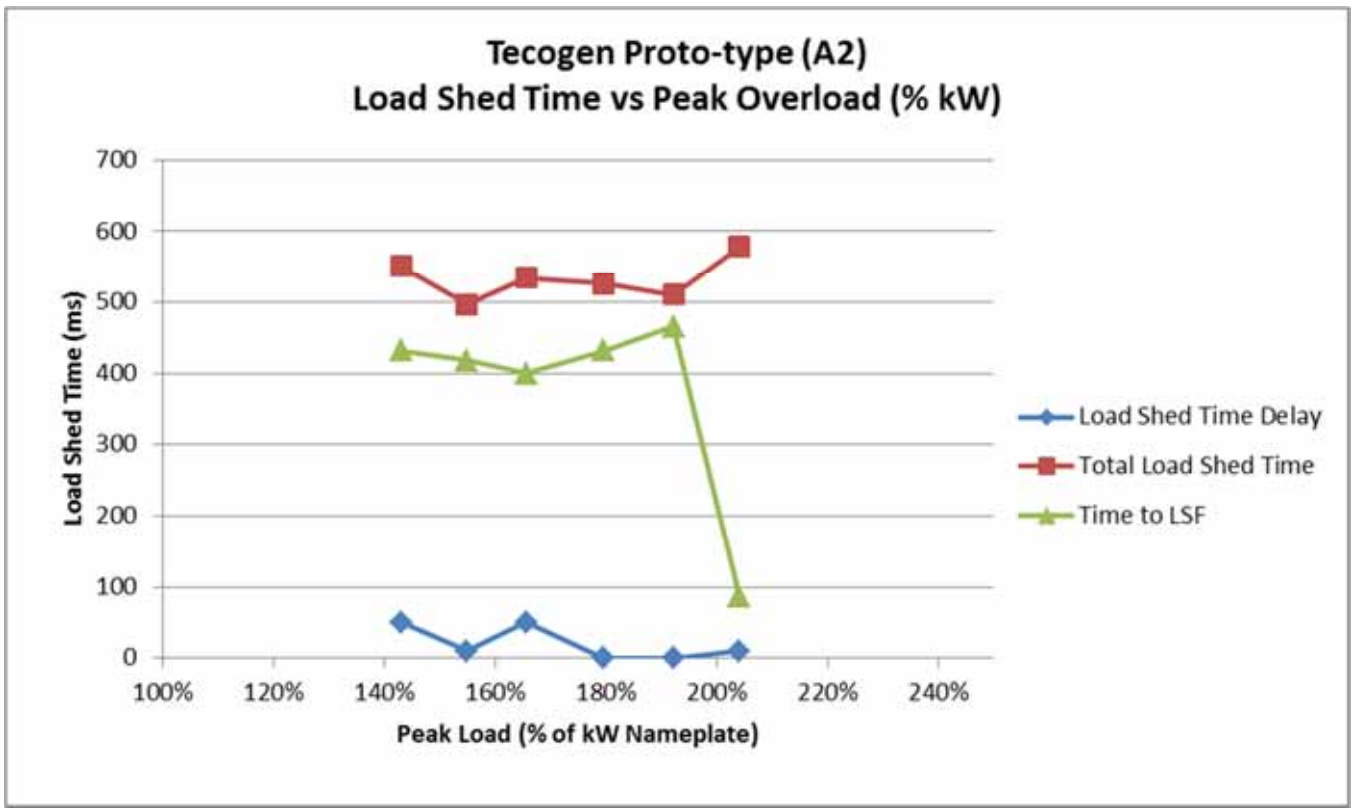

Figure 136: A2 Envelope of Survivability – Load Shed Time vs. Peak Load

Figure 137 shows A2's frequency and current during Event 6A which provides a significant overload condition. During this event the LSTD = 0 ms and the overload is 75 kW or 125% above its nameplate rating of 60 kW. It can be seen that the system has a difficult time driving the frequency below the LSF of 59.2 Hz. Figure 138 and Figure 140 show that even though the voltage and current experience a significant dip initially during the overload, the real power remains above the P_{max} setting of 60 kW until the non-critical load is shed.

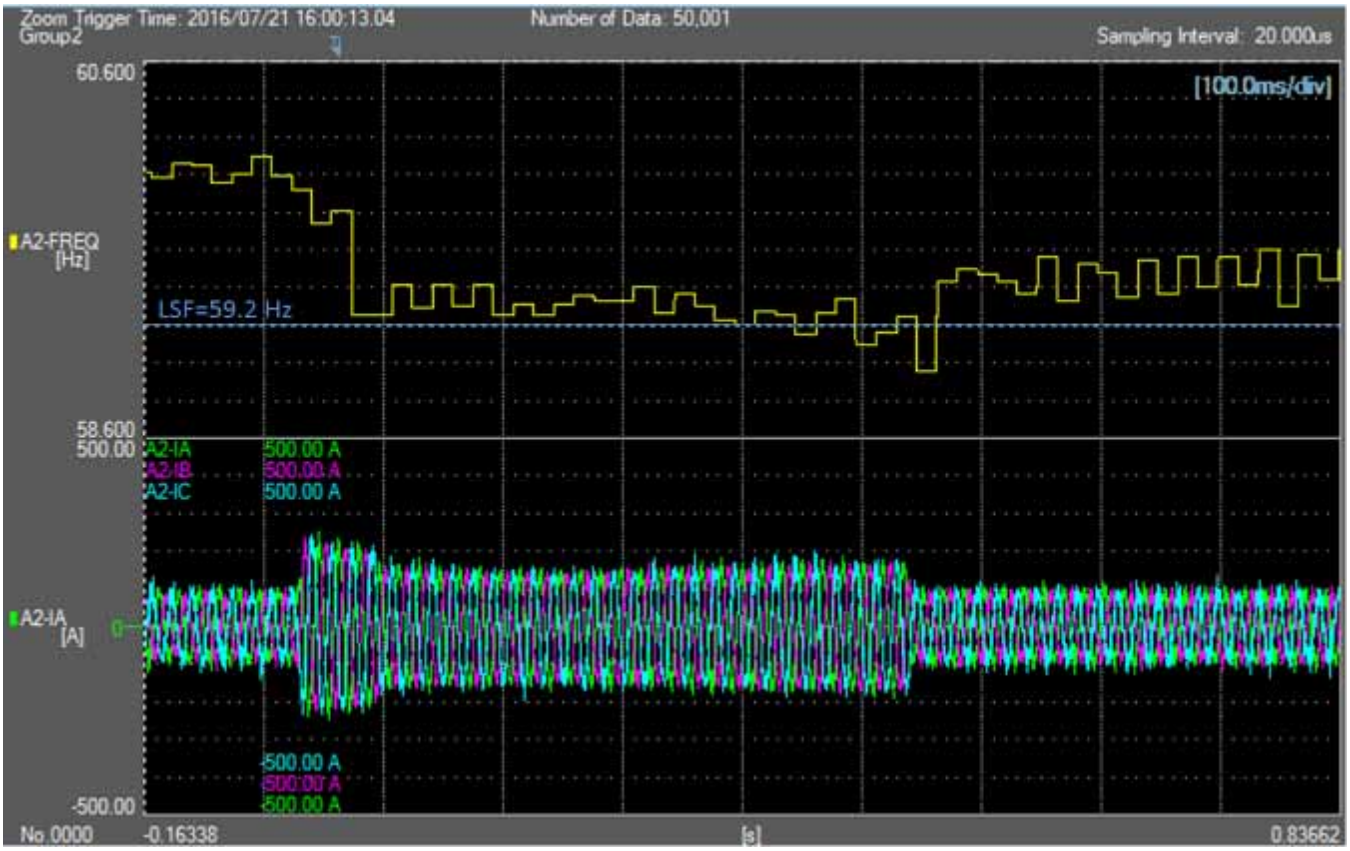

Figure 137: A2 Envelope of Survivability – Frequency and Current Plot (Test Event 6A)

Figure 138 through Figure 141 show A2's voltage, current and real power response to Test Event 6A, in which a significant overload is applied. A severe voltage dip of 16.4% occurs and the real power output is likewise significantly reduced. After the shed event the voltage, current, and real power return to the appropriate steady-state condition.

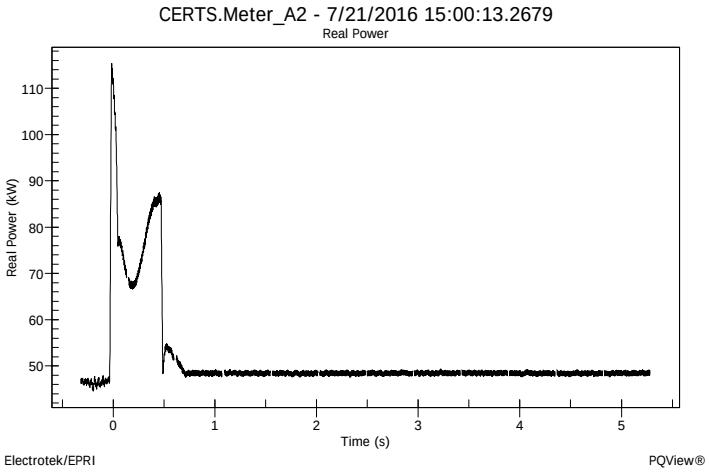

Figure 138: A2 Envelope of Survivability – Real Power (Test Event 6A)

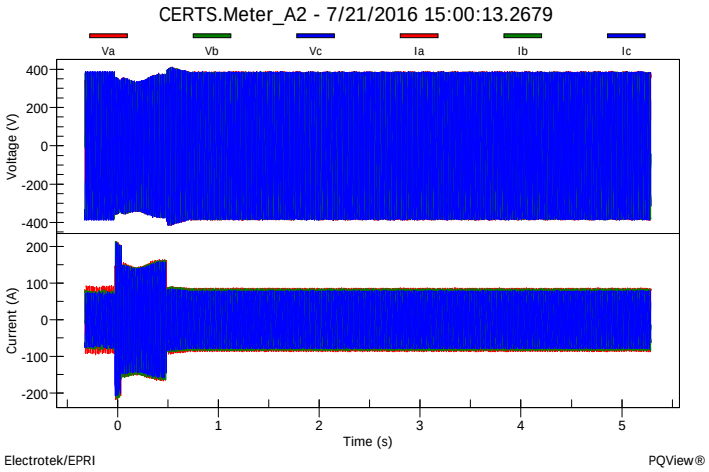

Figure 139: A2 Envelope of Survivability – Waveform Voltage & Current (Test Event 6A)

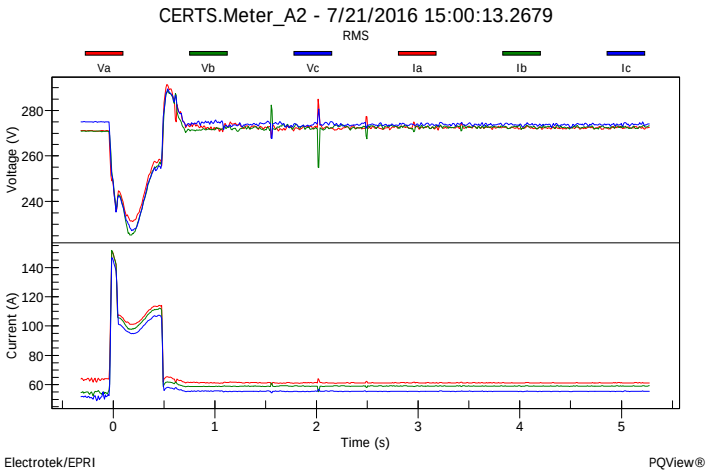

Figure 140: A2 Envelope of Survivability – RMS Voltage & Current (Test Event 6A)

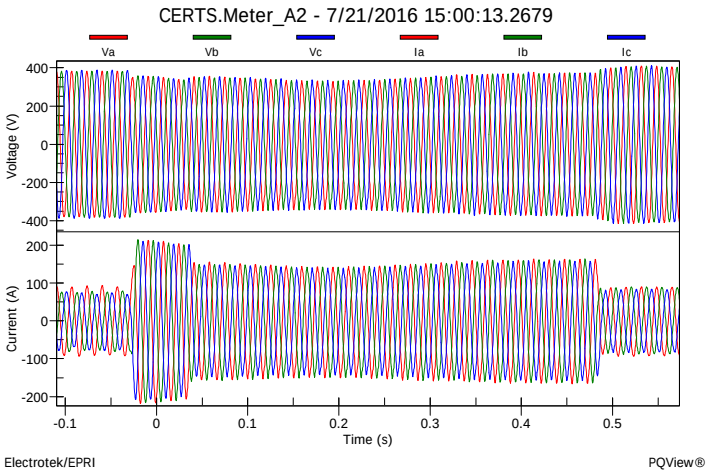

Figure 141: A2 Envelope of Survivability – Waveform (Zoomed) Voltage & Current (Test Event 6A)

The ESS does not exhibit the ability to be saved by load shedding. It has the ability to continuously serve load up to approximately 110% of its 100 kW rating. Above 110% the unit will trip faster than a load shed event can save it. The results of the tests on the ESS are listed in Table 13 on page 85.

Figure 142 shows the ESS's frequency and current during Event 1A which provides a minor overload condition. During the LSTD = 0 ms and the overload is 9 kW or 9% above its nameplate rating of 100 kW.

At t = 242 ms the LSF is reached. 54 ms later, at t = 296 ms, LB5 sheds 27 kW of load and the ESS continues to serve 80 kW. The frequency returns to 60 Hz and the microgrid survives.

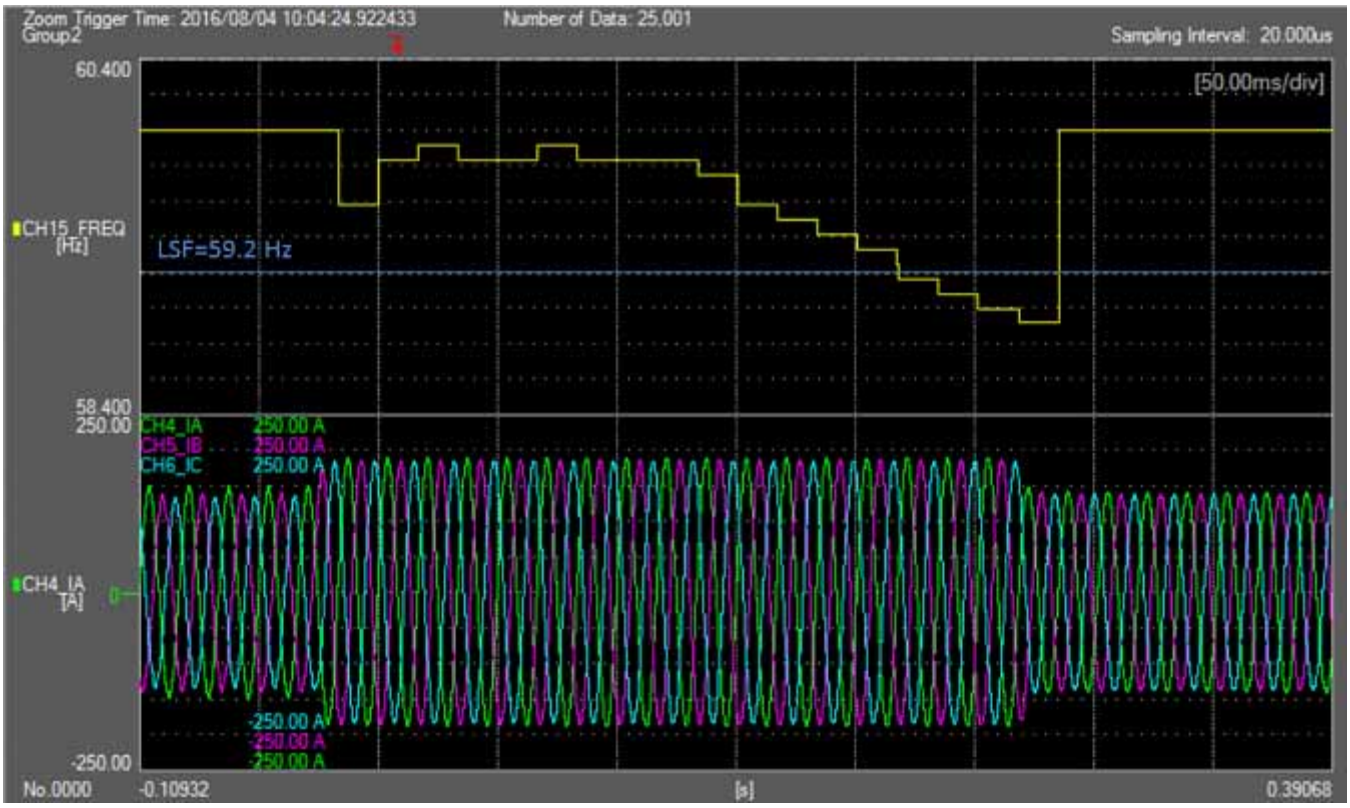

Figure 142: ESS Envelope of Survivability – Frequency and Current Plot (Test Event 1A)

Figure 143 shows the ESS's frequency and current during Event 1B which provides the same minor overload condition as Event 1A except that load shedding is not enabled. In this case the P_{max} functionality drives the frequency down to 50 Hz at which point it levels off. This is due to the ESS

having its minimum frequency set at 50 Hz. With the under frequency relay disabled, the ESS continues to serve the overload condition.

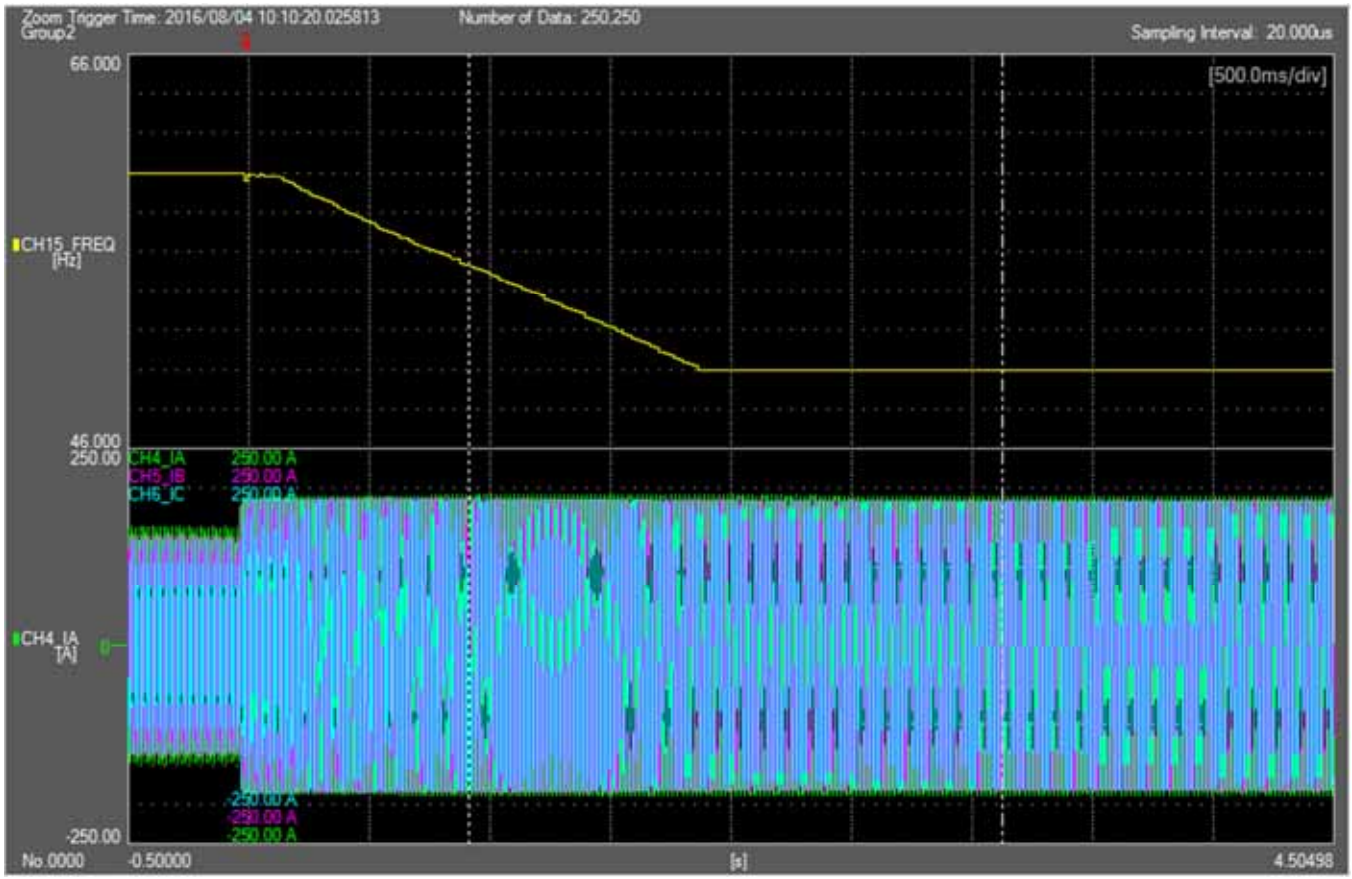

Figure 143: ESS Envelope of Survivability – Frequency and Current Plot (Test Event 1B - Same as 1A except without load shedding)

Figure 144 shows the ESS's frequency and current during Event 2A which provides a minor overload condition. During the LSTD = 0 ms and the overload is 14 kW or 14% above its nameplate rating of 100

kW. At t = 155 ms the LSF is reached. 77 ms later, at t = 232 ms, LB5 sheds 32 kW of load. However, this is not fast enough to save the ESS and 16 ms later, at t = 248 ms, the ESS trips.

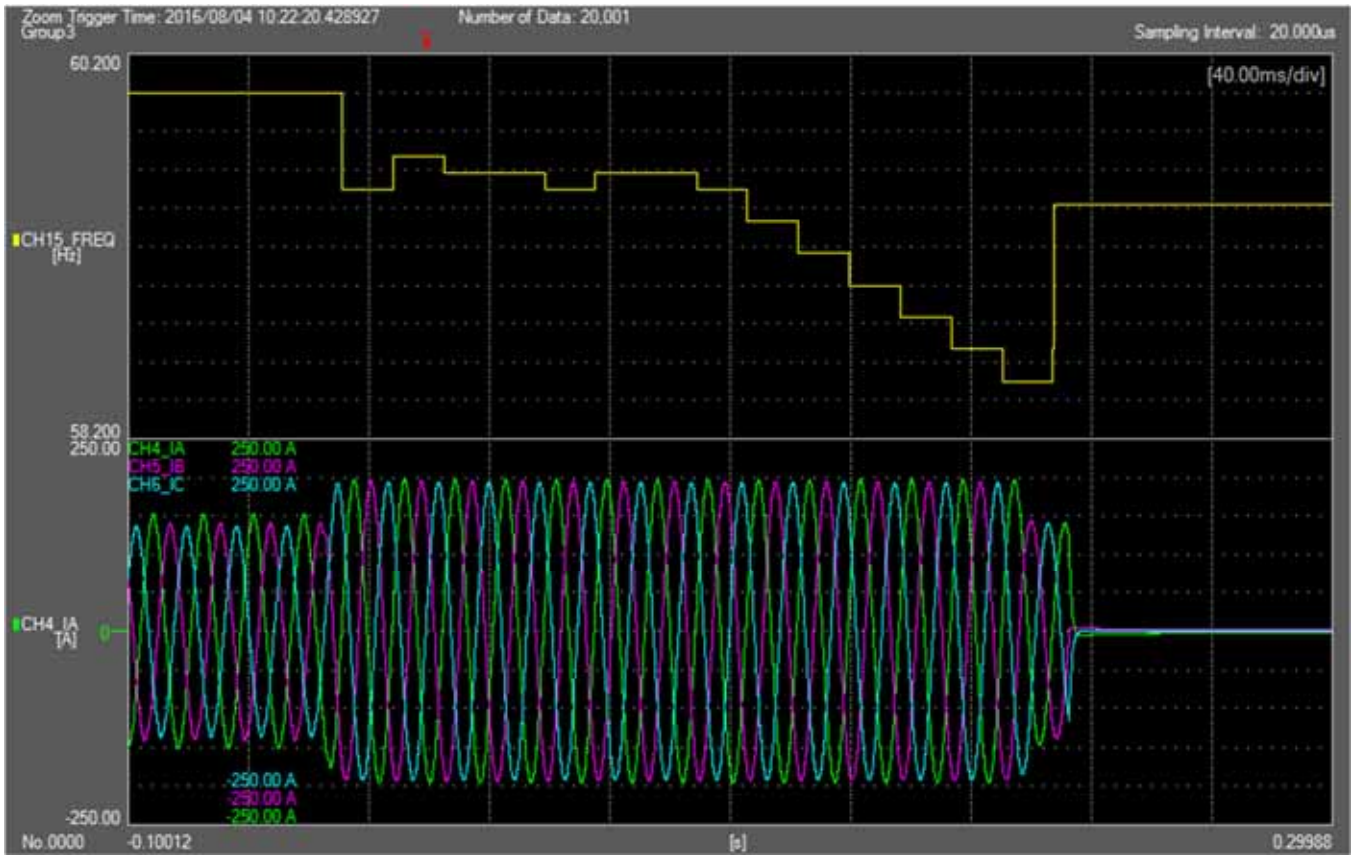

Figure 144: ESS Envelope of Survivability – Frequency and Current Plot (Test Event 2A)

Figure 145 through Figure 148 show the ESS's voltage, current, and real power response to Test Event 1A, in which a minor overload is applied. A mild voltage dip of 1.5% occurs. After the shed event the voltage, current, and real power return to the appropriate steady-state condition.

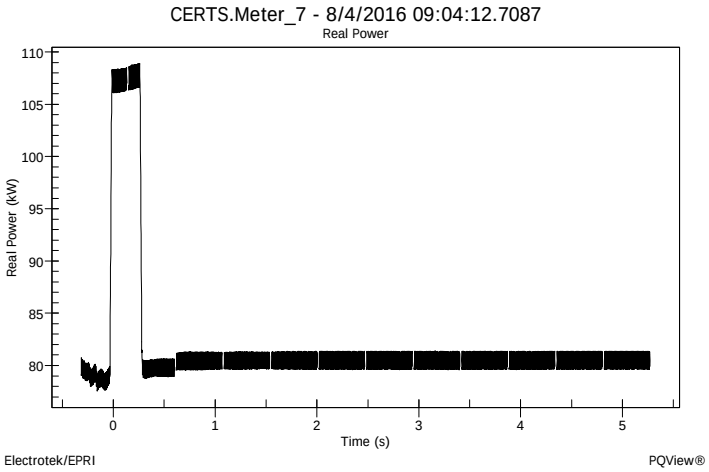

Figure 145: ESS Envelope of Survivability – Real Power (Test Event 1A)

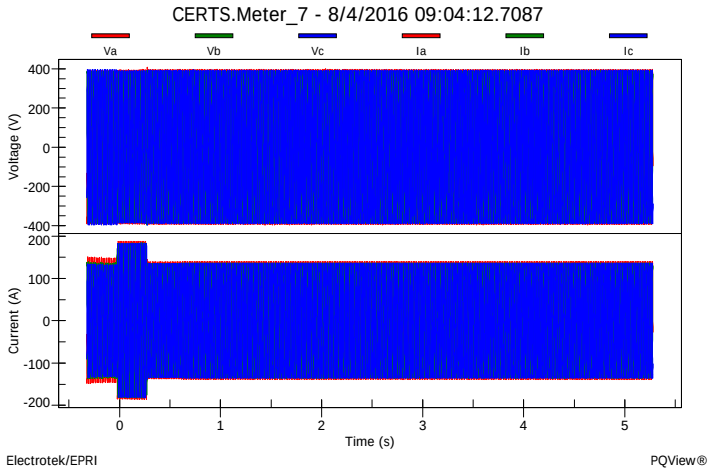

Figure 146: ESS Envelope of Survivability – Waveform Voltage & Current (Test Event 1A)

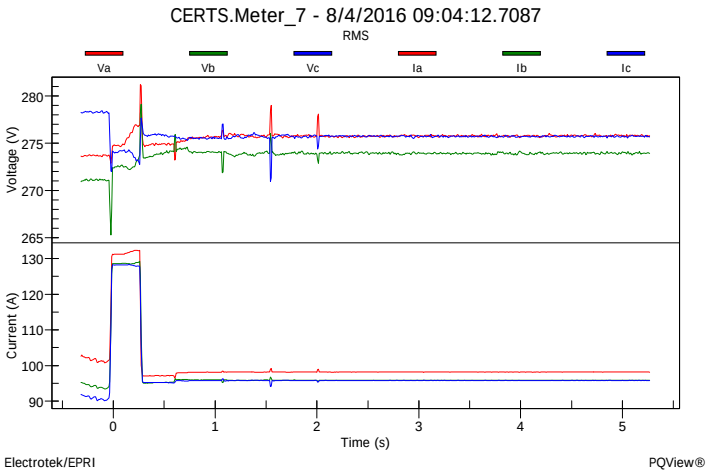

Figure 147: ESS Envelope of Survivability – RMS Voltage & Current (Test Event 1A)

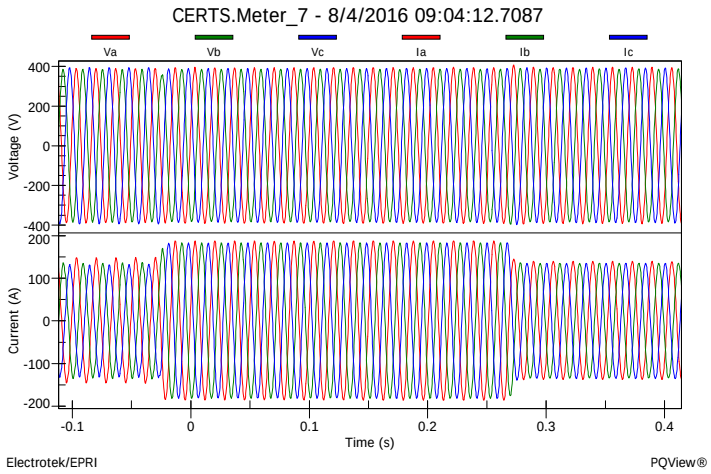

Figure 148: ESS Envelope of Survivability – Waveform (Zoomed) Voltage & Current (Test Event 1A)

Figure 149 shows a comparison of the envelope of survivability of A1, A2, and B1. The ESS is excluded since it does not exhibit the ability to be saved by a load shed event. It can be seen that these three units do not share similar load shed time saving characteristics. The inverter-connected units, A1 and A2, have little to no ability to be saved by a load shedding time delay scheme. Any mixed DER system based on these three units would have to effectively use a Load Shed Time Delay of 0 ms.

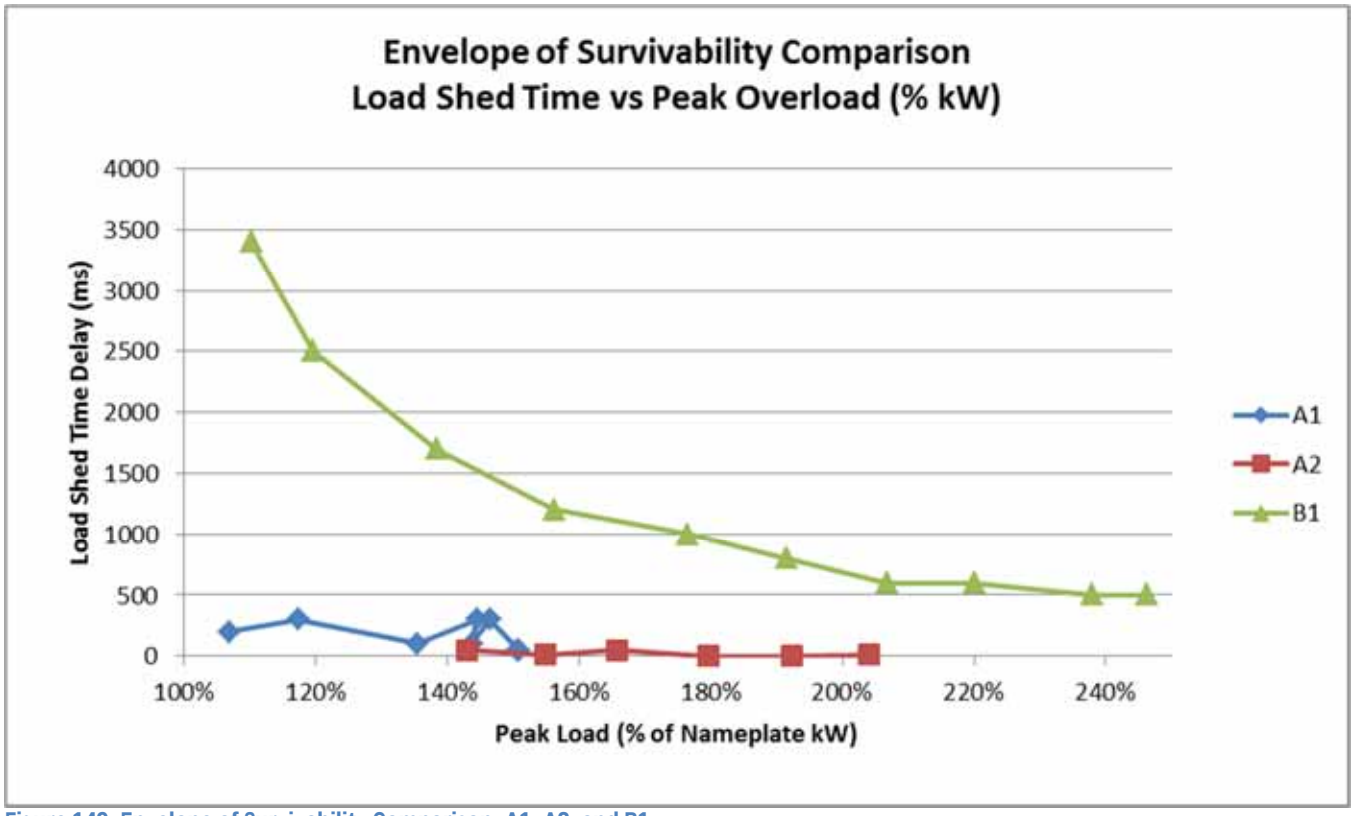

Figure 149: Envelope of Survivability Comparison: A1, A2, and B1

While these tests explored the envelope of survivability of each individual DER, other factors need to be taken into consideration when using load shedding as an option to increase the survivability of the microgrid. In these cases significant power quality issues were observed in some cases, such as severe voltage depressions, as much as 48%, and frequency excursions down to 27 Hz. For many applications this level of power quality would be unacceptable and alternative methods would be required.

7.0 Conclusions

The tests conducted for the CERTS Smart Loads Phase 2 project were designed primarily to examine two areas of interest: 1) could the smart load shedding routine implemented at the test bed be a useful tool for improving the survivability of an overloaded, islanded microgrid; and 2) could envelope of survivability curves be developed for each DER such that load shedding could be used in coordination with standard protective equipment such as fuses and reclosers to avoid the operation of such protective equipment unless absolutely necessary thus avoiding a momentary or permanent outage of critical load.

Initial tests indicated that the existing load shedding algorithm from 2012 operated in the range of 300 ms to 500 ms. This was found to be too slow to effectively save the microgrid during overload events. The load shedding algorithm was improved and designed to operate in the range of 25 ms to 84 ms (1.5 to 5 cycles).

Using the improved load shedding algorithm, tests were conducted where an islanded pair of DERs was placed into various overload conditions ranging from mild to severe overloads. Two different pairs of DERs were used for these tests: 1) A1 and B1, an inverter-connected and a synchronous natural gas generator-set, and 2) A1 and A2, both inverter-connected natural gas generator-sets. The load shedding algorithm behaves as expected and operates for all test cases. The time it takes for the load shed algorithm to execute a load shed event ranges from 23 ms to 87 ms which agrees well with the designed range. The microgrid survives all events that it is expected to including the most severe ones where the units are overloaded by at least 40%, the most that could be applied in the test bed, and then returned to a 95% load condition after the shed event. Given the two different pairs of DERs used in these tests, the load shedding algorithm appears to work well for both a homogenous and heterogeneous set of DERs.

It should be noted that in the islanded multi-unit tests that were performed there were limitations to the test conditions that could be applied. One limitation is that the overload condition that could be applied to the pair of DERs is limited by the amount of shedable load in Load Bank 4 which is 95 kW. For the combination of A1 and B1 this results in a total overload limit of 40% for their combined nameplate rating and in the case of A1 and A2 an overload limit of 48% is achievable. Another limitation is that the load shedding was synchronized within one load bank, LB4, and in these tests occurred all at once, i.e. there was no randomness introduced by multiple loads shedding at different times. This is a result of LB4 being the only smart load in the microgrid at the time the multi-unit tests were performed. Multiple loads shedding at different times would have an effect on the frequency profile during an overload condition and would affect the survivability under certain conditions.

These multi-unit islanded tests considered only one set of initial conditions and one method of load shedding. An expanded set of tests could be performed to evaluate the system's behavior under different conditions. For example, these tests were performed with A1 initially loaded to 80% and the other DER, A2 or B1, loaded to 3 kW below its nameplate rating – the initial loading on each DER could be varied over a wide range to determine its effect on the system's behavior. In addition, the load was shed as one entire block without intentional delay in all cases. It would also be of interest to evaluate the behavior of the system when the load is shed in different amounts over a period of time such as in a stair-step fashion and with an intentional delay to determine the maximum time delay allowed before load shedding is required.

The other area of interest was to determine whether individual DERs have an envelope of survivability such that a smart load could be used to shed load just in time to allow the single DER microgrid to survive. The theory being that the Load Shed Time Delay (LTSD) used to save an overloaded DER would be longer for a unit that is slightly overloaded and would decrease as the unit's overload is increased. Furthermore, that the relationship might be similar to the time-current characteristics curves used in common overcurrent protective devices such as relays, reclosers, and fuses. If this is true, it might be possible to determine a load shedding algorithm for a heterogeneous multi-DER microgrid if the envelope of survivability information is known for each individual DER.

The synchronous gen-set, B1, behaves as expected in that the load shed times are inversely proportional to the load. The LSTD versus percent overload relationship resembles the inverse time-current characteristics curves used in common overcurrent protective devices such as relays, reclosers, and fuses and thus appears to provide the opportunity to coordinate the load shedding characteristics with those protective devices.

The inverter-connected gen-sets, A1 and A2, do not exhibit a clear inverse relationship between the load shed times and the amount of load. This would suggest it would be difficult to coordinate the load shedding characteristics of these DERs with typical protective devices. However, as described in this report, there are some adjustments that could be made to A1 or the load shedding scheme that might allow A1 to be compatible with a protection scheme. A2 suffers from a design constraint that further limits its ability to respond similar to B1, namely that it is programmed not to allow its frequency to go below 59 Hz. If this were changed, it would likely behave similarly to A1.

The ESS does not exhibit the ability to be saved by load shedding. It has the ability to continuously serve load up to approximately 110% of its 100 kW rating. Above 110% the unit will trip faster than a load shed event can save it.

It was shown that the three gen-sets, A1, A2, and B1, do not share similar load shed time saving characteristics. The inverter-connected units, A1 and A2, have little to no ability to be saved by a load shedding time delay scheme. Any mixed DER system based on these three units would have to effectively use a Load Shed Time Delay of 0 ms.

While these tests explored the envelope of survivability of each individual DER, other factors need to be taken into consideration when using load shedding as an option to increase the survivability of the microgrid. In these cases significant power quality issues were observed in some cases, such as severe voltage depressions, as much as 48%, and frequency excursions down to 27 Hz. For many applications this level of power quality would be unacceptable and alternative methods would be required.