CERTS Phase III: Smart Load Report:

Smart Loads as a Functional Component

when Installed in a CERTS Microgrid

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Table of Contents

Table of Figures:

Table of Tables:

1. Introduction

This document is a report on testing conducted with Smart Load connected to the CERTS Microgrid Test Bed, located at American Electric Power's Walnut Test Site in Groveport, OH. The testing was designed to demonstrate the ability of the Smart Load to both interact with the existing CERTS compatible distributed energy resources and to operate when necessary to improve the microgrid stability.

2. 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 sheddable. 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.

– ***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.***

– ***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 700kBtu/hr of thermal load. The inverter on this unit allows it increased flexibility, as if frees the engine to operate over a wide range of rotational speeds (RPM), as opposed to a fixed speed.

– ***Generator "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 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".***

– ***Load Bank 4***: Load Bank 4 is one of the 4 load banks located within the CERTS Microgrid Test Bed: Load Bank 3, Load Bank 4, Load Bank 5, and Load Bank 6. Each is capable of consuming a maximum 95 kW of real load. 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 4 is located in Zone 4. ***Also referred to as: LB3, LB4, LB5 and LB6.***

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

– ***National Instruments Compact RIO:*** NI cRio is a re-configurable embedded control and acquisition system manufactured by National Instruments. The cRIO system's rugged hardware architecture includes I/O modules, a reconfigurable FPGA chassis, and an embedded real time controller. This replaced the existing PLC equipment in Load Bank 4 and was 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 has been converted to a Smart Load with load-shedding functions with 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. The CERTS Microgrid Test Bed

The Walnut Test Bed is a facility in an extension of the American Electric Power Dolan Technology Center and is designed for the purpose of testing various microgrid and distributed generation components and concepts. The facility 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 Smart Loads, and an extensive data collection network. The test facility also supplies a low impedance electric utility connection with protective equipment, a high pressure natural gas supply, a cooling water supply and a security network for physical equipment protection.

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

This section of Smart Load Testing utilizes one production inverter unit “A1” and a synchronous generator “B1”. The device specifications are listed below:

<u>Tecogen Inverde 100 CHP Generator “A1”</u>
Natural Gas V-8, 454 CID, Spark Ignition Engine
Governor America Corp. SDG 700 Series Governor
125kW Permanent Magnet Generator, Water Cooled
Youtility CERTS Compatible Inverter
480/277V, 150A, 125kW, 125kVA
700 kBtu/hr Thermal

<u>MTU Synchronous Standby Generator “B1”</u>
Natural Gas V-8, 8.1L Vortec, Spark Ignition Engine
E-Controls 128 EPR Governor
116 kVA Synchronous Generator, Air Cooled
Marathon DVR2000E Voltage Exciter
Woodward easYgen 3200 p2 Generator Controller
480/277V, 139A, 93kW, 116kVA

Figure 3.1: CERTS Microgrid Aerial Photo

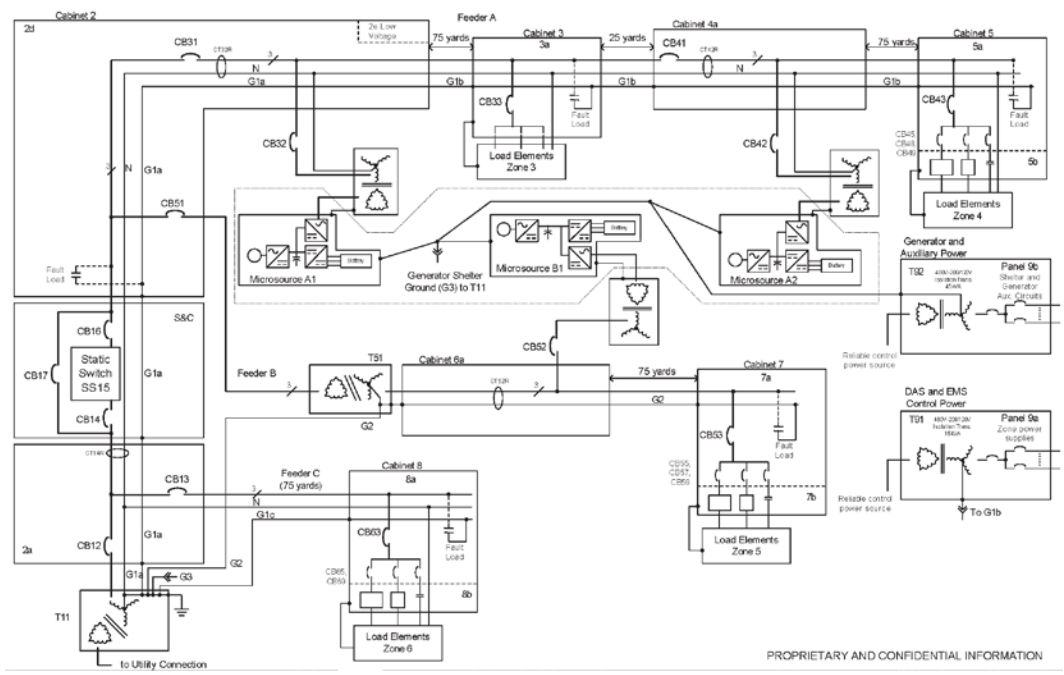

Figure 3.2: CERTS Microgrid One-line Diagram

4. Executive Summary

The sequences of tests that follow were designed to assess the compatibility and capabilities of a Smart Load connected to the CERTS Microgrid. Based on the results that follow, the Smart Load was both compatible with the existing CERTS Microgrid equipment and benefitted the microgrid system through increased power quality and reliability.

A sequence of tests was developed with the intention of examining the functionality and compatibility of the Smart Load with the existing CERTS Microgrid. These tests are designed specifically to test the Smart Load's ability to shed non-critical load in response to overload conditions within the system. Both the inverter-based generator A1 and the synchronous generator B1 were utilized in these tests. The test results examine the interaction and coordination of the Smart Load with each generator's P_{max} controller. As each overload occurred, the generator P_{max} controller would react by lowering the generator's electrical frequency. This reduced frequency when measured by the Smart Load provided for a load shedding response of non-critical load in an effort to restore system to acceptable levels. In this testing the goal of the Smart Load was to prevent system shutdown by actively adjusting energy consumption to preserve the system.

Part of the test sequence was designed to discover the envelope of acceptable operating and response times necessary for a Smart Load to actively participate in microgrid stability. As such tests were chosen to include a range of overload response sensitivities. At high sensitivities, load shedding was expected to occur under conditions which would not require load shedding for survivability, such as motor starts, where large inrushes are short term. At low sensitivities, load shedding was expected to be too little load, too late, to prevent system collapse due to overload protection on the source side. Finally with both boundaries outlined it should then be possible to find appropriate set points for Smart Loads which strike the necessary balance in sensitivity and survivability.

Overall, the results demonstrate that Smart Loads can perform an active role in the stability of the microgrid system. Its ability to stabilize system during overload situations is certainly beneficial to the reliability and power quality delivered by the system. During testing the generator sources proved to be more robust than originally assumed and system collapse was avoided under all load shedding conditions. It is recommended that future work further develop the operational window of source vs. load as well as develop a methodology for coordinating Smart Loads with the energy sources present on the microgrid bus.

Finally to achieve maximum benefit it is important that Smart Loads be properly configured for the microgrid environment they reside in. Although source shutdown was averted, after all load shedding events there remained unused source capacity, which results in an under-utilized microgrid bus and sources. In general smart loads should be adjusted to minimize this under-utilization. A method of automatically returning shed load to the microgrid bus could be implemented to reduce this under-utilization and further improve robustness.

5. Test Results

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 in an effort to sustain the critical load. The criteria which govern its function are:

- Load Shedding Frequency (f) = A predetermined, measured frequency at which the Load Shedding Time Delay begins.
- Load Shedding Time Delay (s) = A predetermined time delay below the Load Shedding Frequency 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 59.5 Hz. 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.

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 the system is overloaded, the DER's P_{max} controller will begin to lower the system frequency in an effort to deliver less power from overloaded units. If the bus 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 thru 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

It was desired to investigate the Smart Load's range of responsiveness. Three levels of sensitivity were selected for the sequence of tests: High, Medium, and Low. The values of each setting were selected primarily based upon prior experience.

The microgrid sources were generally configured so that the lowest continuously sustainable frequency was 59.5 Hz, the Minimum Bus Frequency. For this testing, it is assumed that steady state frequencies below 59.5 Hz communicate that the microgrid bus is overloaded. Further when each source is overloaded the P_{max} controller will continually drive the frequency downward, at approximately 1 Hz/s until the overload is removed. Also from prior experience, when large loads are applied, including those within the capacity of the microgrid system, the frequency can dip briefly below 59.5Hz as the sources dynamically readjust. As such an independent Load Shedding Frequency and Load Shedding Time Delay were chosen for each sensitivity level.

Finally, the 'Load Shedding Rate' was chosen such that the entire load shedding event would last no longer than 10 seconds. It was assumed that any load shedding which occurred beyond this time would fail in preventing the overload protection of the sources from operating. Each source had overload protection which would trip after approximately 10 seconds of overload condition. In testing the microgrid sources proved to be more robust that originally assumed, carrying overloads for nearly 13 seconds before overload protection shutdown.

With these assumptions the following settings were selected for the three sensitivities:

High Overload Sensitivity

- Load Shedding Frequency = 59.0 Hz
- Load Shedding Time Delay = 1.0 seconds
- Load Shedding Rate = 0.111 pu (non-critical)/s
- Minimum Bus Frequency = 59.5 Hz

Medium Overload Sensitivity

- Load Shedding Frequency = 58.5 Hz
- Load Shedding Time Delay = 2.0 seconds
- Load Shedding Rate = 0.125 pu (non-critical)/s
- Minimum Bus Frequency = 59.5 Hz

Low Overload Sensitivity

- Load Shedding Frequency = 58.0 Hz
- Load Shedding Time Delay = 3.0 seconds
- Load Shedding Rate = 0.143 pu (non-critical)/s
- Minimum Bus Frequency = 59.5 Hz

5.3. Measurement Process

Measurements were made using Schneider Electric PowerLogic ION7650 meters and analyzed with a combination of Schneider Electric Ion Enterprise and Electrotek PQView/PQWeb. In prior testing 5 second capture windows were utilized. In detail the Ion meters are actually repeatedly triggered 12 times, each time capturing a 28 cycle window. These smaller windows are then stitched into a larger one by the PQView software. However, this Smart Load testing required longer event observation compared to prior testing, approximately 15 seconds in length. This longer collection window allowed the entire event from overload initiation to full load shed to be captured. Unfortunately it also presented challenges during analysis as our present analyses software has difficulty manipulating these large datasets. A significant amount additional post processing was carried out using Microsoft Excel.

During analysis a number of interesting points were found, some attributed the measurement and analysis techniques used. Some of these points are explained here briefly so as to not confuse the later analysis of the intelligent load, topic of this report.

The first point deals with the measurement collection technique used to collect each window of data and the method by which they are stitched together in post processing. As mentioned above each window of data is 28 cycles long and the metering equipment is repeatedly triggered to collect events which span longer than ~0.5 seconds. Generally this process happens smoothly with no discontinuities in the captures. However, occasionally the meter requires additional time to rearm between successive captures, which results in a small data loss during that rearm period. Fortunately each data point is time stamped during collection. During post processing windowed waveforms with very little time between them are assumed to be from the same event and are concatenated together. When this data is graphed, the slight loss of data becomes obvious as shown in Figure 5.3.1. This can also affect other post processed quantities such as RMS, Power, and Frequency as exampled in Figure 5.3.2 below.

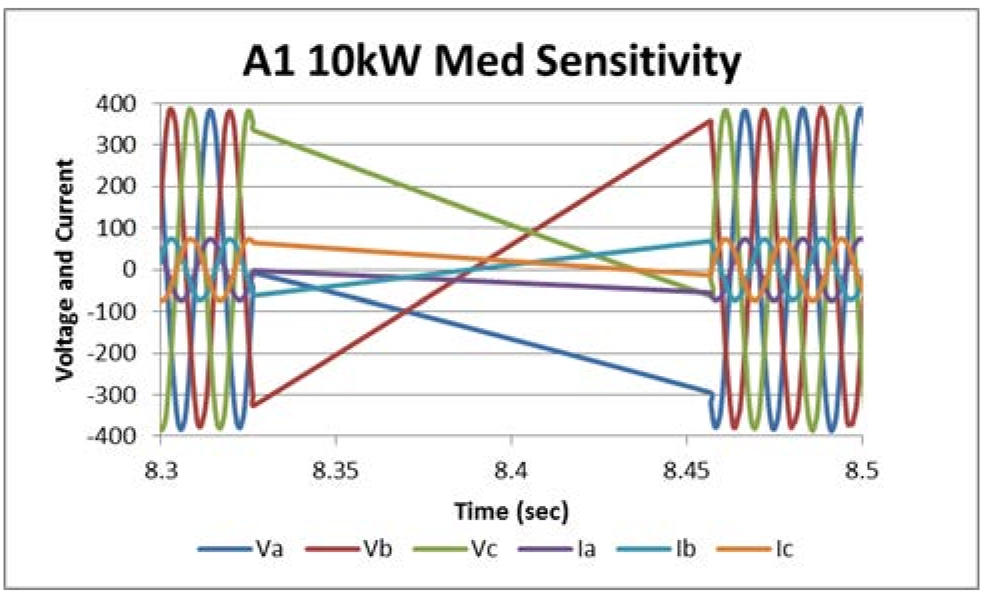

Figure 5.3.1 : Data Collection Discontinuity in Waveform

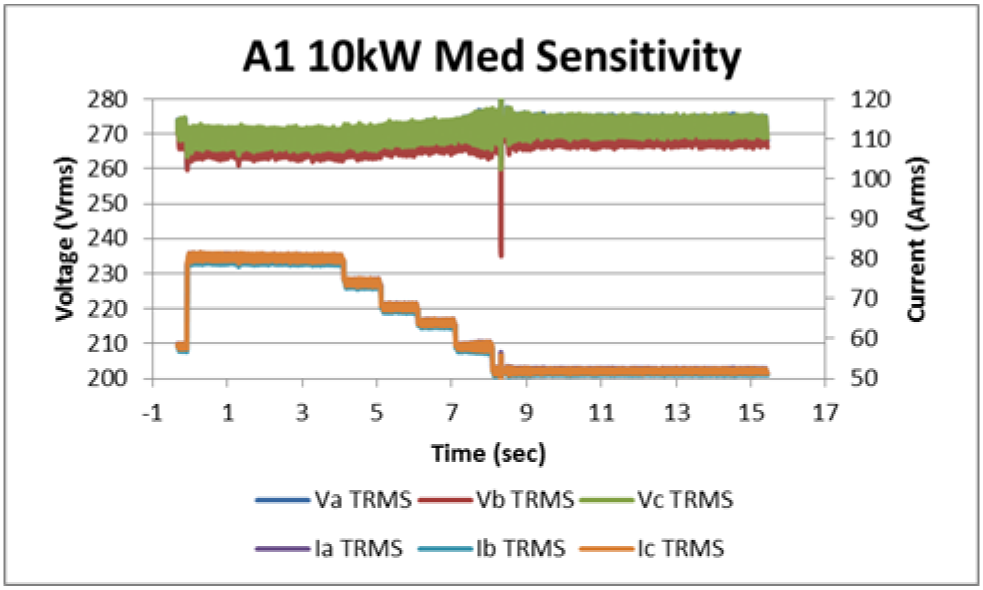

Figure 5.3.2: Data Collection Discontinuity effects on RMS calculations

A second point deals with the analysis technique used to derive real, reactive, and apparent power. There are a few methods and filtering techniques available to calculate these quantities. The present analysis software performs a point by point product of voltage and current to arrive at instantaneous apparent power and then uses the phase angle difference between voltage and current to arrive at real and reactive quantities. This unfiltered measurement gives the true power at any giving moment, although it also shows details usually obscured when a 3 phase average RMS voltage and current are used to derive power. An example is illustrated below in Figure 5.3.3 and Figure 5.3.4. Being aware of this we have taken care to reasonably filter the test results to ensure no unsupportable conclusions were drawn.

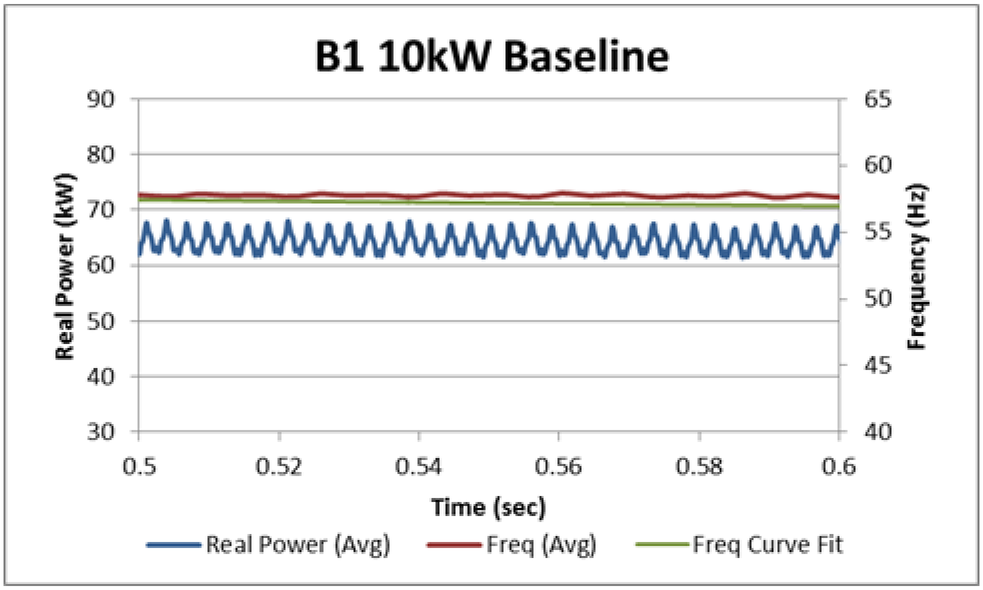

Figure 5.3.3: Power Analysis Technique Illustration

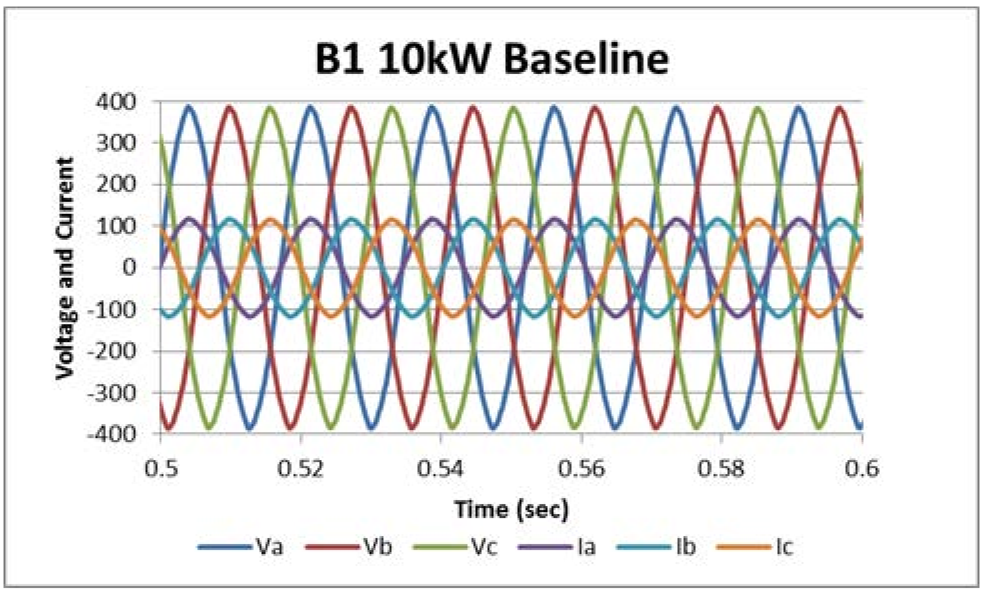

Figure 5.3.4: Voltage and Current for Power Analysis Technique

6. Load Shedding Functionality – Generator A1

Performance Goal

Verify the Smart Load's ability to recover system frequency in the event of an overload on Generator A1, an inverter interfaced generator. The system was tested with one baseline (Baseline) and three load shedding sensitivity levels (High, Medium, Low) each against three levels of overload (10kW, 20kW, 30kW), for a total of 12 different tests. Each generator's P_{max} set point was artificially reduced from the unit's rated capacity intentionally to observe the P_{max} control response independent of physical constraints presented by the prime mover of each generator. The testing sequence was also designed to find the envelope of acceptable interaction between the Smart Load and generating source; both nuisance operations and system shutdowns were expected results. The acceptance criterion for this testing was a load shedding event, in response to system overload, which maintained microgrid operation.

Description of Procedure

Generator A1 was dispatched to 60 kW, $277V_{l-n}$, -0.006 Hz/kW Frequency Droop, and disconnected from the utility source ("islanded"). The generator was started and connected to the islanded microgrid electrical bus with a balanced load of 50kW in LB4, consisting of 30kW critical load and 20kW non-critical load. Once the system reached steady state, an additional non-critical load was added to the system to create the overload condition. In each test the overload was increased in order to measure the effects of overload magnitude and examine the timing of the load shedding response. When the load was applied, the data collection system records until the load shedding event is completed or the system experienced a protection shut down.

The InVerde was configured with the following settings:

Voltage Dispatch: $277V_{l-n}$
P_{max} controller: 60kW
Frequency Droop: -0.006 Hz/kW
Voltage Droop: 0.47 V/kVar

	CASE	1	2	3	4
10kW Overload	A	Baseline (No Load Shedding)	High Overload Sensitivity	Medium Overload Sensitivity	Low Overload Sensitivity
20kW Overload	B	Baseline (No Load Shedding)	High Overload Sensitivity	Medium Overload Sensitivity	Low Overload Sensitivity

30kW Overload	**C**	Baseline (No Load Shedding)	High Overload Sensitivity	Medium Overload Sensitivity	Low Overload Sensitivity

Table 6.1: Smart Load Sensitivity and Magnitude Settings – Generator A1

Test Results

Generator A1		Prior to Overload		During Overload		After Load Shed	
Event		Real Power (kW)	Frequency (Hz)	Lowest Trend Frequency (Hz)	Frequency Drop (Hz)	Real Power (kW)	Frequency (Hz)
A1	10kW / Baseline	46.59	59.76	50.57	9.19	NA	NA
A2	10kW / High Sensitivity	46.89	60.20	58.62	1.59	52.28	60.07
A3	10kW / Medium Sensitivity	46.93	60.17	57.42	2.75	42.08	60.07
A4	10kW / Low Sensitivity	47.42	60.10	56.40	3.70	37.37	60.17
B1	20kW / Baseline	46.96	60.12	40.17	19.95	NA	NA
B2	20kW / High Sensitivity	46.30	59.69	56.47	3.22	41.97	60.07
B3	20kW / Medium Sensitivity	46.82	59.83	54.55	5.27	34.59	60.09
B4	20kW / Low Sensitivity	47.26	60.08	53.16	6.91	29.71	60.43
C1	30kW /Baseline	47.50	60.10	28.44	31.66	NA	NA
C2	30kW / High Sensitivity	46.34	60.08	53.37	6.71	34.65	60.11
C3	30kW / Med Sensitivity	46.95	60.03	51.25	8.79	29.75	60.25
C4	30kW / Low Sensitivity	46.37	59.95	49.65	10.30	29.72	60.24

Table 6.2: Smart Load Test Results - Generator A1

Analysis

A detailed walkthrough of each event is described. The first event in each series is a baseline reference in which a similar overload is applied but load shedding is inhibited. The overload continues until the source performs a protection shutdown. The remaining three events in each series examine the three levels of load shedding sensitivity at each level of overload. In general all events follow a similar pattern although timing and quantity of final load shed may differ. These differences and any other points of interest will be individually described for the remaining events. Also worth note actual load steps vary from the test dispatch due to a number of factors such as resistive element tolerance and applied voltage.

6.1. A1 10 kW Baseline

In Event A1, an overload of approximately 10 kW is placed on the islanded, inverter based generator. Further in this test the Smart load, load shedding is inhibited, which will knowingly lead to the eventual protection trip of the source.

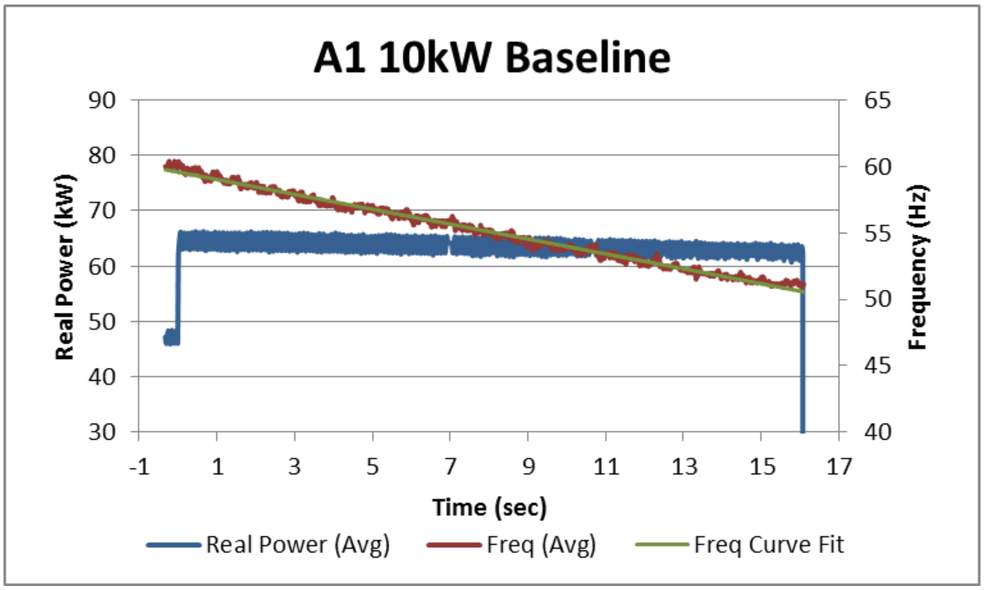

Figure 6.1.1: A1 10 kW High Sensitivity Real Power and Frequency

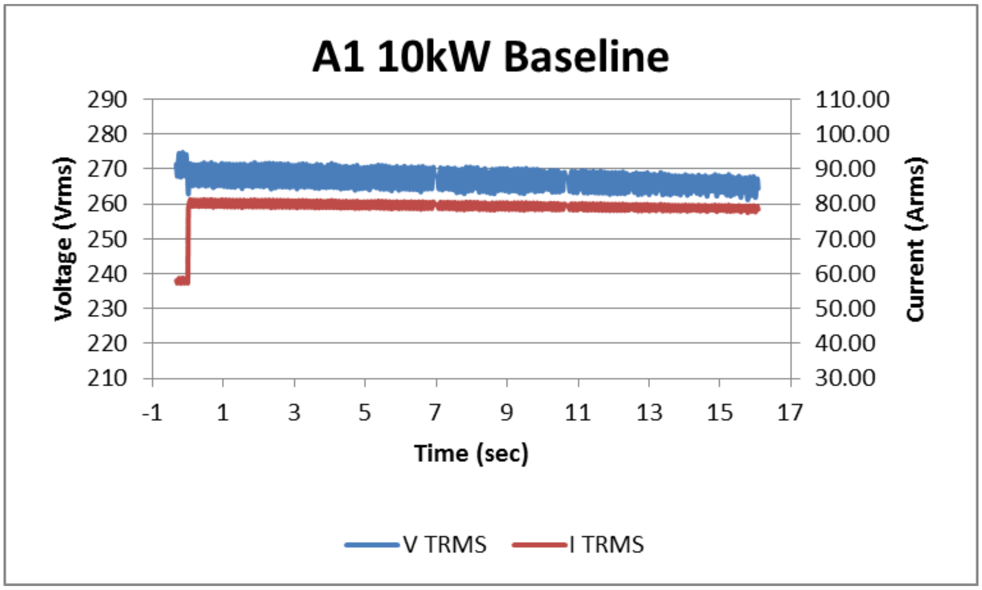

Figure 6.1.2: A1 10 kW High Sensitivity RMS Voltage and Current

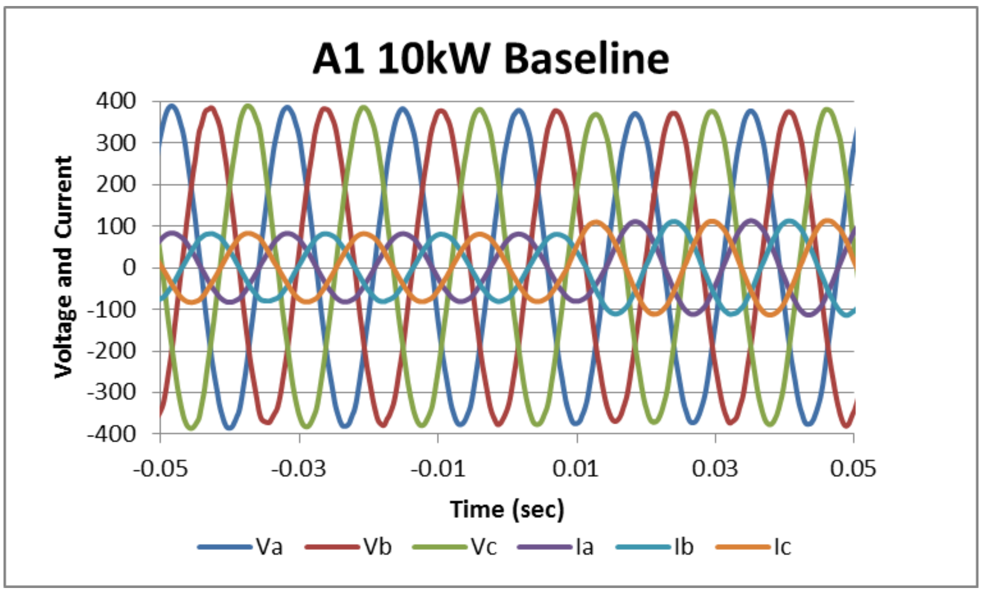

Figure 6.1.3: A1 10 kW High Sensitivity Waveform Voltage and Current

In Figure 6.1.1 above the initial load is approximately 47 kW and the bus frequency is approximately 59.76 Hz. At time 0 seconds, approximately 19 kW is added, bringing the total load to 66 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.15 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues dropping at a rate of 0.55 Hz/second. In Figure 6.1.2, there is a slight reduction in voltage, approximately 4 $V_{l\text{-}n}$, during the overload event. This reduction is due to the increased reactive power consumption of transformer equipment connected to the microgrid bus as frequency drops. This increased reactive power consumption leads to a voltage reduction as it affects the voltage vs reactive power controller within the source. At 16 seconds the bus frequency is 50.6 Hz, and the source performs a controlled shutdown due to an overload protection fault. This test case illustrates the expected response if load shedding is unavailable within the microgrid environment.

6.2. A1 10 kW High Sensitivity

In Event A2, an overload of approximately 10 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a High Sensitivity level, which will cause it to react more quickly to an overload condition.

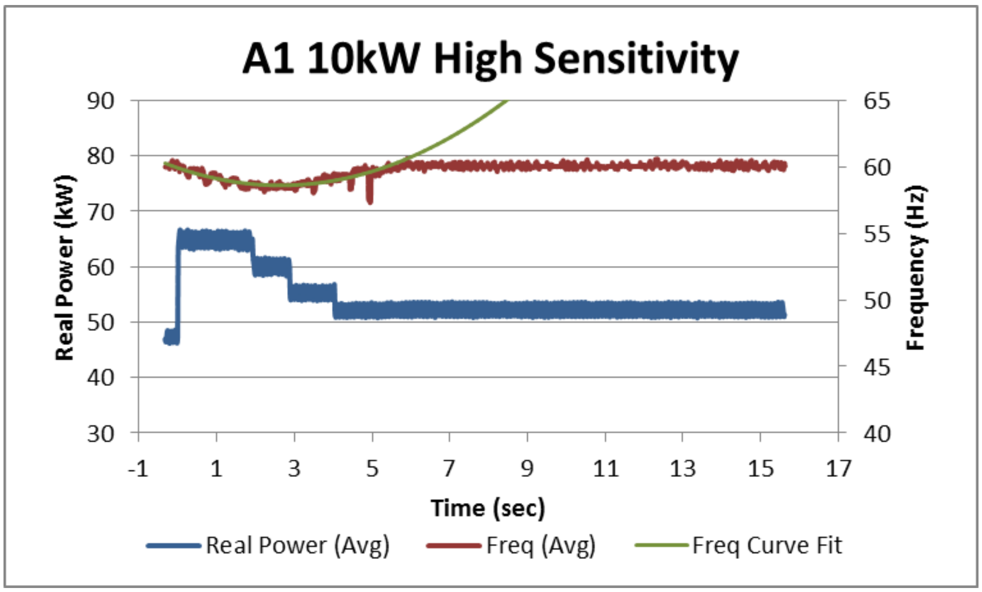

Figure 6.2.1: A1 10 kW High Sensitivity Real Power and Frequency

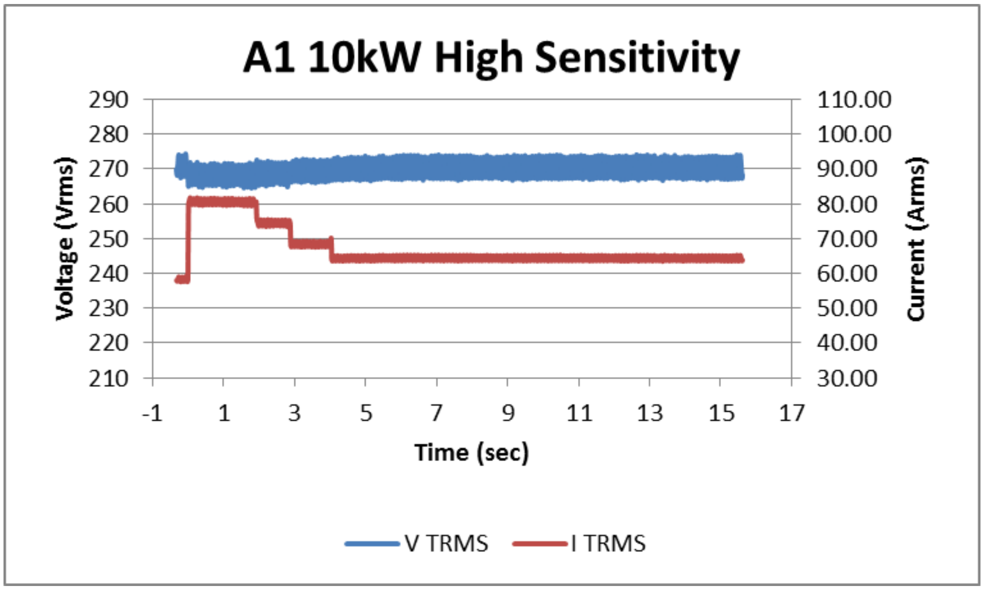

Figure 6.2.2: A1 10 kW High Sensitivity RMS Voltage and Current

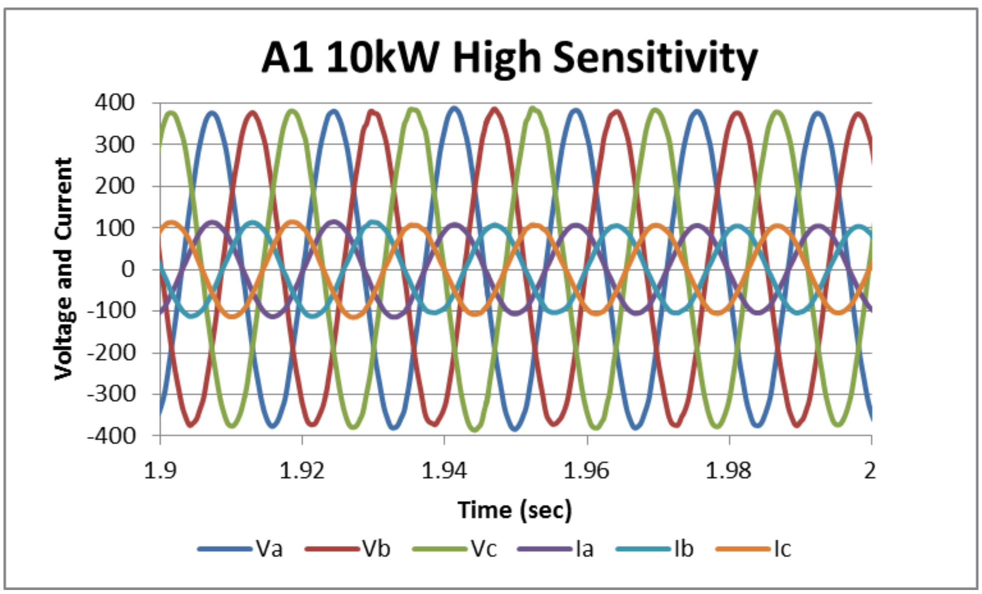

Figure 6.2.3: A1 10 kW High Sensitivity Waveform Voltage and Current

In Figure 6.2.1 above the initial load is approximately 47 kW and the bus frequency is approximately 60.2 Hz. At time 0 seconds, approximately 17 kW is added, bringing the total load to 65 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.5 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 59.0 Hz at 1 second. At this point the Smart Load, Load Shedding Delay timer begins. At 2 seconds the bus frequency is 58.7 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.111 pu/s, dropping 5 kW of non-critical load, to approximately 60 kW.

At 2.9 seconds the bus frequency, 58.6 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 4 kW of non-critical load, bringing the total load to 56 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 4 seconds the bus frequency has recovered to 59.0 Hz, which remains below the Minimum Bus Frequency and an additional 5 kW of non-critical load is removed, bringing the total load to 51 kW. At 4.8 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 52 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 60.1 Hz with 15 kW of total load shed. Using the trended frequency, 1.59 Hz of frequency deviance lasting 4.8 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

6.3. A1 10 kW Medium Sensitivity

In Event A3, an overload of approximately 10 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Medium Sensitivity level, which will cause it to react less quickly to an overload condition.

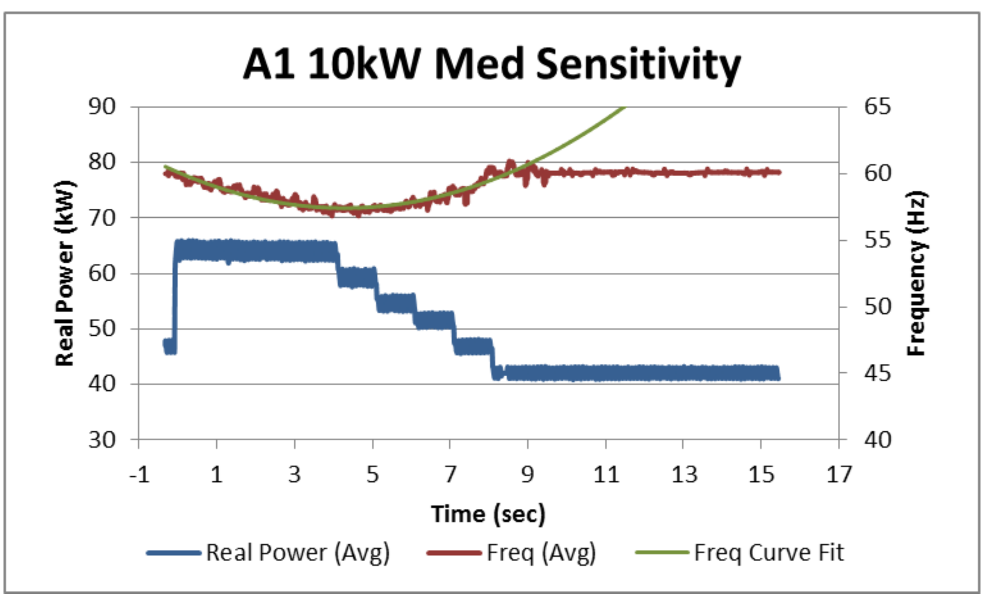

Figure 6.3.1: A1 10 kW Medium Sensitivity Real Power and Frequency

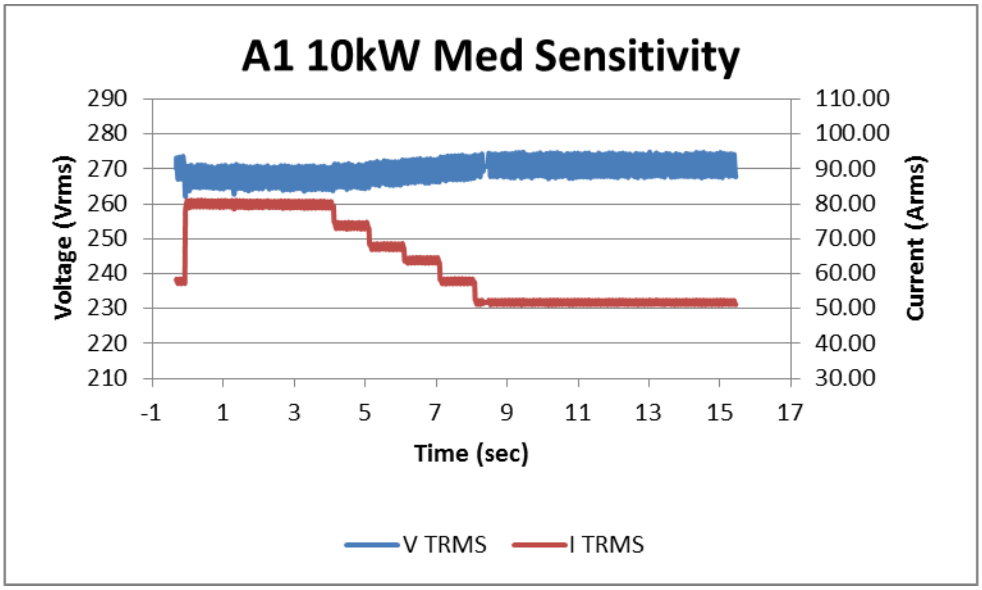

Figure 6.3.2: A1 10 kW Medium Sensitivity RMS Voltage and Current

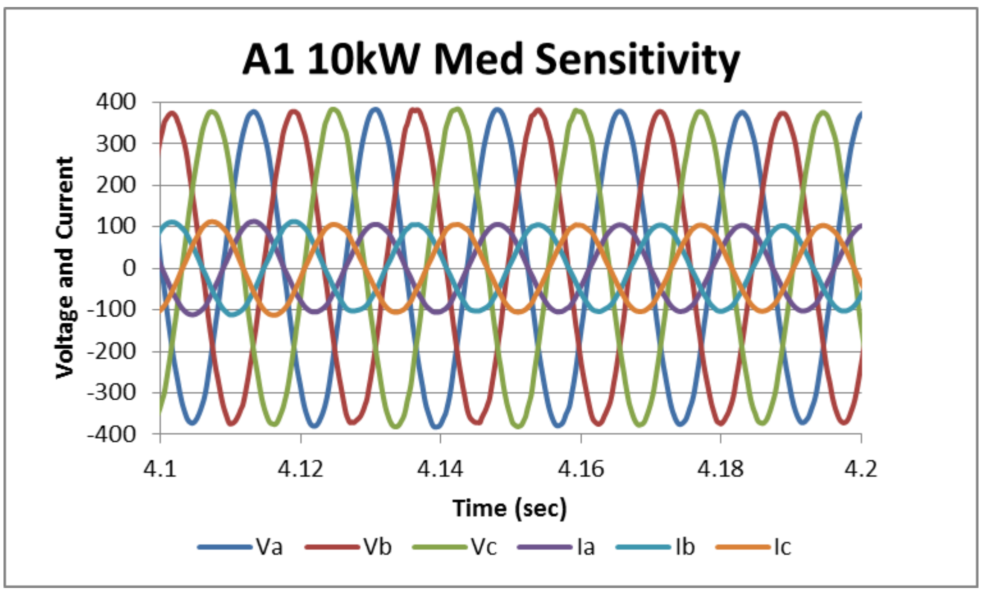

Figure 6.3.3: A1 10 kW Medium Sensitivity Waveform Voltage and Current

In Figure 6.3.1 above the initial load is approximately 47 kW and the bus frequency is approximately 60.17 Hz. At time 0 seconds, approximately 17 kW is added, bringing the total load to 64 kW. At 0.5 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.5 Hz at 1.8 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 4 seconds the bus frequency is 57.4 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.125 pu/s, dropping 5 kW of non-critical load, to approximately 59 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value.

At 5.1 seconds the bus frequency, 57.5 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 5 kW of non-critical load, bringing the total load to 55 kW. At 6.1 seconds the bus frequency has recovered to 57.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 51 kW. At 7.1 seconds the bus frequency has recovered to 58.6 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 47 kW. At 8.1 seconds the bus frequency has recovered to 59.55 Hz, which although above the Minimum Bus Frequency, an additional 5 kW of non-critical load is removed, bringing the total load to 42 kW. Continued load shedding is halted with a total of 42 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 60 Hz with 22 kW of total load shed. Using the trended frequency, 2.75 Hz of frequency deviance lasting 8.1 seconds was experienced during the overload event.

During this test the smart load reacted at 1.8 seconds after the Load Shedding Frequency was reached instead of the expected 2 second delay. Also an additional step of load was shed after the frequency recovered above the Minimum Bus Frequency. Both of these inaccuracies are like due to the difficulty in accurately measuring and calculating frequency in real time. Such inaccuracies can lead to some tolerance in when the Load Shedding Delay timer begins and in the assessment of when the bus frequency has returned above the Minimum Bus Frequency. This frequency inaccuracy can also be seen in the averaged frequency results of Figure 6.3.1. Although the smart load operated with tolerance it successfully protected the microgrid bus from source shutdown.

6.4. A1 10 kW Low Sensitivity

In Event A4, an overload of approximately 10 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Low Sensitivity level, which will cause it to react least quickly to an overload condition.

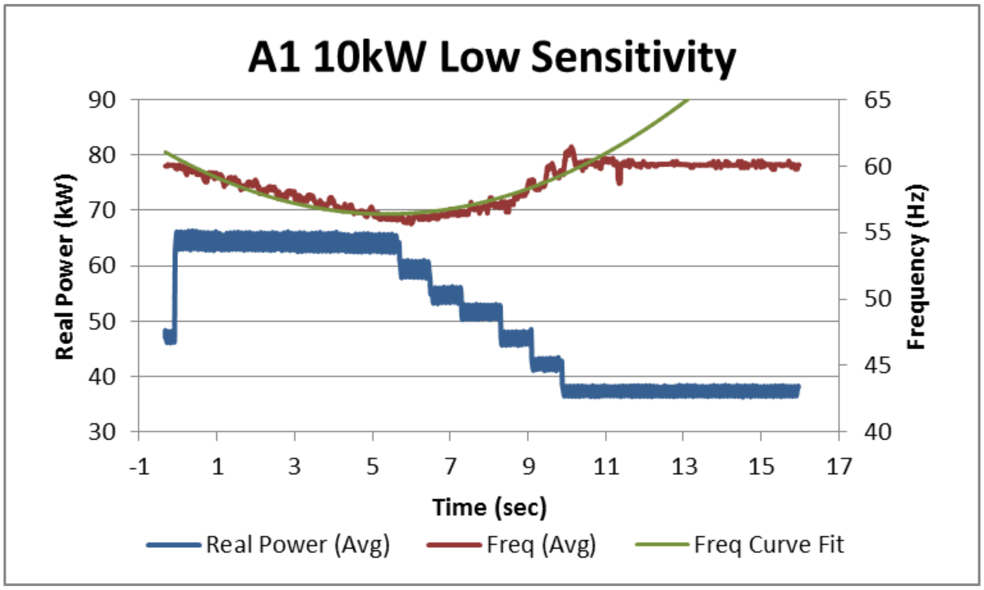

Figure 6.4.1: A1 10 kW Low Sensitivity Real Power and Frequency

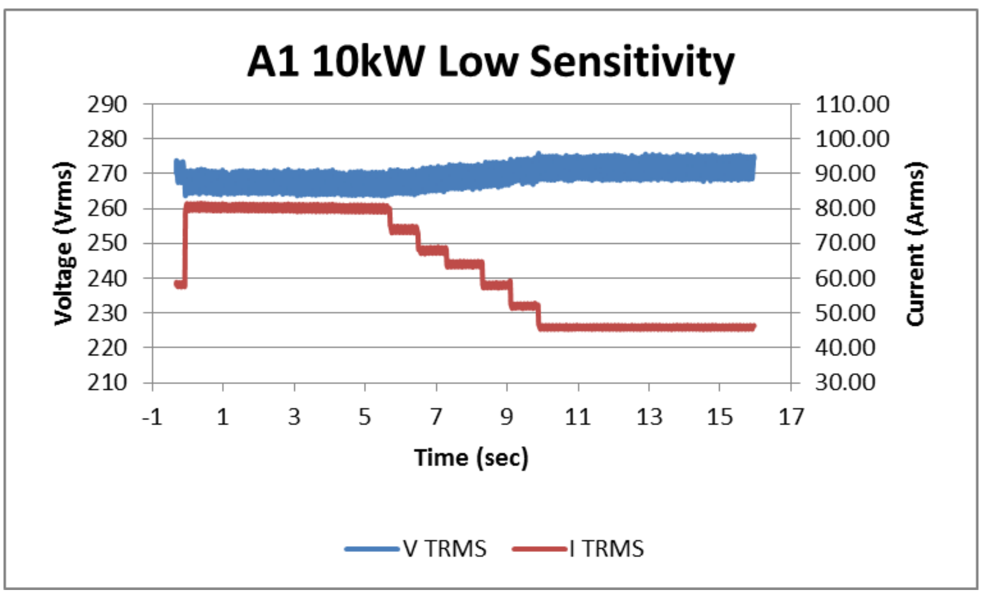

Figure 6.4.2: A1 10 kW Low Sensitivity RMS Voltage and Current

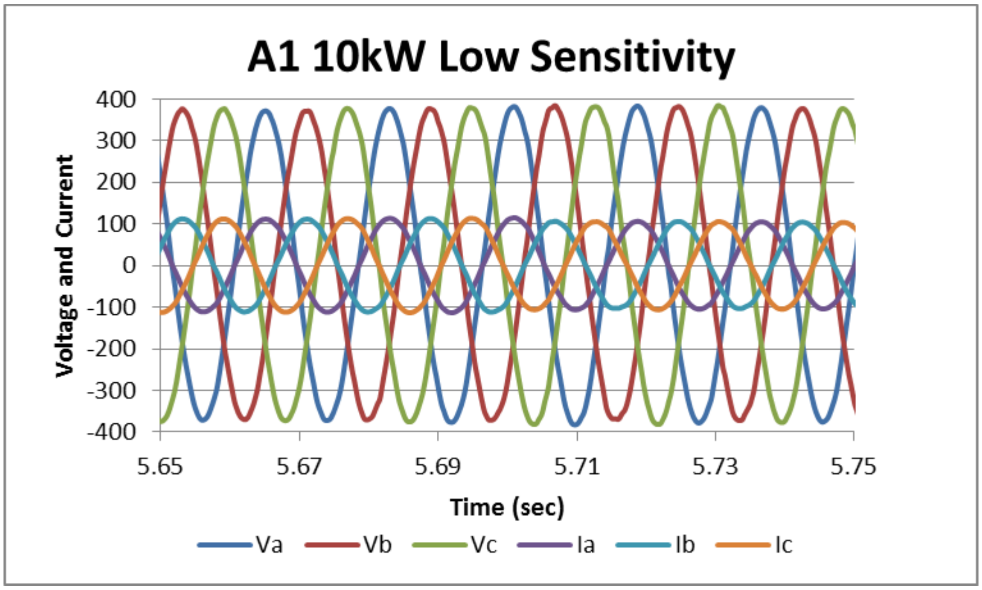

Figure 6.4.3: A1 10 kW Low Sensitivity Waveform Voltage and Current

In Figure 6.4.1 above the initial load is approximately 47 kW and the bus frequency is approximately 60.12 Hz. At time 0 seconds, approximately 18 kW is added, bringing the total load to 65 kW. At 0.6 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.0 Hz at 2.1 second. At this point the Smart Load, Load Shedding Delay timer begins. At 5.7 seconds the bus frequency is 56.4 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.143 pu/s, dropping 5 kW of non-critical load, to approximately 59 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value.

At 6.5 seconds the bus frequency, 56.6 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 5kW of non-critical load, bringing the total load to 55 kW. At 7.3 seconds the bus frequency has recovered to 56.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 51k W. At 8.3 seconds the bus frequency has recovered to 57.7 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 46 kW. At 9.1 seconds the bus frequency has recovered to 58.4 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 41 kW. Finally at 9.9 seconds the bus frequency has recovered to 59.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 37 kW. Shortly after the bus frequency recovers above 59.5 Hz and continued load shedding is halted with a total of 37 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 60.17 Hz with 28 kW of total load shed. Using the trended frequency, 3.70

Hz of frequency deviance lasting 9.9 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown

6.5. A1 20 kW Baseline

In Event B1, an overload of approximately 20 kW is placed on the islanded, inverter based generator. Further in this test the Smart load, load shedding is inhibited, which will knowingly lead to the eventual protection trip of the source.

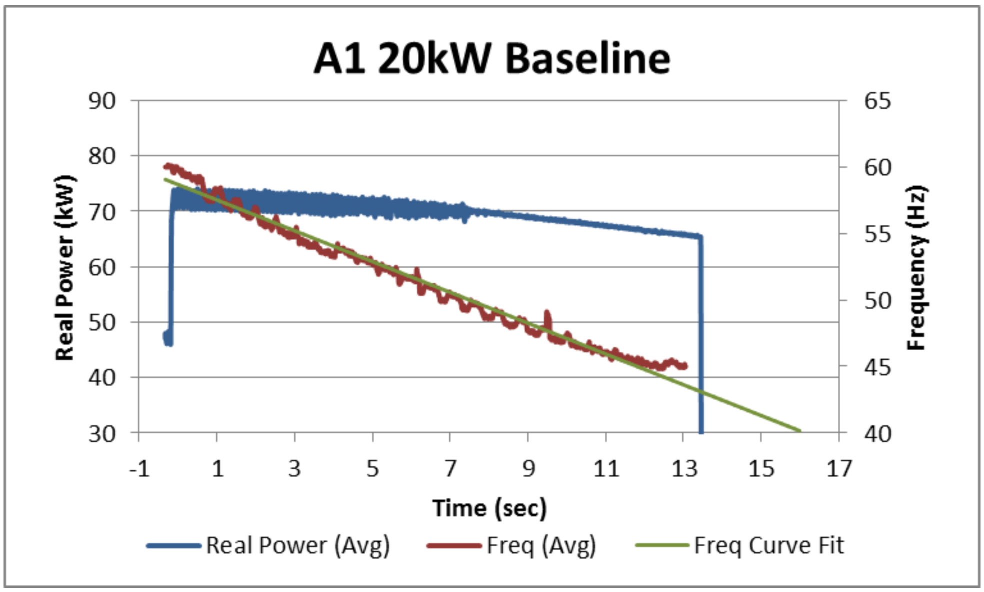

Figure 6.5.1: A1 20 kW High Sensitivity Real Power and Frequency

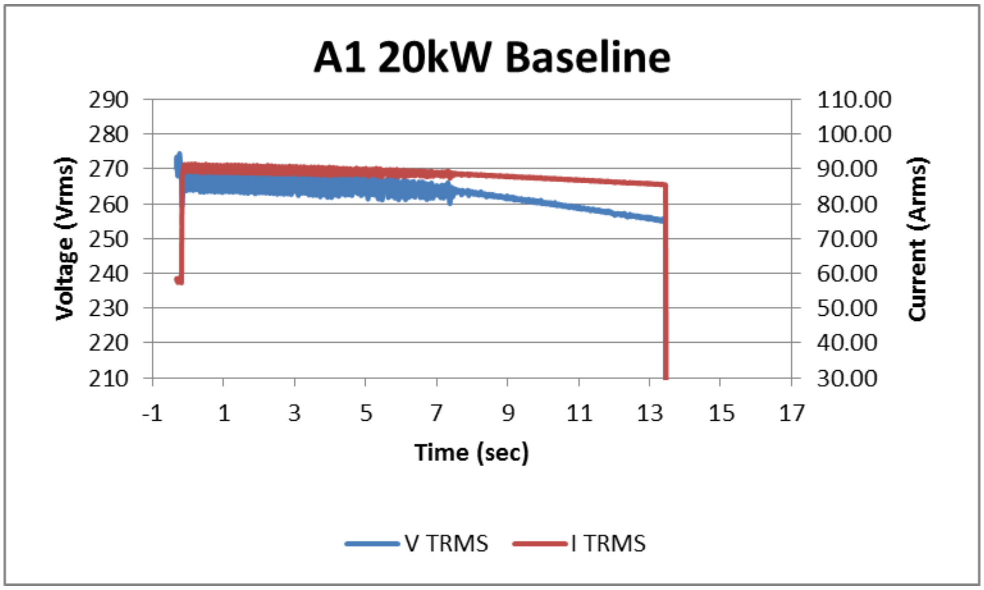

Figure 6.5.2: A1 20 kW High Sensitivity RMS Voltage and Current

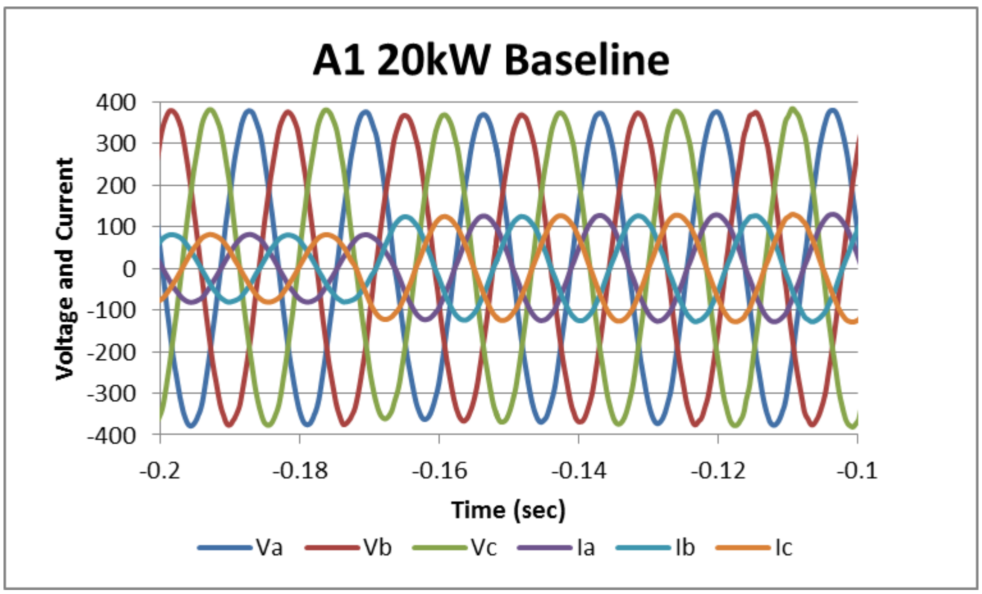

Figure 6.5.3: A1 20 kW High Sensitivity Waveform Voltage and Current

In Figure 6.5.1 above the initial load is approximately 47 kW and the bus frequency is approximately 60.12 Hz. At time -0.1 seconds, approximately 26 kW is added, bringing the total load to 73 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.16 seconds the frequency has dropped below the

Minimum Bus Frequency of 59.5 Hz and continues dropping at a rate of 1.15 Hz/second. In Figure 6.5.2, there is a reduction in voltage, approximately 21 $V_{l\text{-}n}$, during the overload event. This reduction is due to the increased reactive power consumption of transformer equipment connected to the microgrid bus as frequency drops. This increased reactive power consumption leads to a voltage reduction as it affects the voltage vs reactive power controller within the source. At 13.4 seconds the bus frequency is 43.1 Hz, and the source performs a controlled shutdown due to an overload protection fault. This test case illustrates the expected response if load shedding is unavailable within the microgrid environment.

6.6. A1 20 kW High Sensitivity

In Event B2, an overload of approximately 20 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a High Sensitivity level, which will cause it to react more quickly to an overload condition.

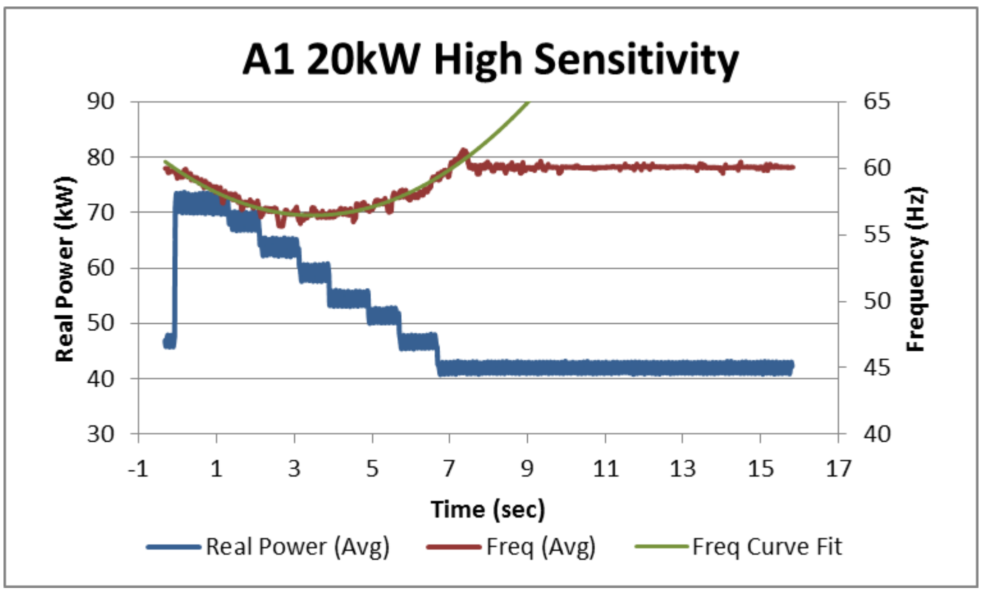

Figure 6.6.1: A1 20 kW High Sensitivity Real Power and Frequency

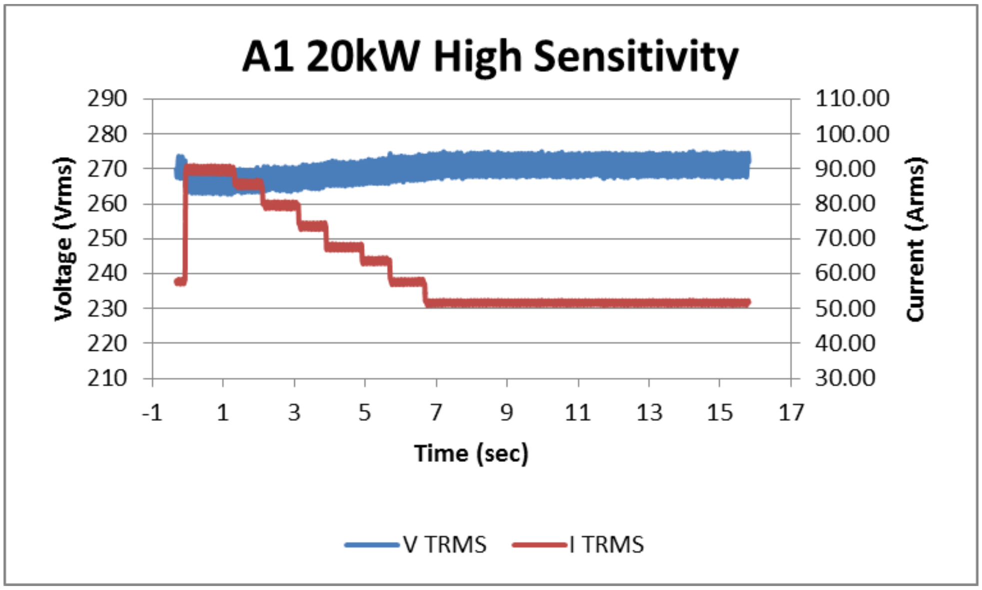

Figure 6.6.2: A1 20 kW High Sensitivity RMS Voltage and Current

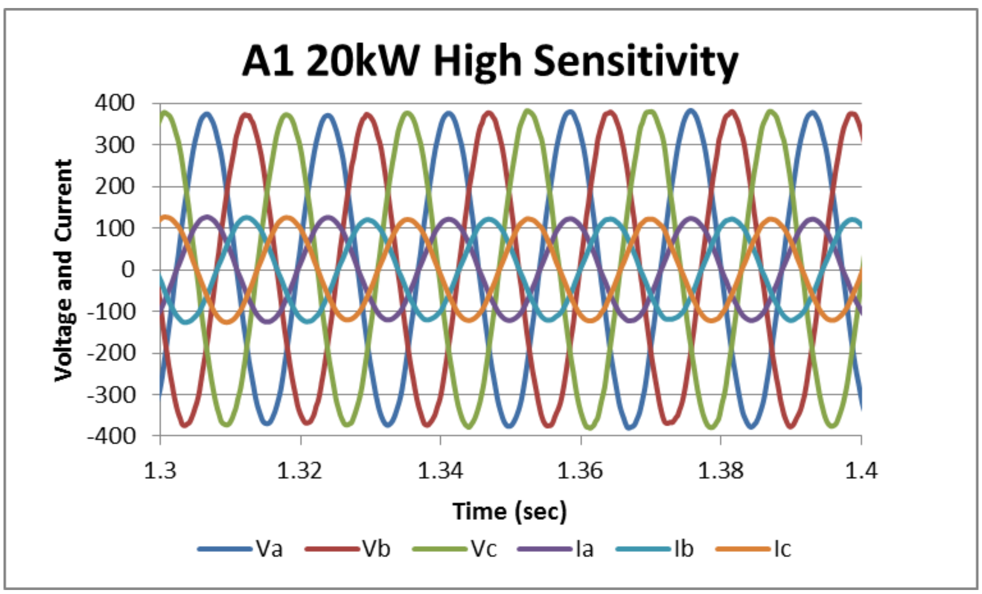

Figure 6.6.3: A1 20 kW High Sensitivity Waveform Voltage and Current

In Figure 6.6.1 above the initial load is approximately 46 kW and the bus frequency is approximately 59.69 Hz. At time 0 seconds, approximately 26 kW is added, bringing the total load to 72 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.2 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 59.0 Hz at 0.4 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 1.3

seconds the bus frequency is 57.8 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.111 pu/s, dropping 4 kW of non-critical load, to approximately 68 kW. At 2.1 seconds the bus frequency has reduced to 56.6 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 63 kW.

At 3.2 seconds the bus frequency, 56.5 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 5 kW of non-critical load, bringing the total load to 58 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 4 seconds the bus frequency remains at 56.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 54 kW. At 4.9 seconds the bus frequency has recovered to 57.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 5.8 seconds the bus frequency has recovered to 57.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 46 kW. At 6.7 seconds the bus frequency has recovered to 59.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 42 kW.

At 6.8 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 42 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 60.07 Hz with 30 kW of total load shed. Using the trended frequency, 3.22 Hz of frequency deviance lasting 6.8 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

6.7. A1 20 kW Medium Sensitivity

In Event B3, an overload of approximately 20 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Medium Sensitivity level, which will cause it to react less quickly to an overload condition.

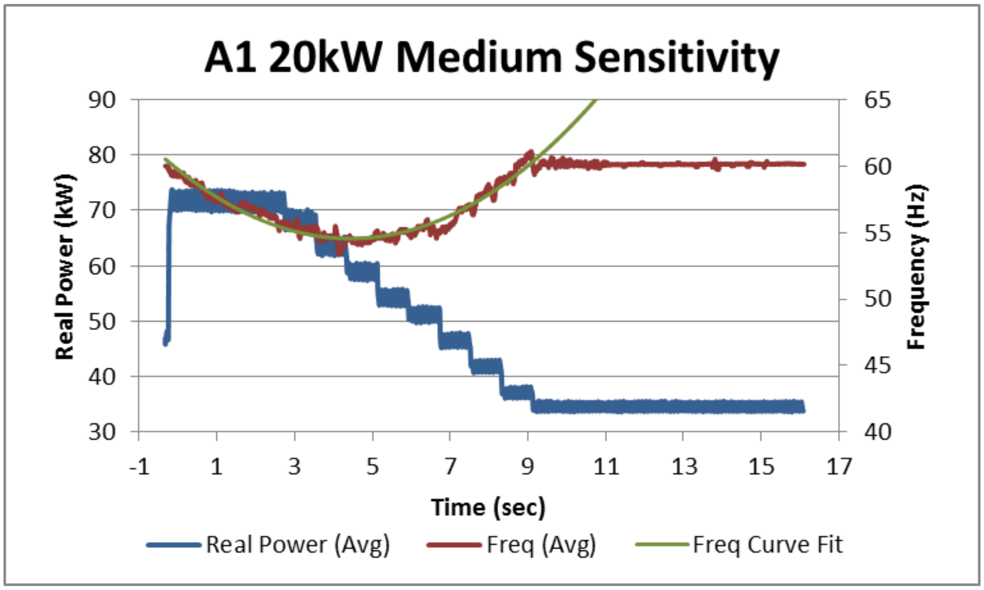

Figure 6.7.1: A1 20 kW Medium Sensitivity Real Power and Frequency

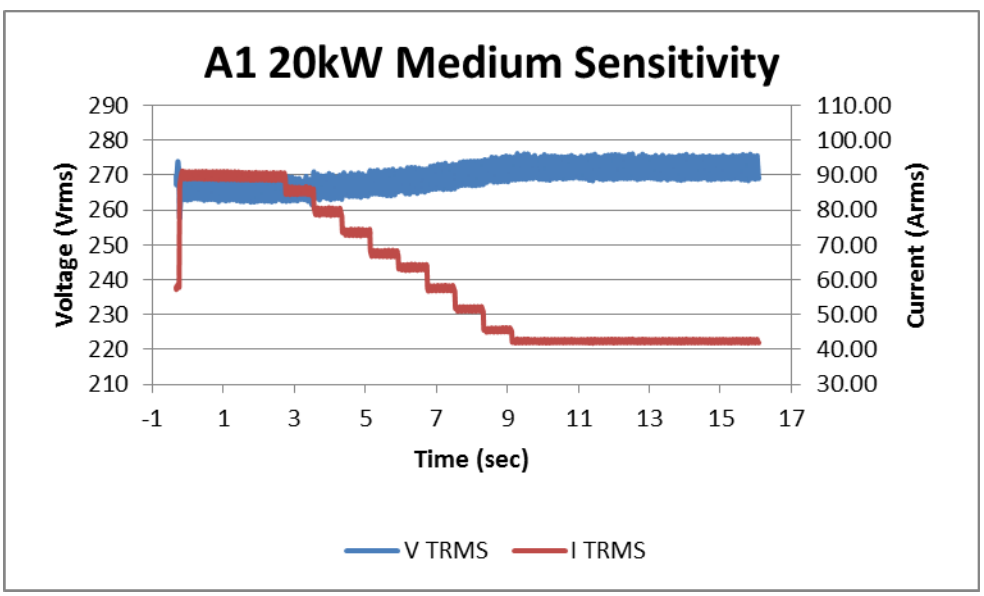

Figure 6.7.2: A1 20 kW Medium Sensitivity RMS Voltage and Current

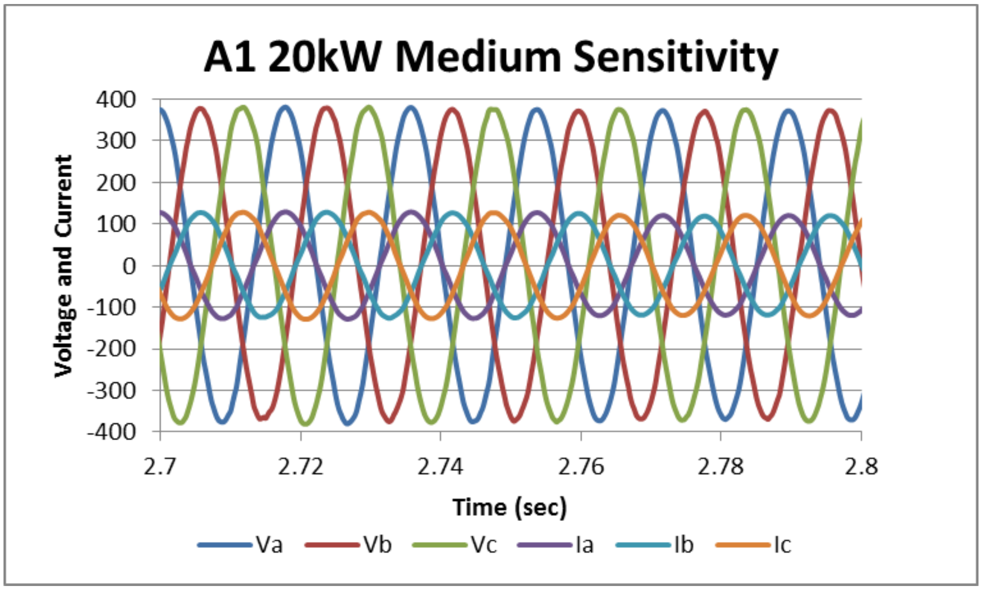

Figure 6.7.3: A1 20 kW Medium Sensitivity Waveform Voltage and Current

In Figure 6.7.1 above the initial load is approximately 47 kW and the bus frequency is approximately 59.83 Hz. At time -0.2 seconds, approximately 25 kW is added, bringing the total load to 72 kW. At 0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.5 Hz at 0.6 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 2.8 seconds the bus frequency is 55.3 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.125 pu/s, dropping 5 kW of non-critical load, to approximately 67 kW. At 3.6 seconds the bus frequency has reduced to 55.0 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 63 kW.

At 4.4 seconds the bus frequency, 54.5 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 4 kW of non-critical load, bringing the total load to 59 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 5.2 seconds the bus frequency has recovered to 54.7 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 54 kW. At 5.9 seconds the bus frequency has recovered to 55.1Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 6.8 seconds the bus frequency has recovered to 56.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 46 kW. At 7.5 seconds the bus frequency has recovered to 57.1 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 42 kW.

At 8.3 seconds the bus frequency has recovered to 58.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 38 kW. At 9.1 seconds the bus frequency has recovered to 59.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 34 kW. At 9.1 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 34 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 60.09 Hz with 38 kW of total load shed. Using the trended frequency, 5.27 Hz of frequency deviance lasting 9.3 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

6.8. A1 20 kW Low Sensitivity

In Event B4, an overload of approximately 20 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Low Sensitivity level, which will cause it to react least quickly to an overload condition.

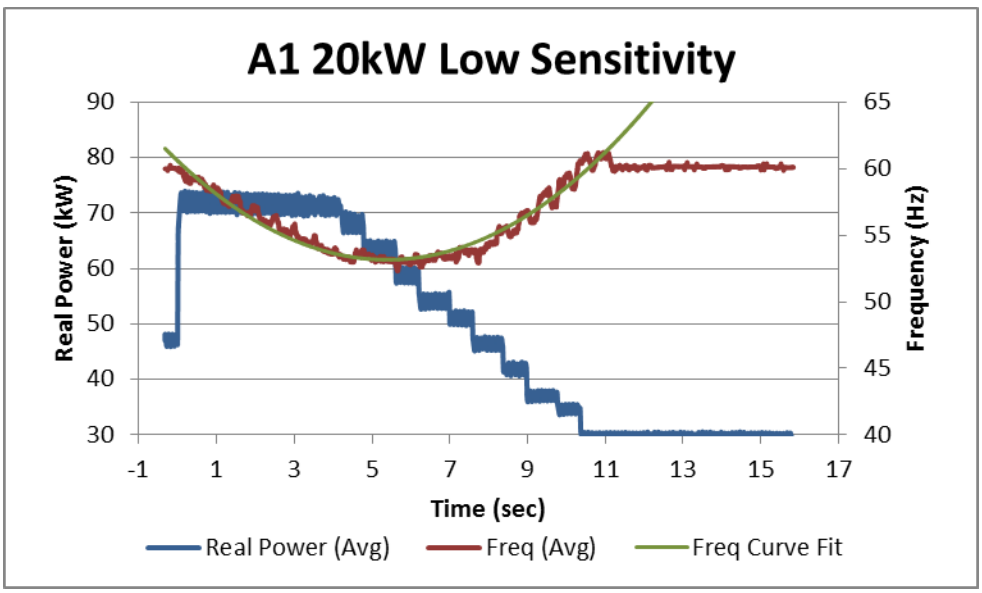

Figure 6.8.1: A1 20 kW Low Sensitivity Real Power and Frequency

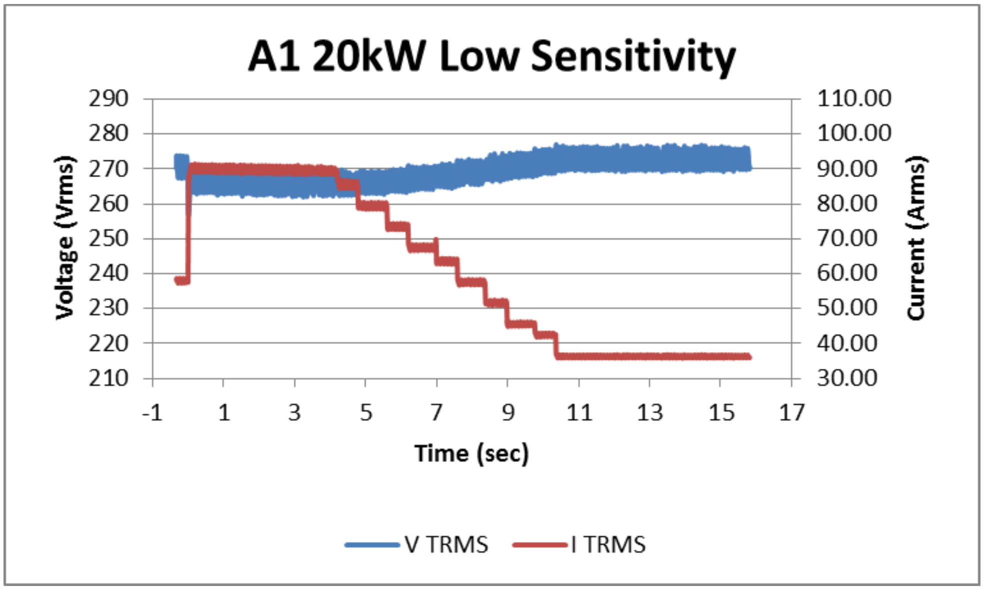

Figure 6.8.2: A1 20 kW Low Sensitivity RMS Voltage and Current

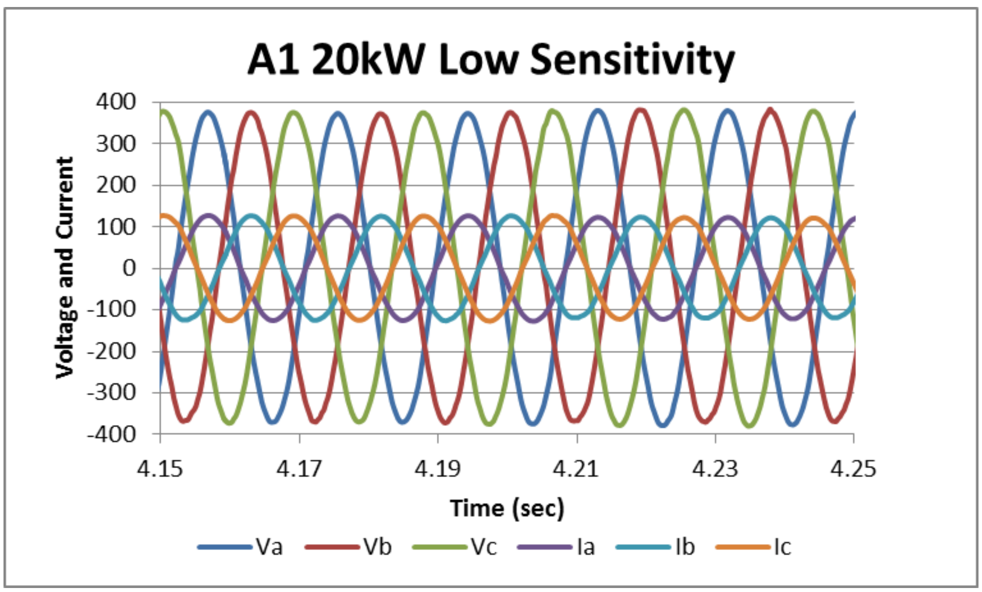

Figure 6.8.3: A1 20 kW Low Sensitivity Waveform Voltage and Current

In Figure 6.8.1 above the initial load is approximately 47 kW and the bus frequency is approximately 60.08 Hz. At time 0 seconds, approximately 25 kW is added, bringing the total load to 72 kW. At 0.4 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.0 Hz at 1.0 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 4.2 seconds the bus frequency is 53.5Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.143 pu/s, dropping 4 kW of non-critical load, to approximately 68 kW. At 4.8 seconds the bus frequency has reduced to 53.2 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 63 kW.

At 5.6 seconds the bus frequency, 53.1Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 4 kW of non-critical load, bringing the total load to 59 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 6.2 seconds the bus frequency has recovered to 53.3 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 54k W. At 7.1 seconds the bus frequency has recovered to 53.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 7.6 seconds the bus frequency has recovered to 54.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 46 kW. At 8.4 seconds the bus frequency has recovered to 55.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 42 kW.

At 9.0 seconds the bus frequency has recovered to 56.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 38 kW. At 9.8 seconds the bus frequency has recovered to 59.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 34 kW. Finally at 10.4 seconds the bus frequency has recovered just below 59.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 30 kW. Shortly after the bus frequency recovers above 59.5 Hz halting the load shedding, although the entire available non-critical load has been shed. A total of 30 kW of critical remain. The bus frequency continues to rise reaching its final stable operating point near 60.43 Hz with 42 kW of total load shed. Using the trended frequency, 6.91 Hz of frequency deviance lasting 10.4 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

6.9. A1 30 kW Baseline

In Event C1, an overload of approximately 30 kW is placed on the islanded, inverter based generator. Further in this test the Smart load, load shedding is inhibited, which will knowingly lead to the eventual protection trip of the source.

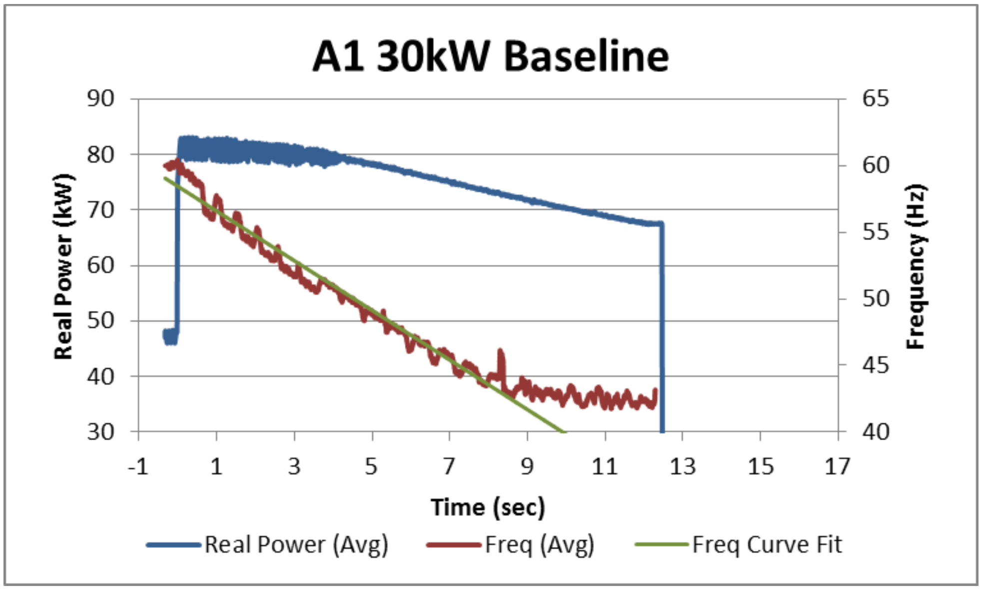

Figure 6.9.1: A1 30 kW High Sensitivity Real Power and Frequency

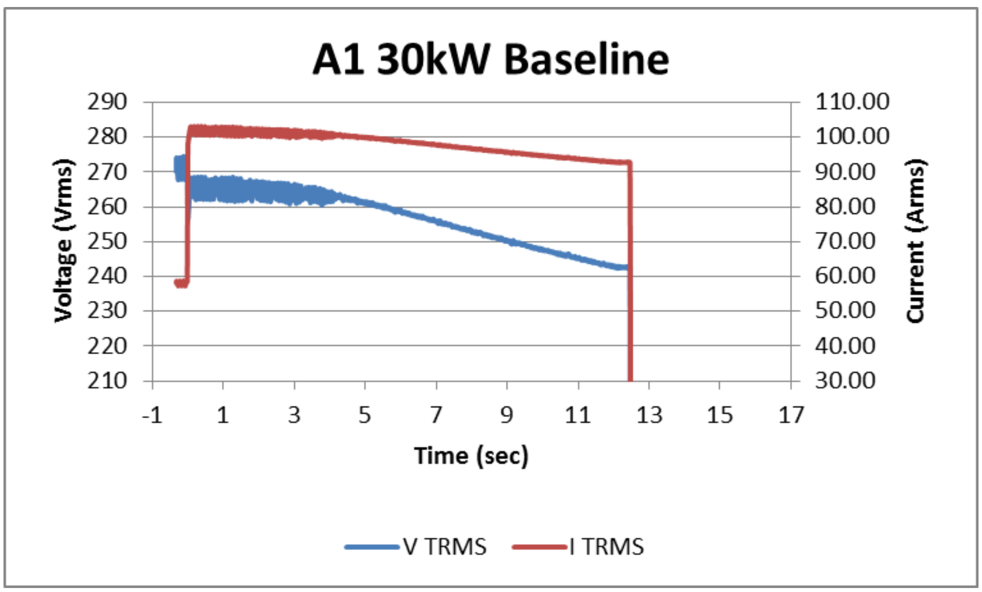

Figure 6.9.2: A1 30 kW High Sensitivity RMS Voltage and Current

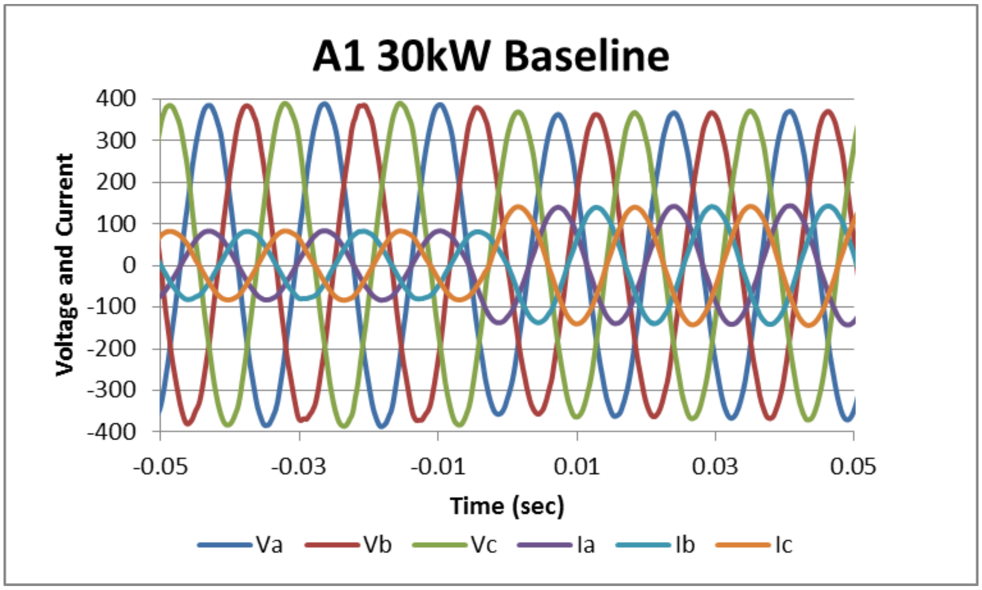

Figure 6.9.3: A1 30 kW High Sensitivity Waveform Voltage and Current

In Figure 6.9.1 above the initial load is approximately 48 kW and the bus frequency is approximately 60.10 Hz. At time 0 seconds, approximately 35 kW is added, bringing the total load to 83 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.13 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues dropping at a rate of 1.86 Hz/second. In Figure 6.9.2, there is a reduction in voltage, approximately 31 V_{l-n}, during the overload event. This reduction is due to the increased reactive power consumption of transformer equipment connected to the microgrid bus as frequency drops. This increased reactive power consumption leads to a voltage reduction as it affects the voltage vs reactive power controller within the source. At 12.5 seconds the bus frequency is 35.2 Hz, and the source performs a controlled shutdown due to an overload protection fault. This test case illustrates the expected response if load shedding is unavailable within the microgrid environment.

6.10. A1 30 kW High Sensitivity

In Event C2, an overload of approximately 30 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a High Sensitivity level, which will cause it to react more quickly to an overload condition.

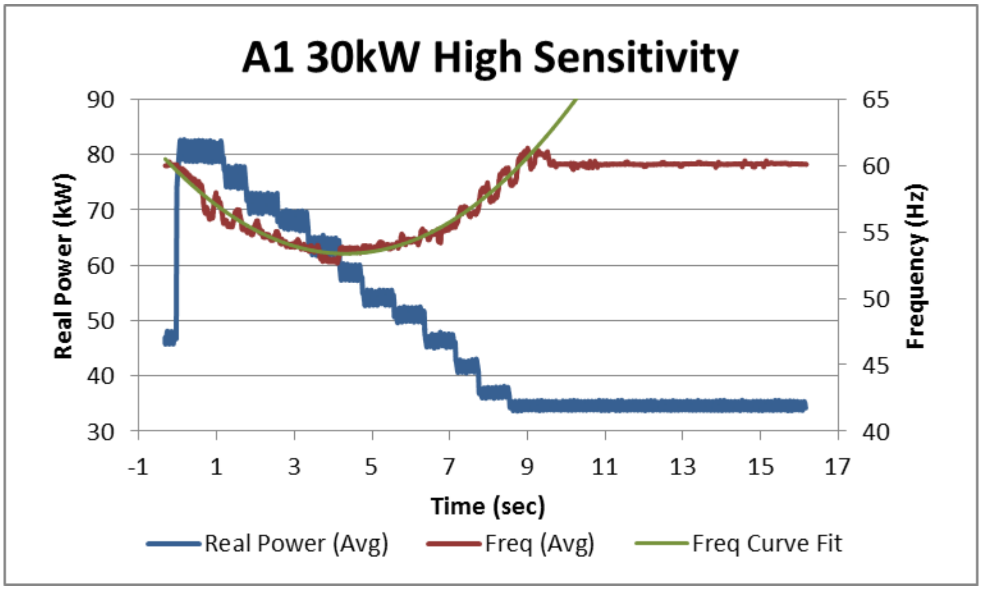

Figure 6.10.1: A1 30 kW High Sensitivity Real Power and Frequency

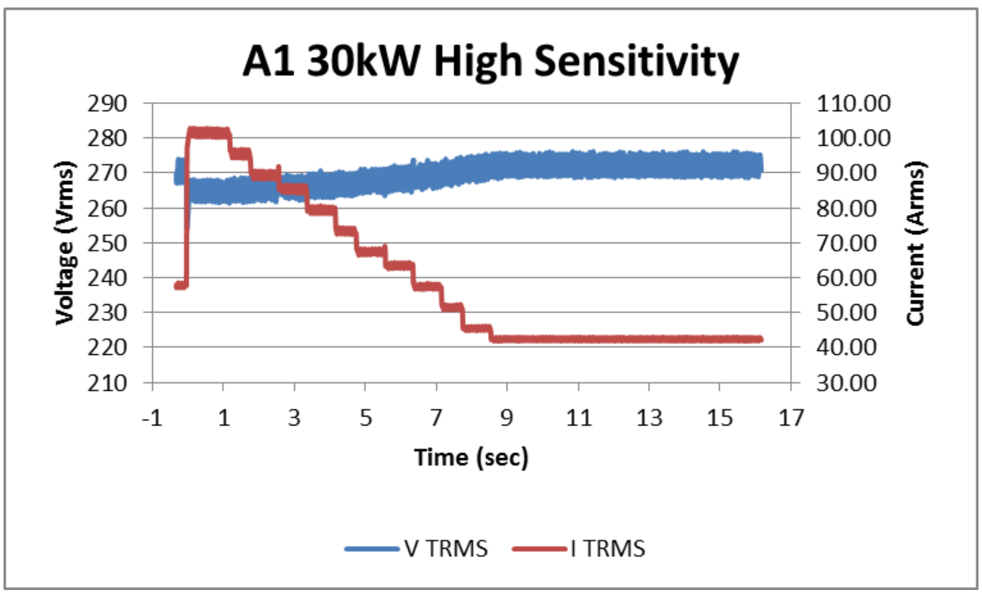

Figure 6.10.2: A1 30 kW High Sensitivity RMS Voltage and Current

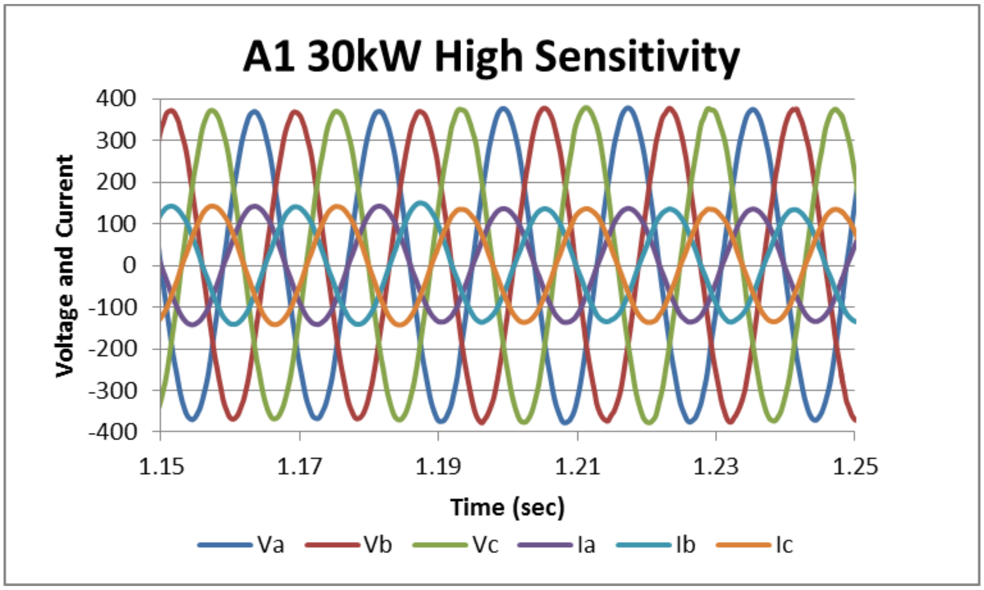

Figure 6.10.3: A1 30 kW High Sensitivity Waveform Voltage and Current

In Figure 6.10.1 above, the initial load is approximately 46 kW and the bus frequency is approximately 60.08 Hz. At time 0 seconds, approximately 35 kW is added, bringing the total load to 81 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 59.0 Hz at 0.2 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 1.2 seconds the bus frequency is 56.6 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.111 pu/s, dropping 4 kW of non-critical load, to approximately 77 kW. At 1.8 seconds the bus frequency has reduced to 55.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 73 kW.

At 2.5 seconds the bus frequency has reduced to 54.3 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 68 kW. At 3.4 seconds the bus frequency has reduced to 53.6 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 63 kW. At 4.2 seconds the bus frequency, 53.4 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 5 kW of non-critical load, bringing the total load to 58 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value.

At 4.8 seconds the bus frequency remains at 53.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 54 kW. At 5.6 seconds the bus frequency has recovered to 53.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 6.4 seconds the bus frequency has recovered to 54.8 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 46 kW. At 7.2 seconds the bus frequency has recovered to 56.1 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 42 kW. At 7.8 seconds the bus frequency has recovered to 57.3 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 38 kW.

Finally at 8.6 seconds the bus frequency has recovered to 59.3 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 34 kW. Shortly after the bus frequency recovers above 59.5 Hz halting the load shedding with a total of 34 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 60.11 Hz with 47 kW of total load shed. Using the trended frequency, 6.71 Hz of frequency deviance lasting 8.6 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

6.11. A1 30 kW Medium Sensitivity

In Event C3, an overload of approximately 30 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Medium Sensitivity level, which will cause it to react less quickly to an overload condition.

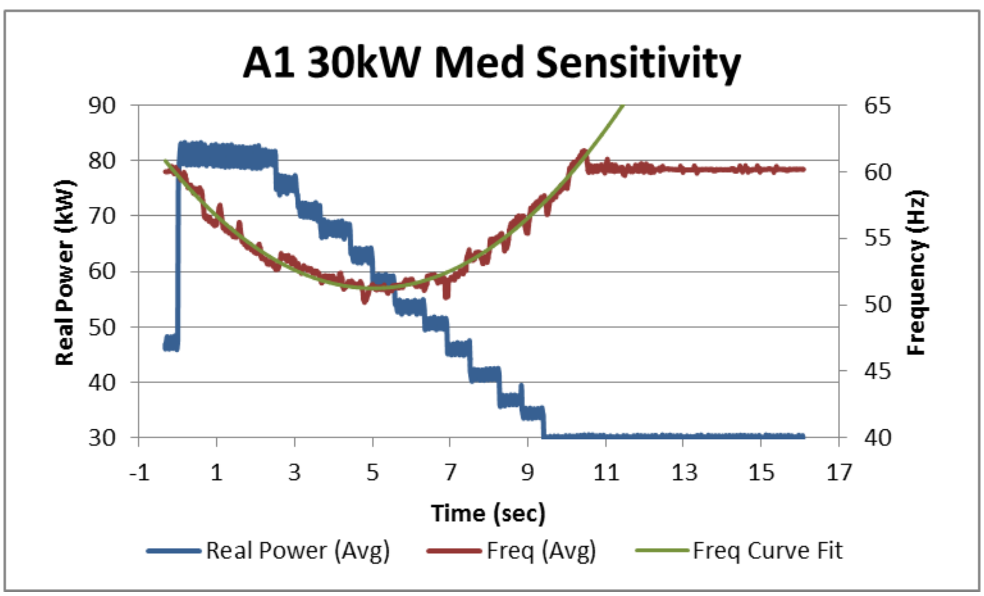

Figure 6.11.1: A1 30 kW Medium Sensitivity Real Power and Frequency

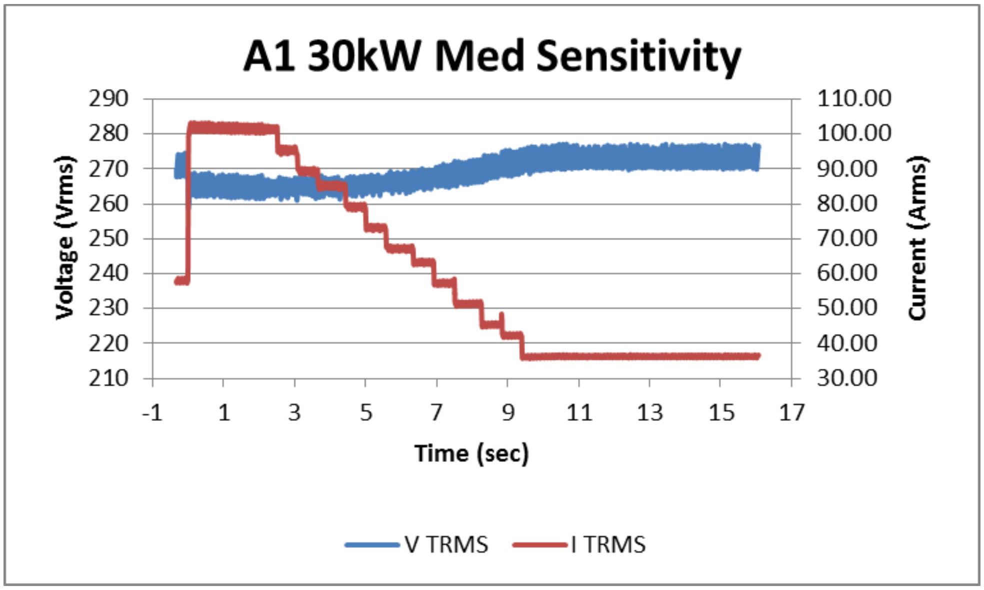

Figure 6.11.2: A1 30 kW Medium Sensitivity RMS Voltage and Current

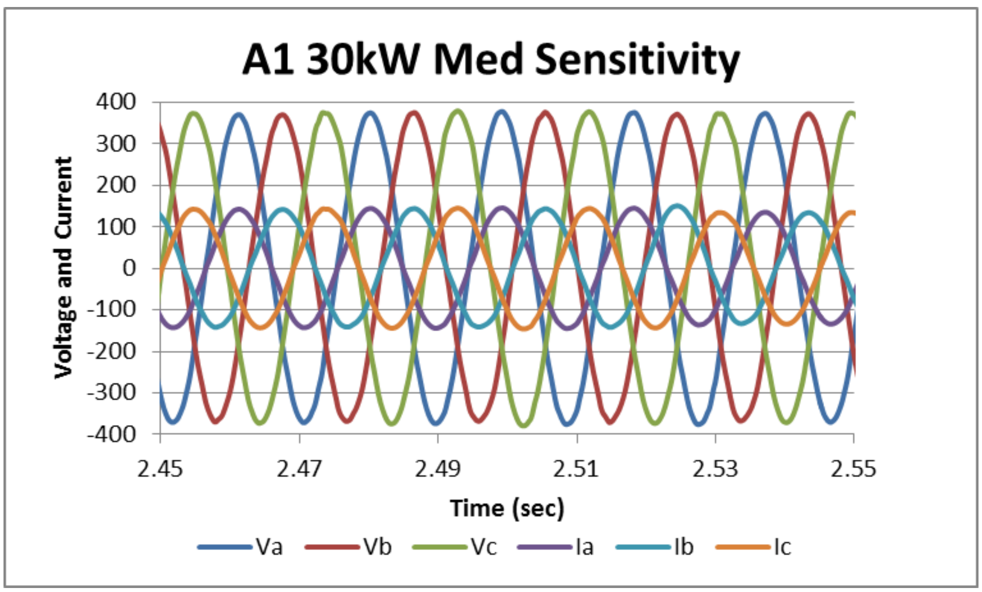

Figure 6.11.3: A1 30 kW Medium Sensitivity Waveform Voltage and Current

In Figure 6.11.1 above, the initial load is approximately 47 kW and the bus frequency is approximately 60.03 Hz. At time 0 seconds, approximately 34 kW is added, bringing the total load to 81 kW. At 0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.5 Hz at 0.4 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 2.5 seconds the bus frequency is 53.3 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.125 pu/s, dropping 5 kW of non-critical load, to approximately 77 kW. At 3.1 seconds the bus frequency has reduced to 52.4 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 72 kW.

At 3.7 seconds the bus frequency has reduced to 51.8 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 68 kW. At 4.4 seconds the bus frequency has reduced to 51.4 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 63 kW. At 5.0 seconds the bus frequency, 51.4 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 5 kW of non-critical load, bringing the total load to 58 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 5.6 seconds the bus frequency has recovered to 51.3 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 54 kW. At 6.4 seconds the bus frequency has recovered to 51.8 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 6.9 seconds the bus frequency has recovered to 52.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 46 kW.

At 7.5 seconds the bus frequency has recovered to 53.3 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 42 kW. At 8.3 seconds the bus frequency has recovered to 54.8 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 38 kW. At 8.9 seconds the bus frequency has recovered to 56.2Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 34 kW. At 9.4 seconds the bus frequency has recovered to 57.7 Hz, and the remaining 4 kW of non-critical load is removed, bringing the total load to 30 kW. The bus frequency recovers above 59.5 Hz at 10 seconds although all non-critical load has been shed and a total of 30 kW of critical remain. The bus frequency continues to rise reaching its final stable operating point near 60.25 Hz with 51 kW of total load shed. Using the trended frequency, 8.79 Hz of frequency deviance lasting 10 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

6.12. A1 30 kW Low Sensitivity

In Event C4, an overload of approximately 30 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Low Sensitivity level, which will cause it to react least quickly to an overload condition.

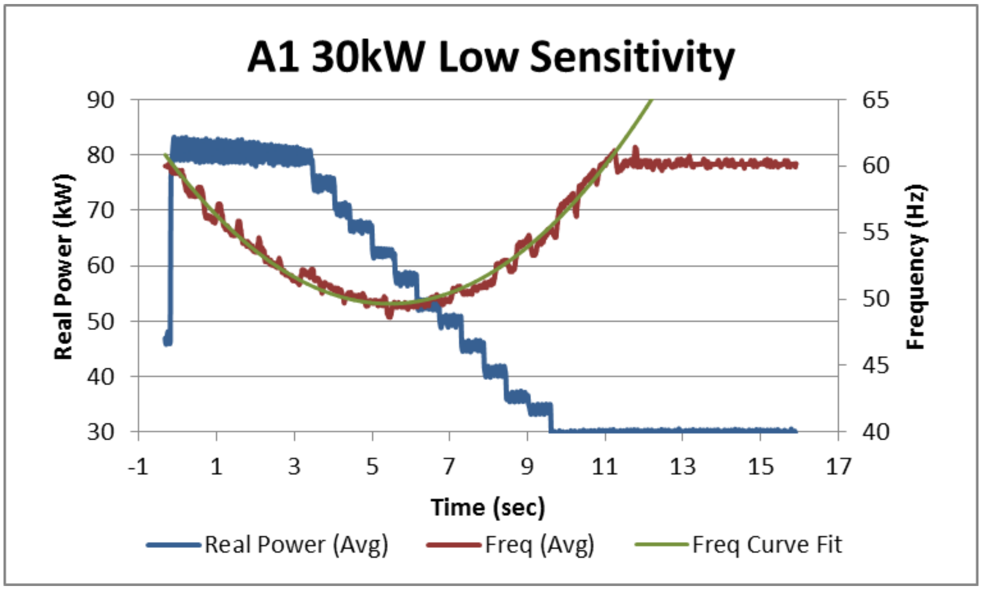

Figure 6.12.1: A1 30 kW Low Sensitivity Real Power and Frequency

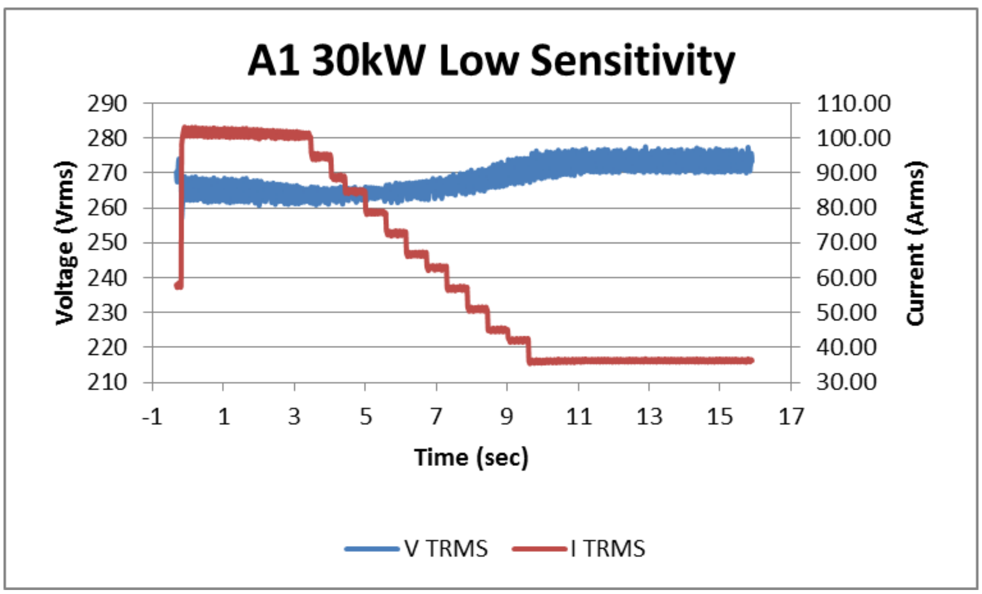

Figure 6.12.2: A1 30 kW Low Sensitivity RMS Voltage and Current

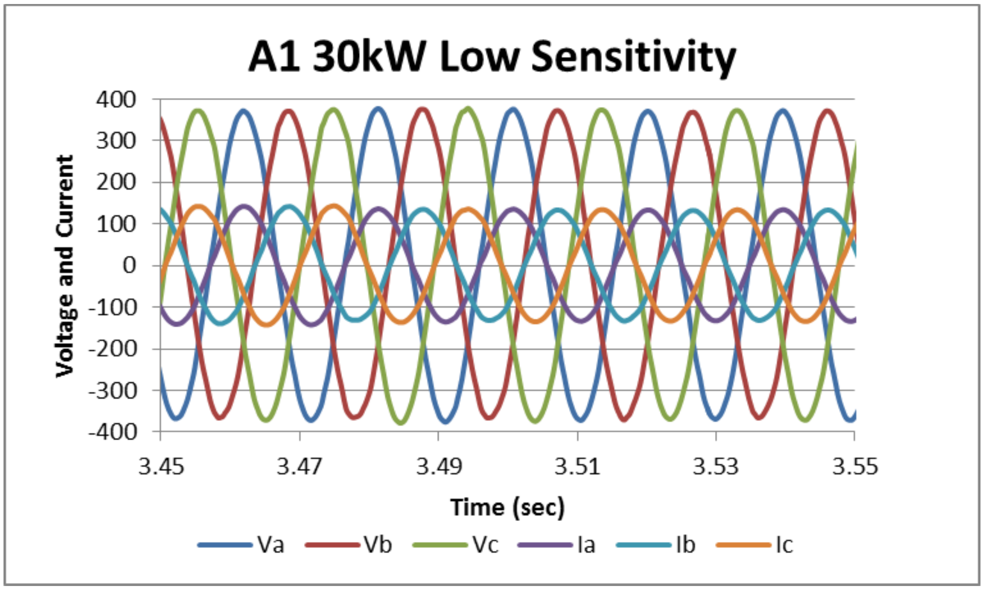

Figure 6.12.3: A1 30 kW Low Sensitivity Waveform Voltage and Current

In Figure 6.12.1 above, the initial load is approximately 46 kW and the bus frequency is approximately 60.24 Hz. At time -0.2 seconds, approximately 36 kW is added, bringing the total load to 82 kW. At approximately 0 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.0 Hz at 0.5 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 3.5 seconds the bus frequency is 50.9 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.143 pu/s, dropping 5 kW of non-critical load, to approximately 76 kW. At 4.0 seconds the bus frequency has reduced to 50.3 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 71 kW.

At 4.4 seconds the bus frequency has reduced to 50.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 67 kW. At 5.0 seconds the bus frequency has reduced to 49.7 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 63 kW. At 5.6 seconds the bus frequency has reduced to 49.7 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 58 kW. The frequency is stable and its slope has flattened. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 6.2 seconds the bus frequency has recovered to 49.8 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 53 kW. At 6.7 seconds the bus frequency has recovered to 50.2 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 49 kW. At 7.3 seconds the bus frequency has recovered to 50.8 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 45 kW. At 7.9 seconds the bus frequency has recovered to 51.7Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 41 kW.

At 8.5 seconds the bus frequency has recovered to 52.7 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 36 kW. At 9.1 seconds the bus frequency has recovered to 54.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 34 kW. At 9.6 seconds the bus frequency has recovered to 55.5 Hz, and the remaining 4 kW of non-critical load is removed, bringing the total load to 30 kW. The bus frequency recovers above 59.5 Hz at 10.8 seconds although all non-critical load has been shed and a total of 30 kW of critical remain. The bus frequency continues to rise reaching its final stable operating point near 60.24 Hz with 52 kW of total load shed. Using the trended frequency, 10.30 Hz of frequency deviance lasting 11.0 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7. Load Shedding Functionality – Generator B1

Performance Goal

Verify the Smart Load's ability to recover system frequency in the event of an overload on Generator B1, a synchronous directly coupled generator. The system was tested with one baseline (Baseline) and three load shedding sensitivity levels (High, Medium, Low) each against three levels of overload (10kW, 20kW, 30kW), for a total of 12 different tests. Each generator's P_{max} set point was artificially reduced from the unit's rated capacity intentionally to observe the P_{max} control response independent of physical constraints presented by the prime mover of each generator. The testing sequence was also designed to find the envelope of acceptable interaction between the Smart Load and generating source; both nuisance operations and system shutdowns were expected results. The acceptance criterion for this testing was a load shedding event, in response to system overload, which maintained microgrid operation.

Description of Procedure

Generator B1 was dispatched to 60 kW, $480V_{l\text{-}l}$, 1% Frequency Droop, and disconnected from the utility source ("islanded"). The generator was started and connected to the islanded microgrid electrical bus with a balanced load of 50kW in LB4, consisting of 30kW critical load and 20kW non-critical load. Once the system reached steady state, an additional non-critical load was added to the system to create the overload condition. In each test the overload was increased in order to measure the effects of overload magnitude and examine the timing of the load shedding response. When the load was applied, the data collection system records until the load shedding event is completed or the system experienced a protection shut down.

The InVerde was configured with the following settings:

Voltage Dispatch: $480V_{l\text{-}l}$
P_{max} controller: 60kW
Frequency Droop: 1%
Voltage Droop: 5%

	CASE	1	2	3	4
10kW Overload	A	Baseline (No Load Shedding)	High Overload Sensitivity	Medium Overload Sensitivity	Low Overload Sensitivity
20kW Overload	B	Baseline (No Load Shedding)	High Overload Sensitivity	Medium Overload Sensitivity	Low Overload Sensitivity

30kW Overload	**C**	Baseline (No Load Shedding)	High Overload Sensitivity	Medium Overload Sensitivity	Low Overload Sensitivity

Table 7.1: Smart Load Sensitivity and Magnitude Settings – Generator B1

Test Results

GENERATOR B1		Prior to Overload		During Overload		After Load Shed	
CASE		Real Power (kW)	Frequency (Hz)	Lowest Trend Frequency (Hz)	Frequency Drop (Hz)	Real Power (kW)	Frequency (Hz)
A1	10kW / Baseline	49.77	60.37	47.65	12.72	NA	NA
A2	10kW / High Sensitivity	48.27	59.62	58.08	1.54	43.35	60.03
A3	10kW / Medium Sensitivity	48.37	59.62	56.67	2.95	38.34	59.86
A4	10kW / Low Sensitivity	48.24	60.11	55.92	4.19	35.67	59.59
B1	20kW / Baseline	49.17	61.28	46.31	14.97	NA	NA
B2	20kW / High Sensitivity	48.19	59.96	55.26	4.70	35.77	59.66
B3	20kW / Medium Sensitivity	48.15	59.90	55.14	4.76	35.63	59.65
B4	20kW / Low Sensitivity	48.20	60.34	55.03	5.31	30.60	59.61
C1	30kW /Baseline	47.84	59.72	40.75	18.97	NA	NA
C2	30kW / High Sensitivity	48.32	59.71	53.97	5.73	30.38	59.77
C3	30kW / Med Sensitivity	48.35	59.78	52.94	6.84	30.49	59.64
C4	30kW / Low Sensitivity	48.46	60.28	54.40	5.88	30.59	59.50

Table 7.2: Smart Load Test Results - Generator B1

Analysis

A detailed walkthrough of each event is described. The first event in each series is a baseline reference in which a similar overload is applied but load shedding is inhibited. The overload continues until the source performs a protection shutdown. The remaining three events in each series examine the three levels of load shedding sensitivity at each level of overload. In general all events follow a similar pattern although timing and quantity of final load shed may differ. These differences and any other points of interest will be individually described for the remaining events. Also worth note actual load steps vary from the test dispatch due to a number of factors such as resistive element tolerance and applied voltage.

7.1. B1 10 kW Baseline

In Event A1, an overload of approximately 10 kW is placed on the islanded, inverter based generator. Further in this test the Smart load, load shedding is inhibited, which will knowingly lead to the eventual protection trip of the source.

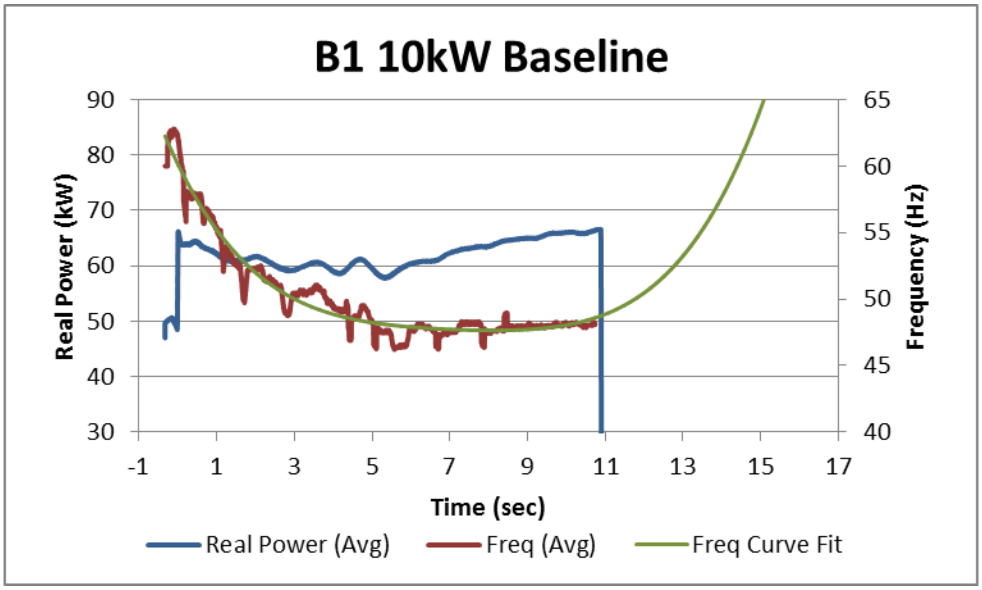

Figure 7.1.1: B1 10 kW High Sensitivity Real Power and Frequency

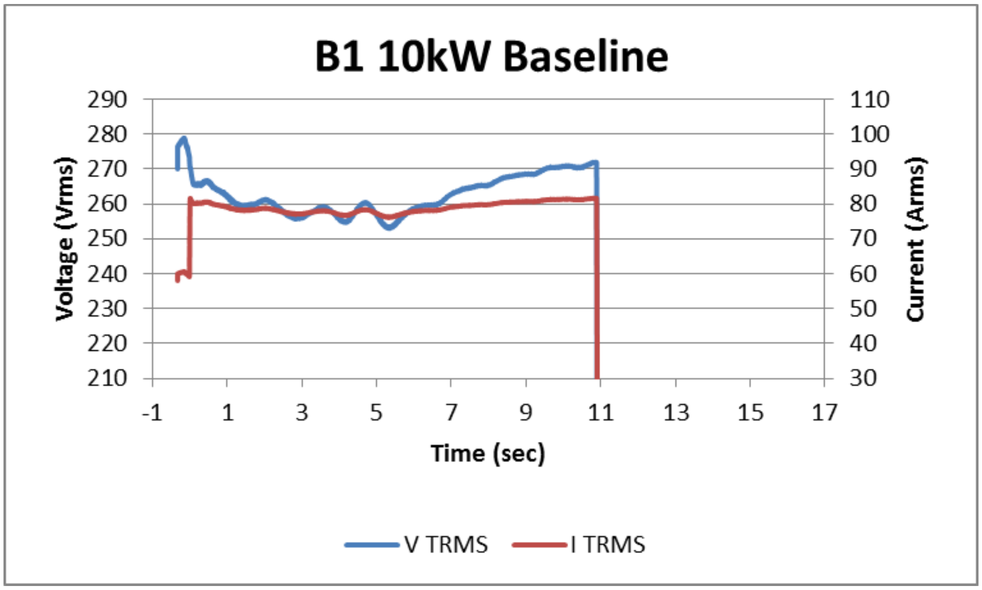

Figure 7.1.2: B1 10 kW High Sensitivity RMS Voltage and Current

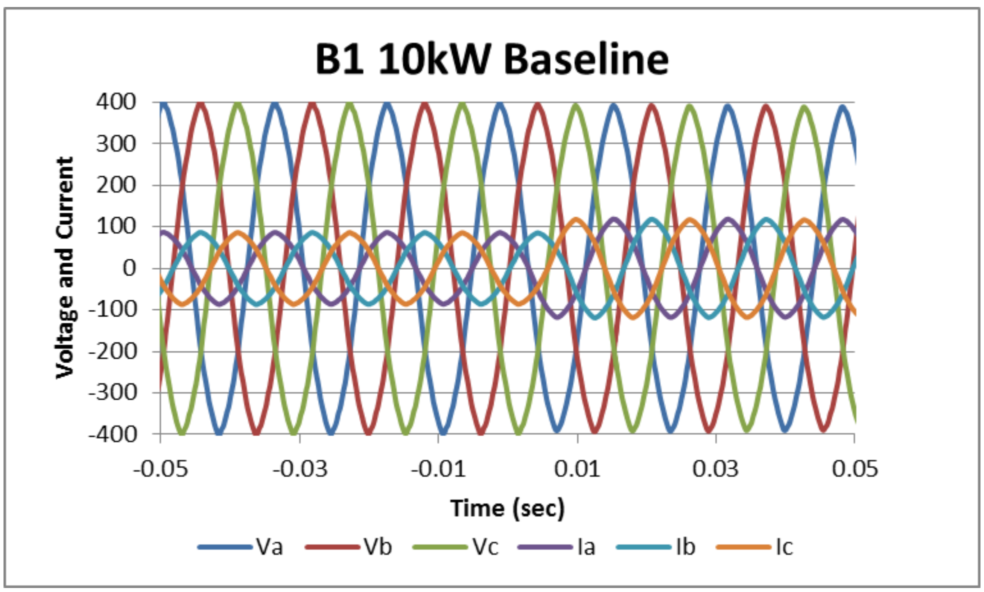

Figure 7.1.3: B1 10 kW High Sensitivity Waveform Voltage and Current

In Figure 7.1.1 above, the initial load is approximately 50 kW and the bus frequency is approximately 60.37 Hz. At time 0 seconds, approximately 15 kW is added, bringing the total load to 65 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues dropping at a rate of 3.8 Hz/second. In Figure 7.1.2, there is a slight reduction in voltage, approximately 14 $V_{l\text{-}n}$, during the overload event. This reduction is due to two main factors, the voltage vs reactive power controller and the voltage exciter of the synchronous generator. The voltage vs reactive power controller reduces the commanded voltage output as the reactive power consumption of transformer equipment connected to the microgrid bus increases with frequency reduction. The voltage exciter also lags in response to the voltage drop associated with the generator impedance and the changed in load current. At 10.9 seconds the bus frequency is 47.65 Hz, and the source performs a controlled shutdown due to an overload protection fault. This test case illustrates the expected response if load shedding is unavailable within the microgrid environment.

7.2. B1 10 kW High Sensitivity

In Event A2, an overload of approximately 10 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a High Sensitivity level, which will cause it to react more quickly to an overload condition.

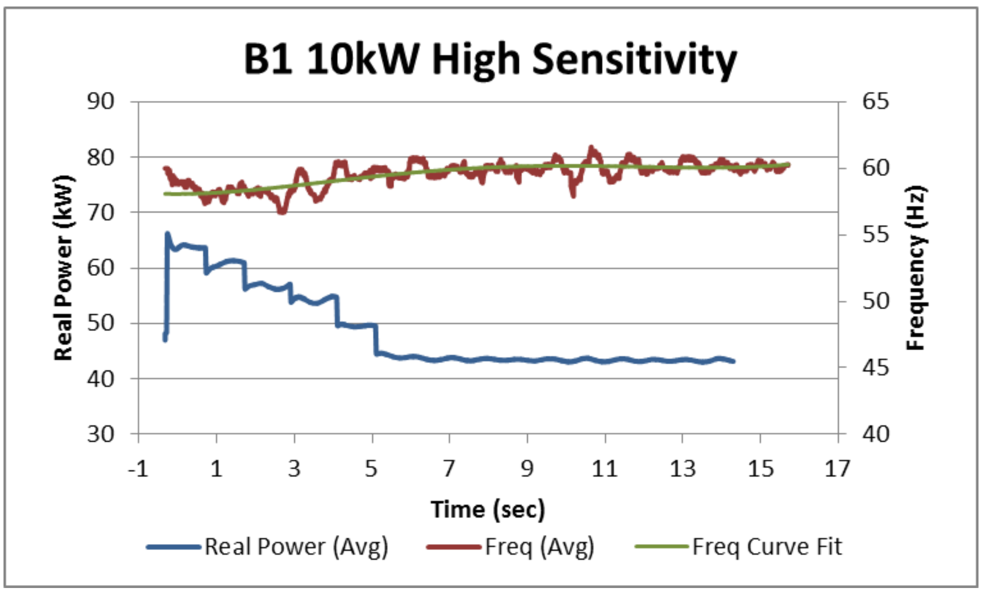

Figure 7.2.1: B1 10 kW High Sensitivity Real Power and Frequency

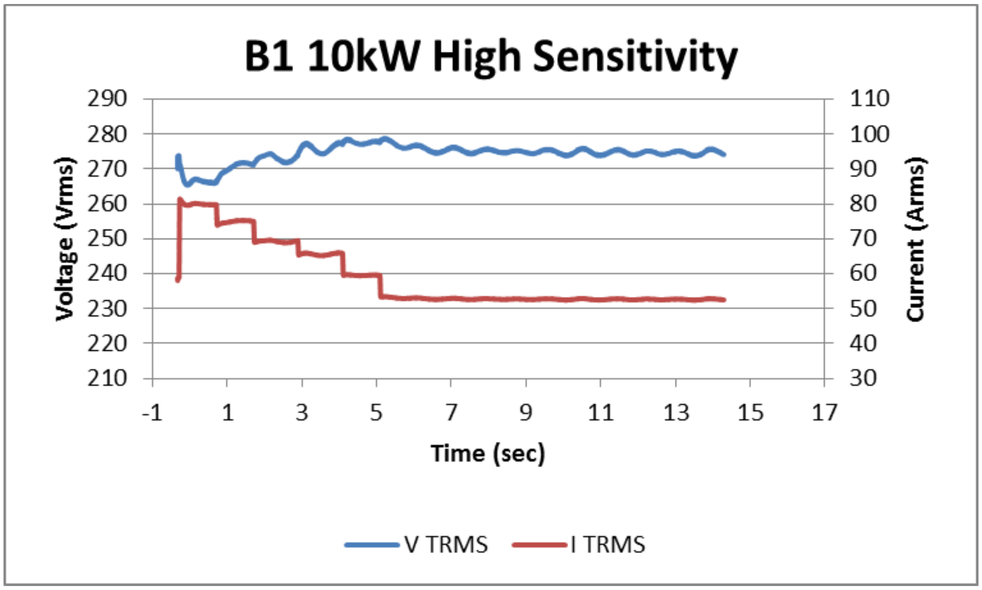

Figure 7.2.2: B1 10 kW High Sensitivity RMS Voltage and Current

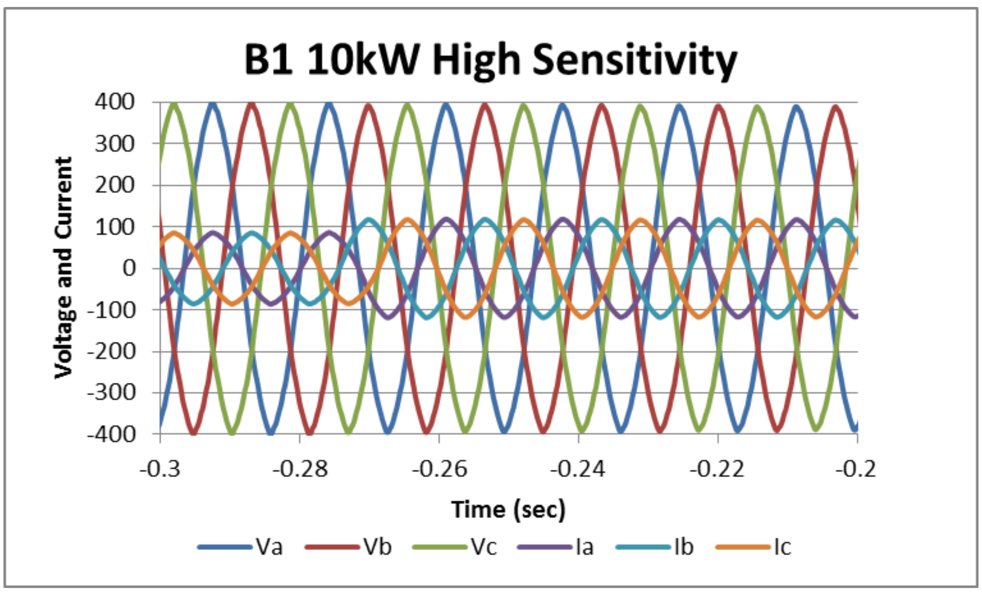

Figure 7.2.3: B1 10 kW High Sensitivity Waveform Voltage and Current

In Figure 7.2.1 above, the initial load is approximately 48 kW and the bus frequency is approximately 59.62 Hz. At time -0.3 seconds, approximately 17 kW is added, bringing the total load to 65 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At -0.2 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 59.0 Hz at -0.15 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 0.7

seconds the bus frequency is 58.1 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.111 pu/s, dropping 5 kW of non-critical load, to approximately 60 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value.

At 1.7 seconds the bus frequency has recovered to 58.3 Hz, which remains below the Minimum Bus Frequency and an additional 4 kW of non-critical load is removed, bringing the total load to 56 kW. At 2.9 seconds the bus frequency has recovered to 58.7 Hz, which remains below the Minimum Bus Frequency and an additional 4 kW of non-critical load is removed, bringing the total load to 52 kW. At 4.1 seconds the bus frequency has recovered to 59.1Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 48 kW. At 5.1 seconds the bus frequency has recovered to 59.4Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 43 kW. At 5.4 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 43 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 60.03 Hz with 22 kW of total load shed. Using the trended frequency, 1.54 Hz of frequency deviance lasting 5.7 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7.3. B1 10 kW Medium Sensitivity

In Event A3, an overload of approximately 10 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Medium Sensitivity level, which will cause it to react less quickly to an overload condition.

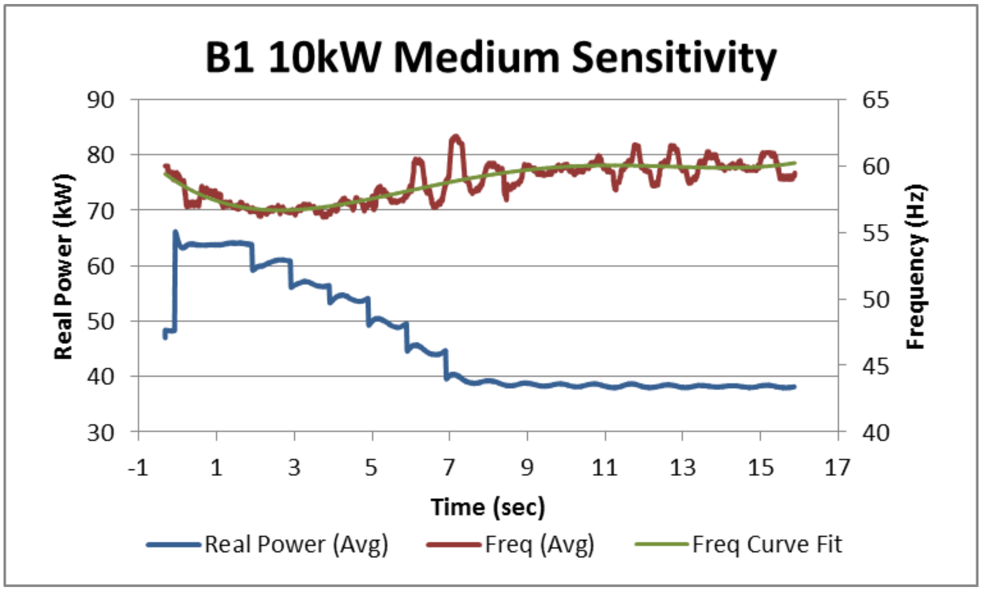

Figure 7.3.1: B1 10 kW Medium Sensitivity Real Power and Frequency

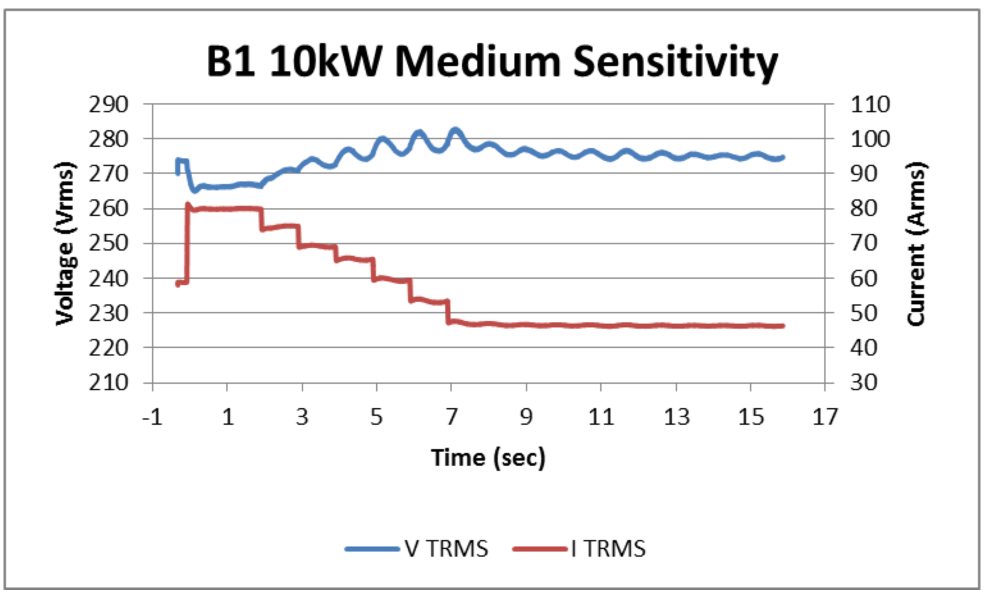

Figure 7.3.2: B1 10 kW Medium Sensitivity RMS Voltage and Current

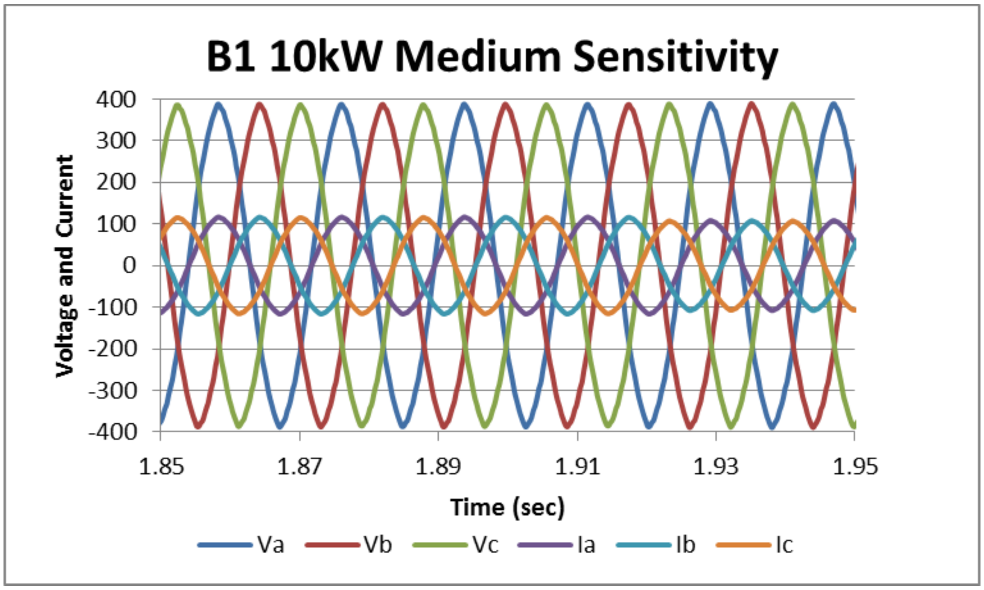

Figure 7.3.3: B1 10 kW Medium Sensitivity Waveform Voltage and Current

In Figure 7.3.1 above, the initial load is approximately 48 kW and the bus frequency is approximately 59.62 Hz. At time -0.1 seconds, approximately 16 kW is added, bringing the total load to 64 kW. At 0.0 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.5 Hz at 0.15 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 1.9 seconds the bus frequency is 56.8 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.125 pu/s, dropping 4 kW of non-critical load, to approximately 59 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value.

At 2.9 seconds the bus frequency, 56.7 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 4 kW of non-critical load, bringing the total load to 56 kW. At 3.9 seconds the bus frequency has recovered to 57.0 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 53 kW. At 4.9 seconds the bus frequency has recovered to 57.5 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 49 kW. At 5.9 seconds the bus frequency has recovered to 58.1 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 44 kW. At 6.9 seconds the bus frequency has recovered to 58.7 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 39 kW.

At 7.9 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 38 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 59.86 Hz with 26 kW of total load shed. Using the trended frequency, 2.95 Hz of frequency deviance lasting 8.0 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7.4. B1 10 kW Low Sensitivity

In Event A4, an overload of approximately 10 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Low Sensitivity level, which will cause it to react least quickly to an overload condition.

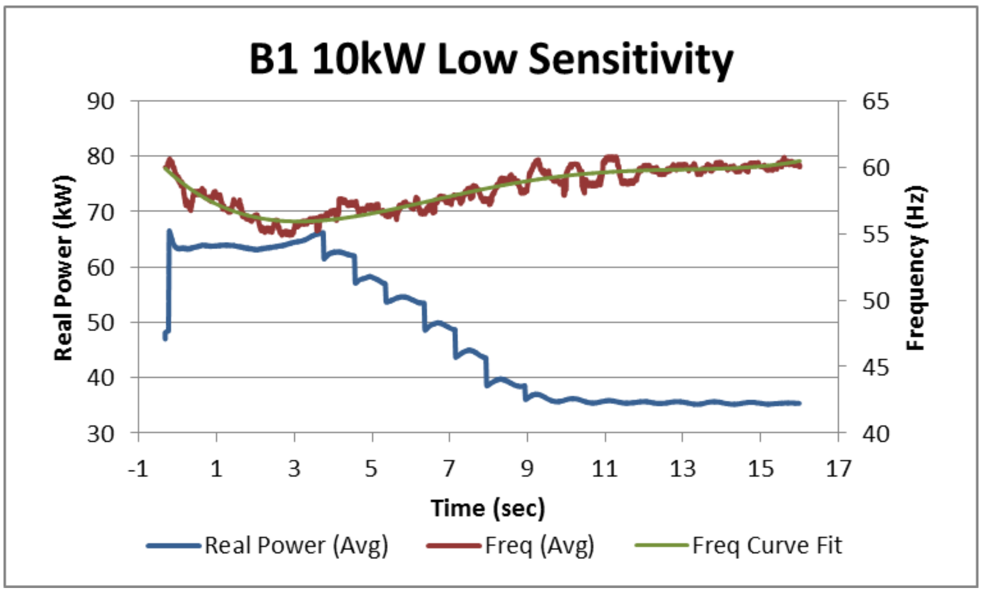

Figure 7.4.1: B1 10 kW Low Sensitivity Real Power and Frequency

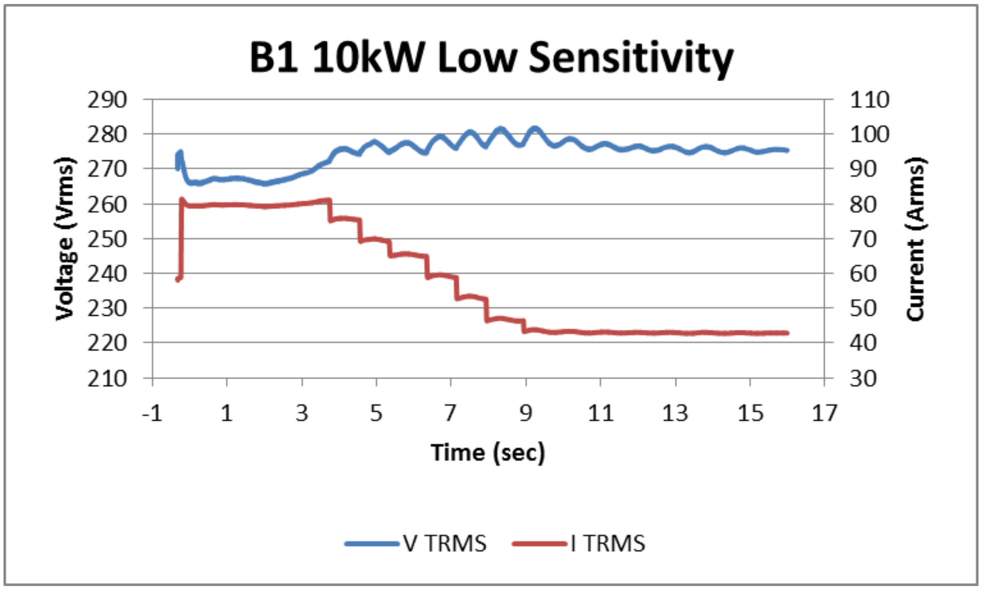

Figure 7.4.2: B1 10 kW Low Sensitivity RMS Voltage and Current

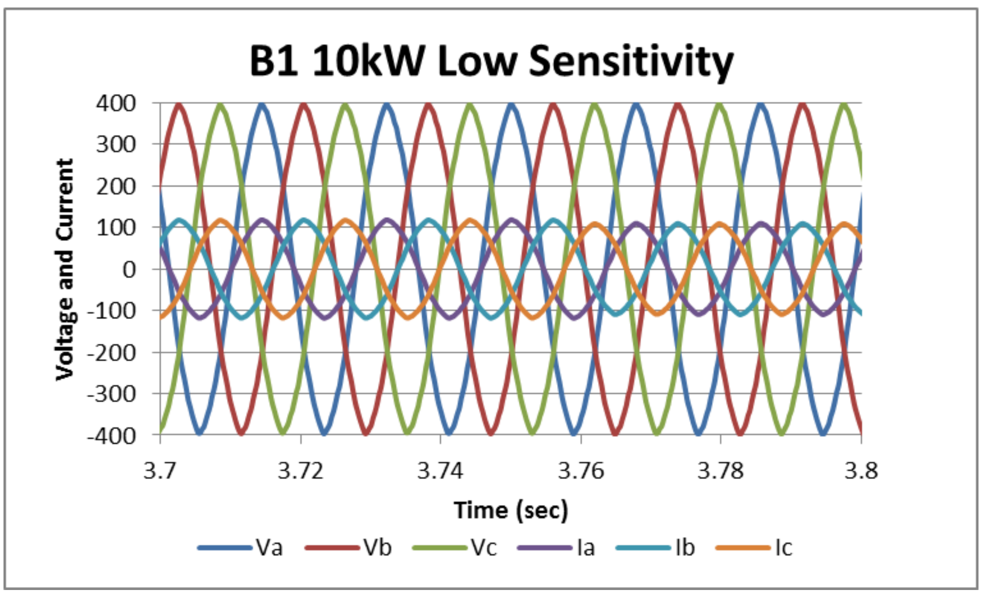

Figure 7.4.3: B1 10 kW Low Sensitivity Waveform Voltage and Current

In Figure 7.4.1 above, the initial load is approximately 48 kW and the bus frequency is approximately 60.11 Hz. At time -0.2 seconds, approximately 18 kW is added, bringing the total load to 66 kW. At -0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.0 Hz at 0.5 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 3.8 seconds the bus frequency is 56.0 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.143 pu/s, dropping 4 kW of non-critical load, to approximately 62 kW. At 4.6 seconds the bus frequency, 56.3 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 5kW of non-critical load, bringing the total load to 57 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value.

At 5.4 seconds the bus frequency, 56.7 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 4kW of non-critical load, bringing the total load to 53 kW. At 6.4 seconds the bus frequency has recovered to 57.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 49 k W. At 7.2 seconds the bus frequency has recovered to 57.9 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 44 kW. At 8.0 seconds the bus frequency has recovered to 58.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 40 kW. Finally at 9.0 seconds the bus frequency has recovered to 59.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 36 kW.

At 10.4 seconds, the bus frequency recovers above 59.5 Hz and continued load shedding is halted with a total of 36 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 59.59 Hz with 30 kW of total load shed. Using the trended frequency, 4.19 Hz of frequency deviance lasting 10.5 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown

7.5. B1 20 kW Baseline

In Event B1, an overload of approximately 20 kW is placed on the islanded, inverter based generator. Further in this test the Smart load, load shedding is inhibited, which will knowingly lead to the eventual protection trip of the source.

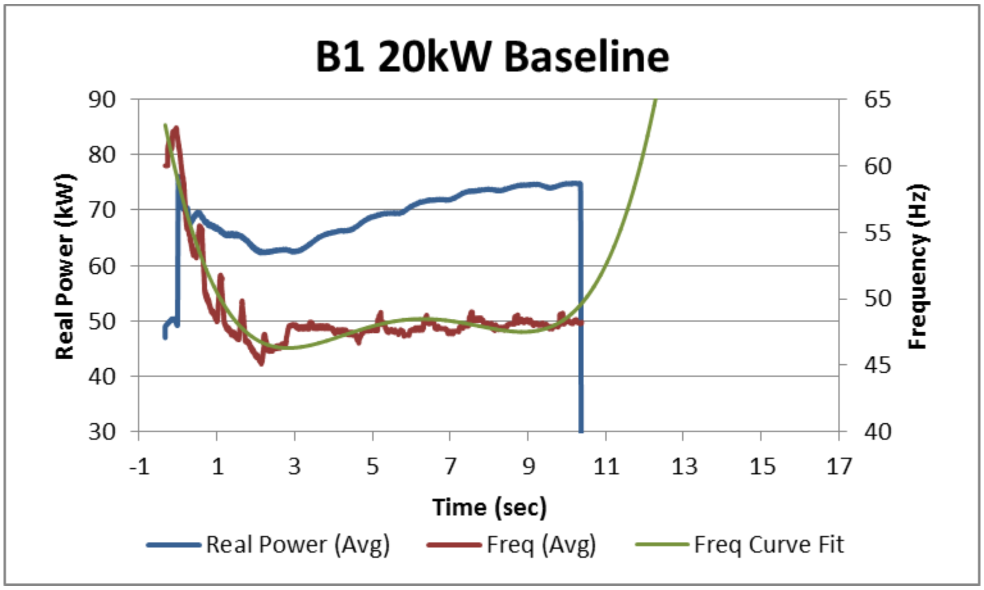

Figure 7.5.1: B1 20 kW High Sensitivity Real Power and Frequency

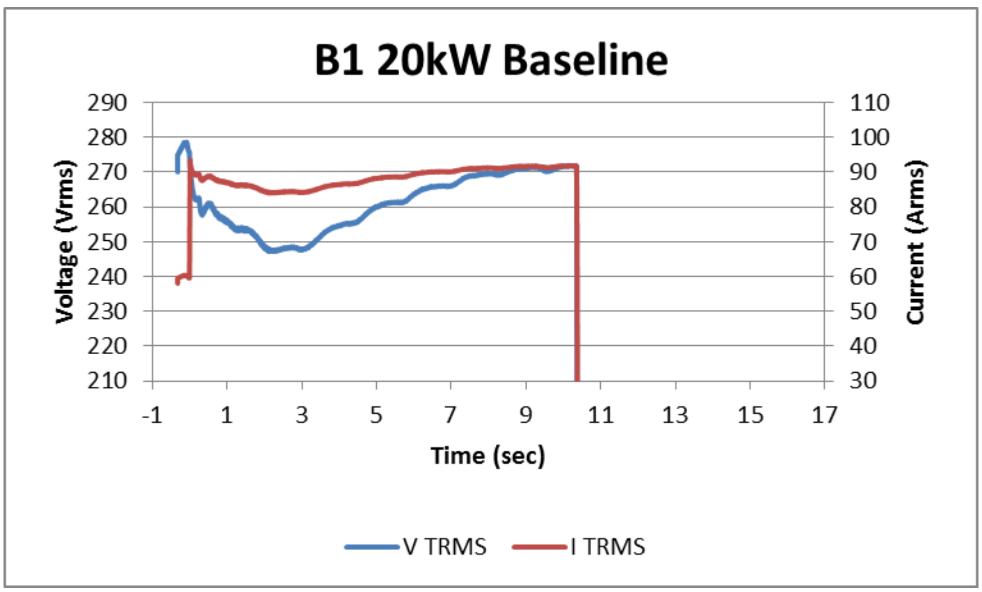

Figure 7.5.2: B1 20 kW High Sensitivity RMS Voltage and Current

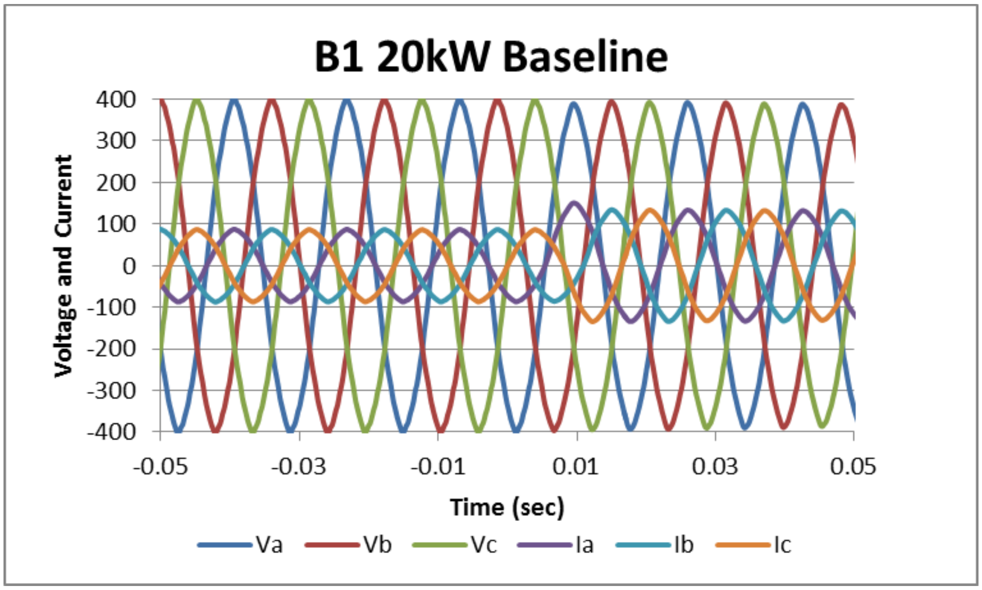

Figure 7.5.3: B1 20 kW High Sensitivity Waveform Voltage and Current

In Figure 7.5.1 above the initial load is approximately 49 kW and the bus frequency is approximately 61.28 Hz. At time 0 seconds, approximately 24 kW is added, bringing the total load to 73 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.15 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues dropping at a rate of 7.5 Hz/second. In Figure 7.5.2, there is a reduction in voltage, approximately 20 $V_{l\text{-}n}$, during the overload event. This reduction is due to two main factors, the voltage vs reactive power controller and the voltage exciter of the synchronous generator. The voltage vs reactive power controller reduces the commanded voltage output as the reactive power consumption of transformer equipment connected to the microgrid bus increases with frequency reduction. The voltage exciter also lags in response to the voltage drop associated with the generator impedance and the changed in load current. At 10.4 seconds the bus frequency is 49.6 Hz, and the source performs a controlled shutdown due to an overload protection fault. This test case illustrates the expected response if load shedding is unavailable within the microgrid environment.

7.6. B1 20 kW High Sensitivity

In Event B2, an overload of approximately 20 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a High Sensitivity level, which will cause it to react more quickly to an overload condition.

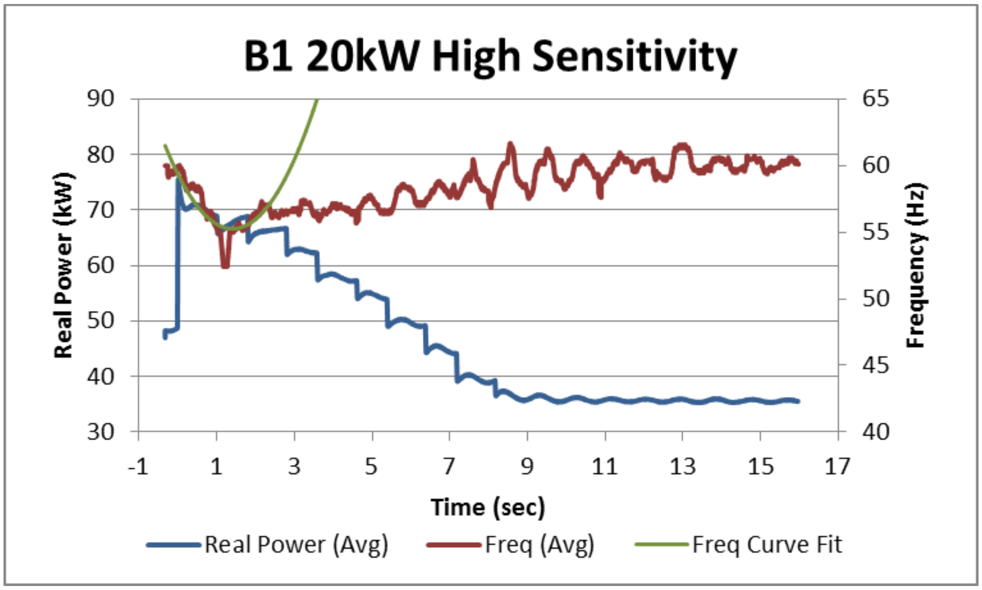

Figure 7.6.1: B1 20 kW High Sensitivity Real Power and Frequency

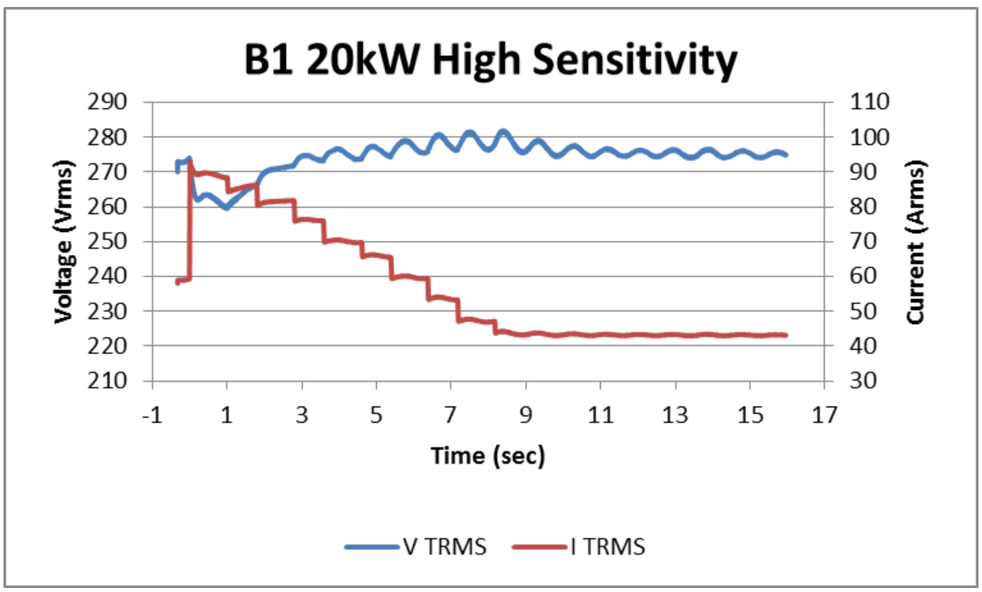

Figure 7.6.2: B1 20 kW High Sensitivity RMS Voltage and Current

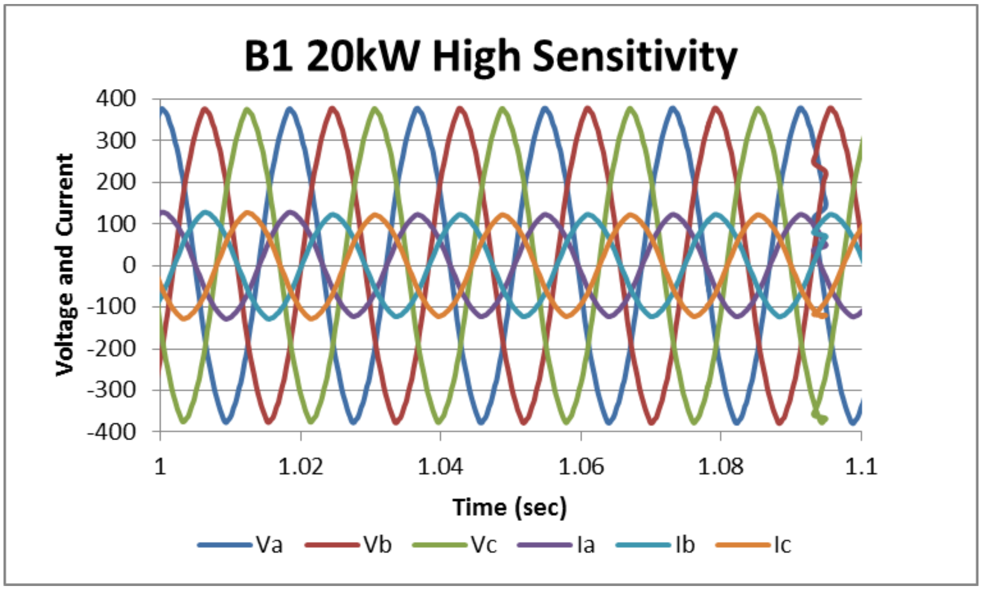

Figure 7.6.3: B1 20 kW High Sensitivity Waveform Voltage and Current

In Figure 7.6.1 above the initial load is approximately 48 kW and the bus frequency is approximately 59.96 Hz. At time 0 seconds, approximately 27 kW is added, bringing the total load to 73 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 59.0 Hz at 0.2 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 1.0 seconds the bus frequency is 55.6 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.111 pu/s, dropping 4 kW of non-critical load, to approximately 69 kW. At 1.9 seconds the bus frequency has reduced to 55.8 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 65 kW.

At 2.8 seconds the bus frequency, 56.5 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 3 kW of non-critical load, bringing the total load to 62 kW. At 3.6 seconds the bus frequency has reduced to 56.8 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 58 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 4.6 seconds the bus frequency remains at 57.1Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 54 kW. At 5.4 seconds the bus frequency has recovered to 57.4 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 49 kW. At 6.4 seconds the bus frequency has recovered to 57.8 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 44 kW. At 7.2 seconds the bus frequency has recovered to 58.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 40 kW.

At 8.2 seconds the bus frequency has recovered to 58.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 36 kW. At 8.4 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 36 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 59.66 Hz with 37 kW of total load shed. Using the trended frequency, 4.7 Hz of frequency deviance lasting 8.3 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7.7. B1 20 kW Medium Sensitivity

In Event B3, an overload of approximately 20 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Medium Sensitivity level, which will cause it to react less quickly to an overload condition.

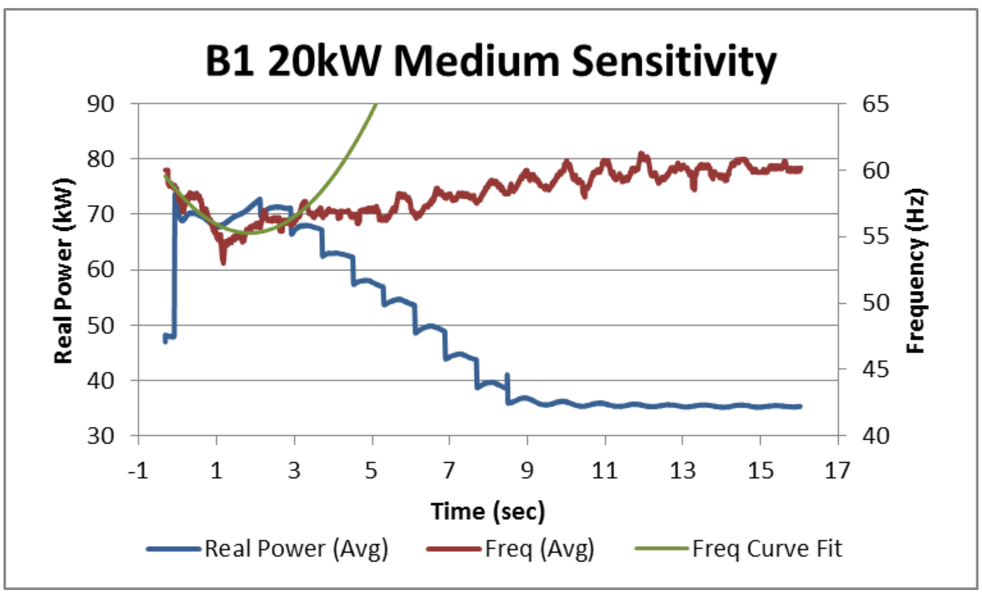

Figure 7.7.1: B1 20 kW Medium Sensitivity Real Power and Frequency

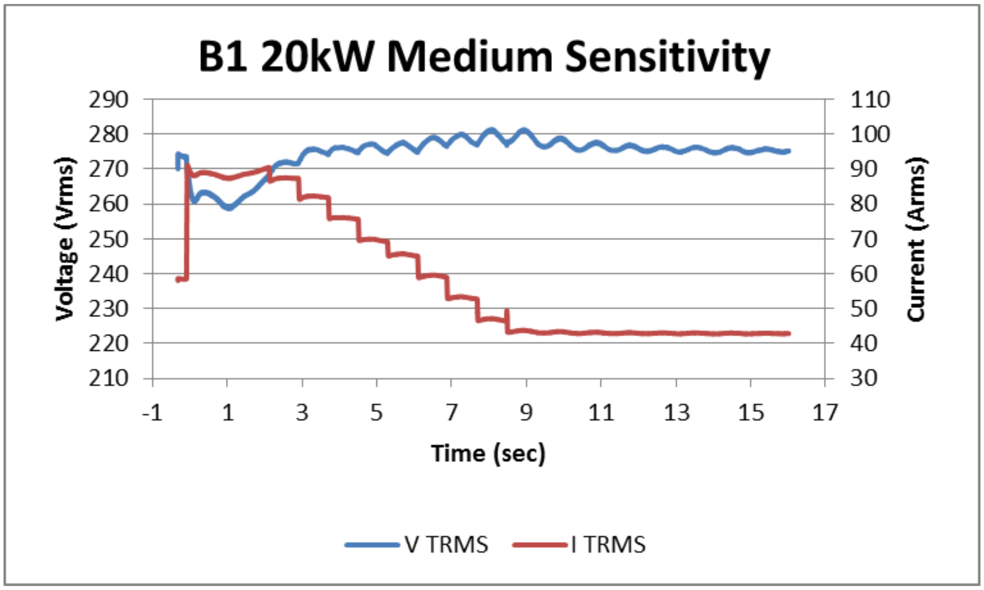

Figure 7.7.2: B1 20 kW Medium Sensitivity RMS Voltage and Current

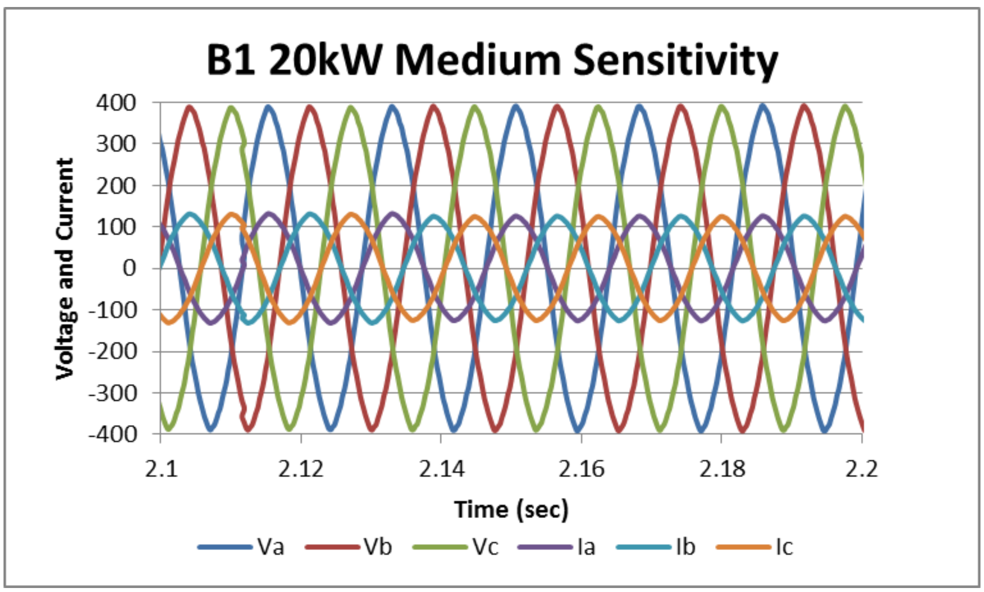

Figure 7.7.3: B1 20 kW Medium Sensitivity Waveform Voltage and Current

In Figure 7.7.1 above, the initial load is approximately 48 kW and the bus frequency is approximately 59.90 Hz. At time -0.2 seconds, approximately 25 kW is added, bringing the total load to 73 kW. At -0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.5 Hz at 0.1 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 2.1 seconds the bus frequency is 55.5 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.125 pu/s, dropping 3 kW of non-critical load, to approximately 70 kW.

At 2.9 seconds the bus frequency, 57.5 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 3 kW of non-critical load, bringing the total load to 67 kW. At 3.7 seconds the bus frequency has recovered to 56.8Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 63 kW. At 4.5 seconds the bus frequency has recovered to 57.1Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 58 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 5.3 seconds the bus frequency has recovered to 57.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 54 kW. At 6.1 seconds the bus frequency has recovered to 57.6 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 6.9 seconds the bus frequency has recovered to 57.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 46 kW. At 7.7 seconds the bus frequency has recovered to 58.2 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 41 kW.

At 8.5 seconds the bus frequency has recovered to 58.4 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 38 kW. At 9.1 seconds the bus frequency has recovered to 59.5 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 35 kW. At 9.2 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 35 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 59.65 Hz with 38 kW of total load shed. Using the trended frequency, 4.76 Hz of frequency deviance lasting 9.3 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7.8. B1 20 kW Low Sensitivity

In Event B4, an overload of approximately 20 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Low Sensitivity level, which will cause it to react least quickly to an overload condition.

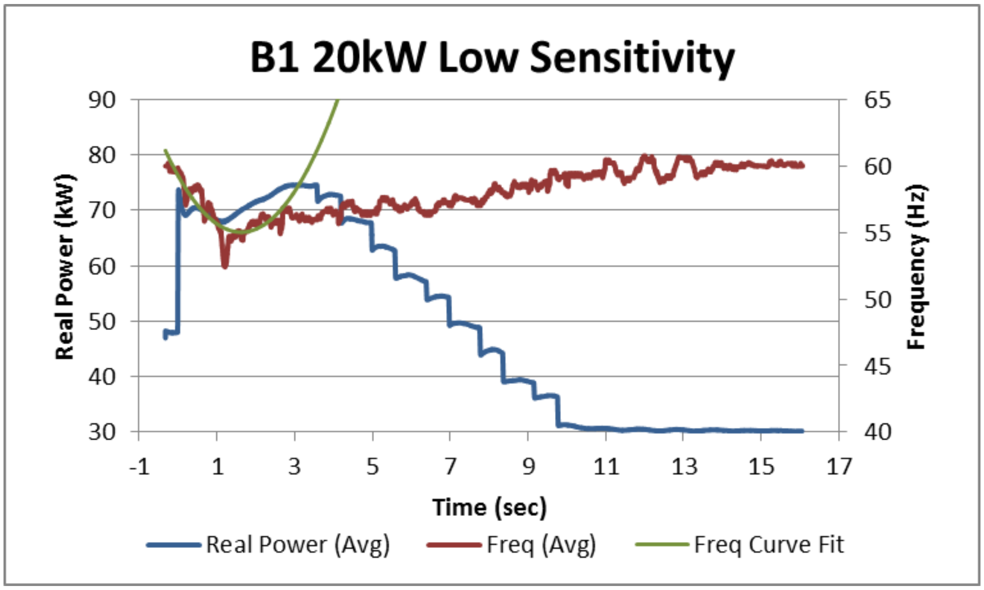

Figure 7.8.1: B1 20 kW Low Sensitivity Real Power and Frequency

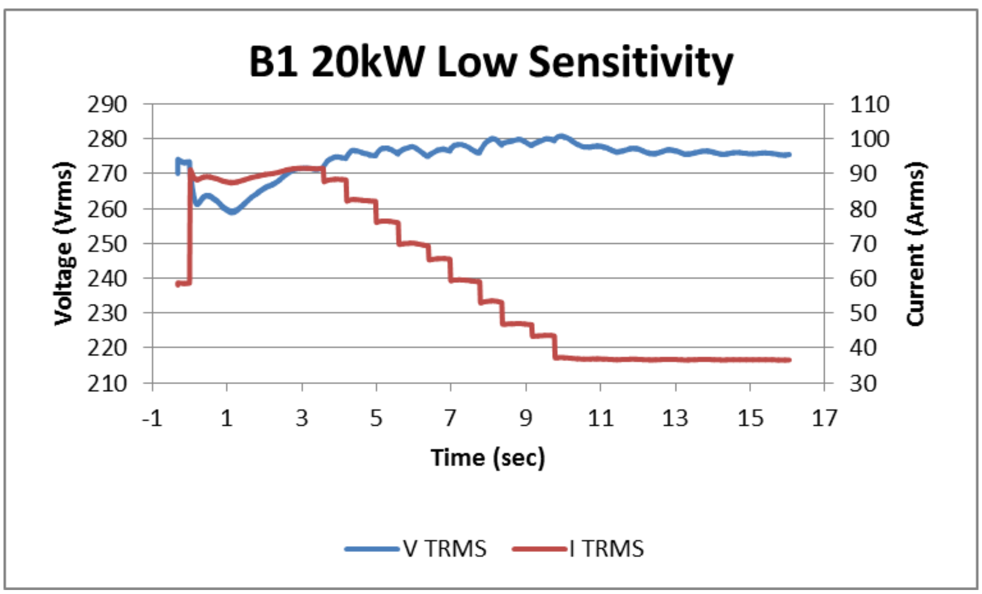

Figure 7.8.2: A1 20 kW Low Sensitivity RMS Voltage and Current

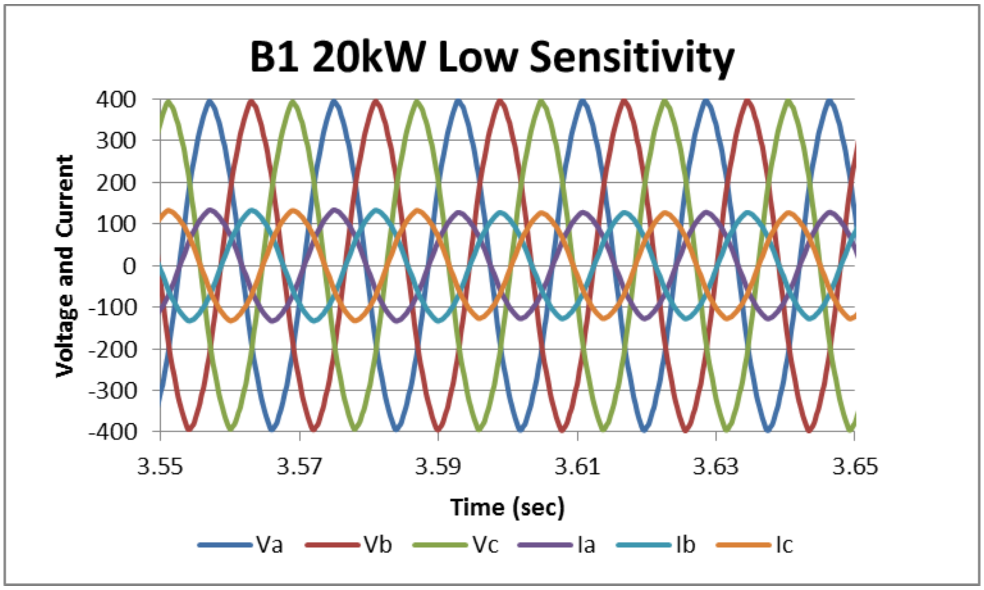

Figure 7.8.3: A1 20 kW Low Sensitivity Waveform Voltage and Current

In Figure 7.8.1 above the initial load is approximately 48 kW and the bus frequency is approximately 60.34 Hz. At time 0 seconds, approximately 26 kW is added, bringing the total load to 74 kW. At 0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.0 Hz at 0.3 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 3.6 seconds the bus frequency is 56.4 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.143 pu/s, dropping 3 kW of non-critical load, to approximately 71 kW. At 4.2 seconds the bus frequency, 56.6Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 4 kW of non-critical load, bringing the total load to 67 kW.

At 5.0 seconds the bus frequency has reduced to 56.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 63 kW. At 5.6 seconds the bus frequency has reduced to 57.1 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 58 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value. At 6.4 seconds the bus frequency has recovered to 57.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 54 kW. At 7.0 seconds the bus frequency has recovered to 53.9 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 7.8 seconds the bus frequency has recovered to 57.9 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 45 kW. At 8.4 seconds the bus frequency has recovered to 58.1 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 40 kW.

At 9.2 seconds the bus frequency has recovered to 58.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 36 kW. At 9.8 seconds the bus frequency has recovered to 58.6 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 31 kW. At 10.4 seconds the bus frequency reaches and exceeds 59.5 Hz, the Minimum Bus Frequency. Continued load shedding is halted with a total of 31 kW remaining. The bus frequency continues to rise reaching its final stable operating point near 59.61 Hz with 43 kW of total load shed. Using the trended frequency, 5.31 Hz of frequency deviance lasting 10.3 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7.9. B1 30 kW Baseline

In Event C1, an overload of approximately 30 kW is placed on the islanded, inverter based generator. Further in this test the Smart load, load shedding is inhibited, which will knowingly lead to the eventual protection trip of the source.

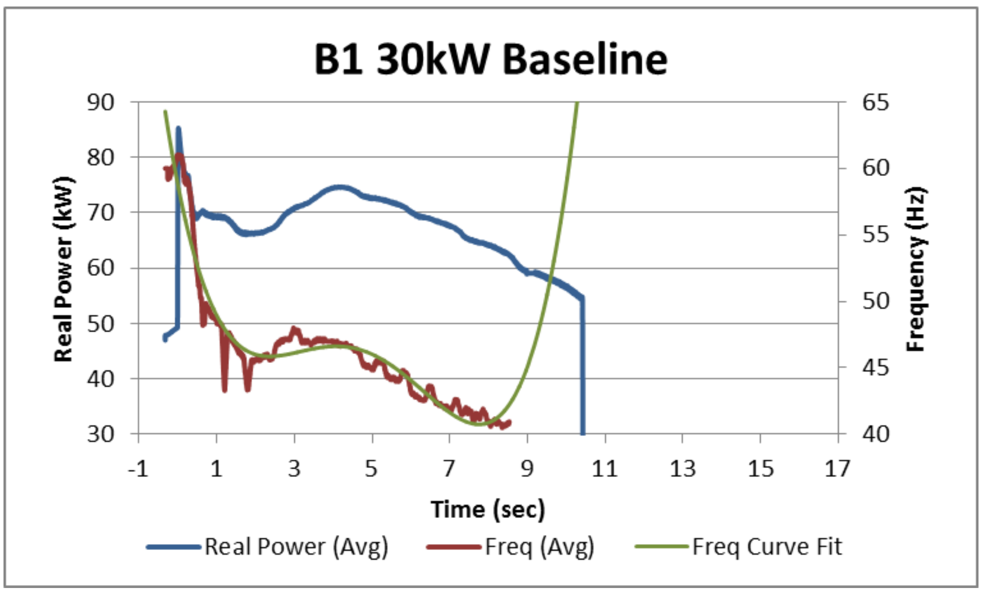

Figure 7.9.1: B1 30 kW High Sensitivity Real Power and Frequency

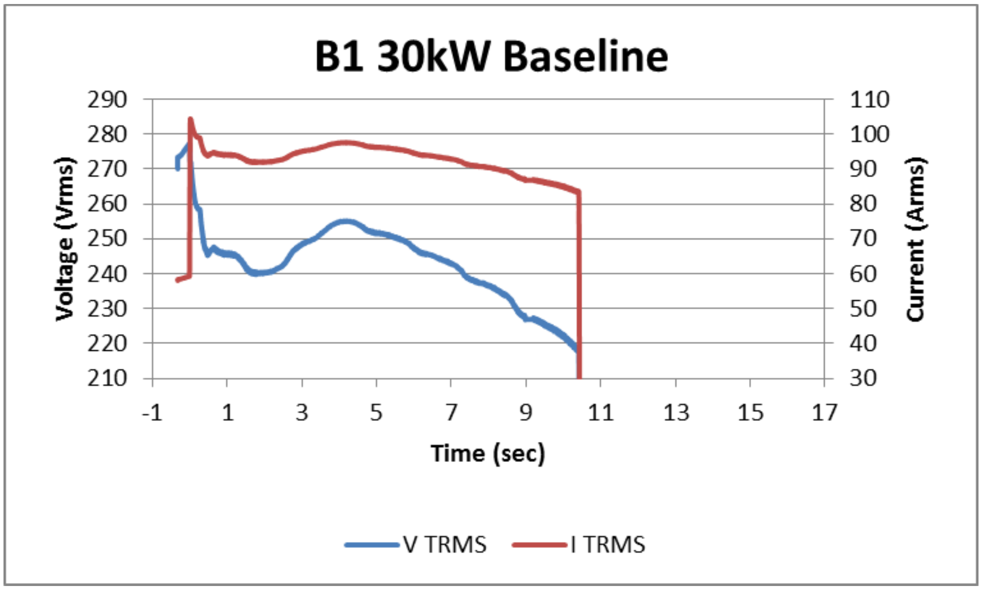

Figure 7.9.2: B1 30 kW High Sensitivity RMS Voltage and Current

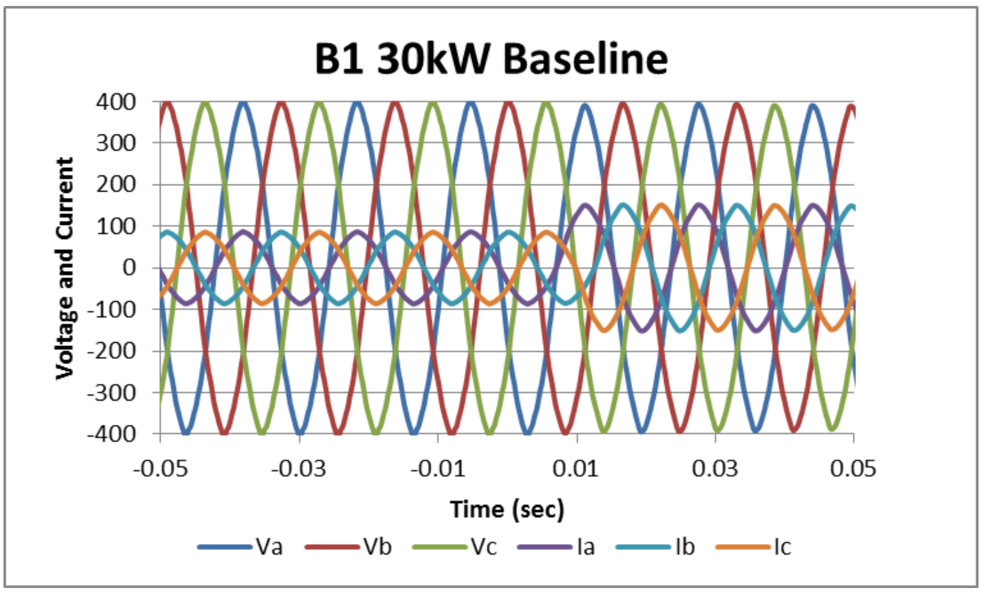

Figure 7.9.3: B1 30 kW High Sensitivity Waveform Voltage and Current

In Figure 7.9.1 above the initial load is approximately 48 kW and the bus frequency is approximately 59.72 Hz. At time 0 seconds, approximately 37 kW is added, bringing the total load to 85 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues dropping at a rate of 11.9 Hz/second. In Figure 7.9.2 there is a reduction in voltage, approximately 37 $V_{l\text{-}n}$, during the overload event.

This reduction is due to two main factors, the voltage vs reactive power controller and the voltage exciter of the synchronous generator. The voltage vs reactive power controller reduces the commanded voltage output as the reactive power consumption of transformer equipment connected to the microgrid bus increases with frequency reduction. The voltage exciter also lags in response to the voltage drop associated with the generator impedance and the changed in load current. At 10.4 seconds the bus frequency is 40.8 Hz, and the source performs a controlled shutdown due to an overload protection fault. This test case illustrates the expected response if load shedding is unavailable within the microgrid environment.

7.10. A1 30 kW High Sensitivity

In Event C2, an overload of approximately 30 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a High Sensitivity level, which will cause it to react more quickly to an overload condition.

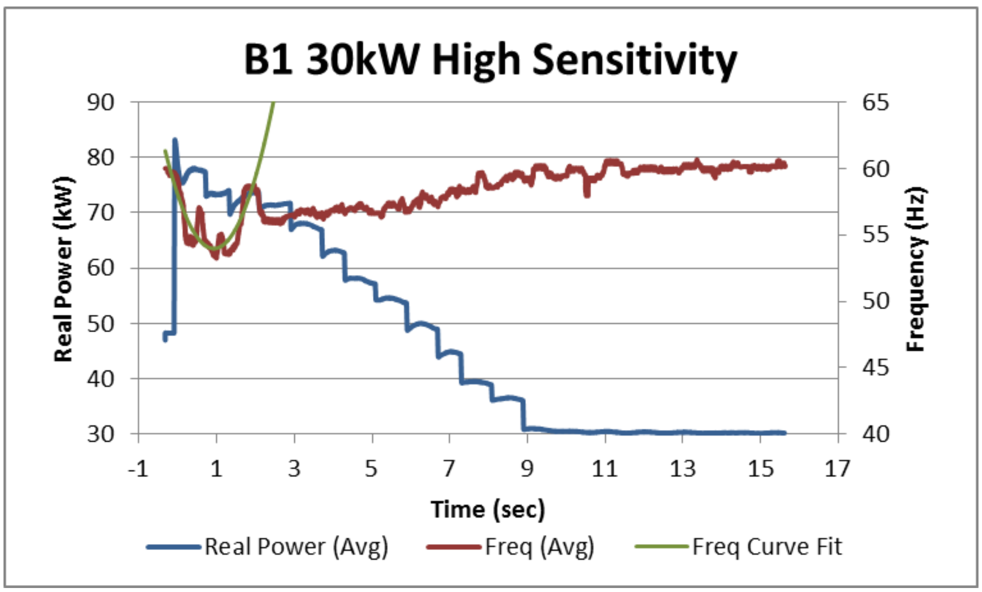

Figure 7.10.1: B1 30 kW High Sensitivity Real Power and Frequency

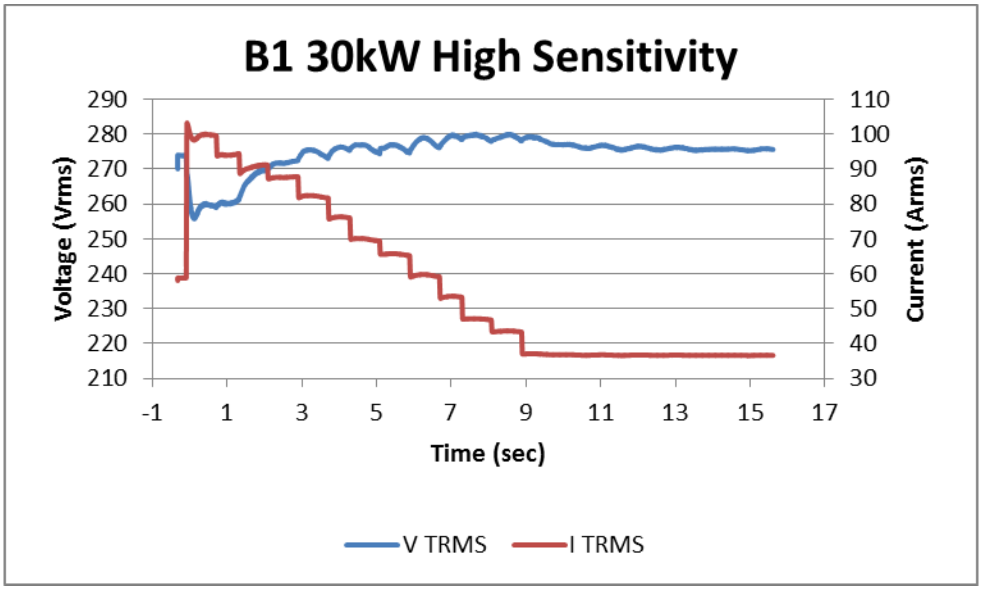

Figure 7.10.2: B1 30 kW High Sensitivity RMS Voltage and Current

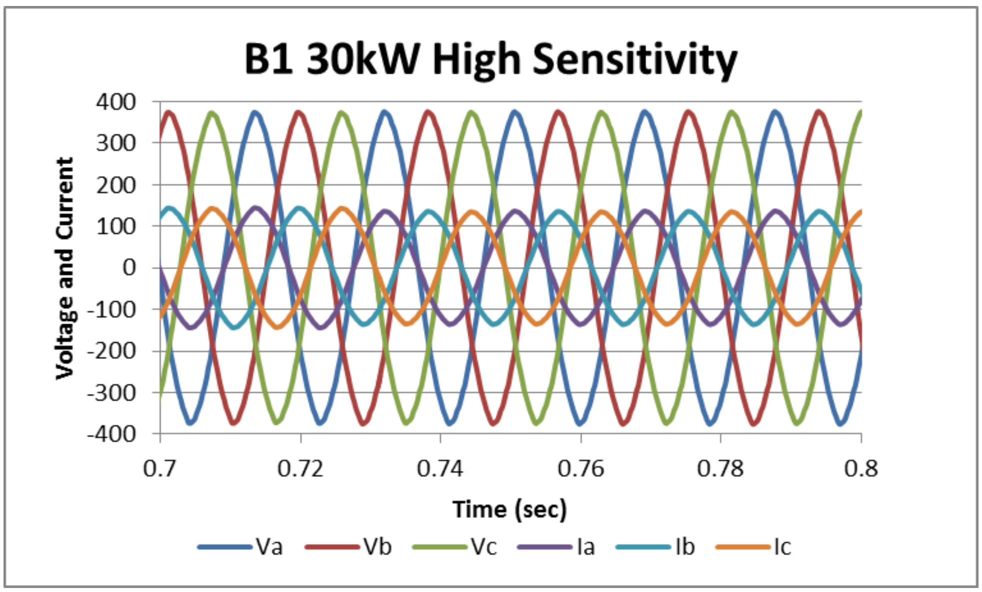

Figure 7.10.3: B1 30 kW High Sensitivity Waveform Voltage and Current

In Figure 7.10.1 above the initial load is approximately 48 kW and the bus frequency is approximately 59.71 Hz. At time -0.1 seconds, approximately 32 kW is added, bringing the total load to 80 kW. The generator, observing a local real power demand beyond its Pmax set point, reduces its output frequency accordingly. At 0 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 59.0 Hz at 0.1 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At approximately 0.8 seconds the bus frequency is 56.2 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.111 pu/s, dropping 4 kW of non-critical load, to approximately 76 kW. At 1.3 seconds the bus frequency has reduced to 56.4Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 73 kW.

At 2.1 seconds the bus frequency has reduced to 56.6 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 70 kW. At 2.9 seconds the bus frequency, 56.9 Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 3 kW of non-critical load, bringing the total load to 67 kW. At 3.7 seconds the bus frequency remains at 57.1Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 63 kW. At 4.3 seconds the bus frequency remains at 57.3 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 59 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated, and the source frequency begins to trend upward towards a stable value.

At 5.1 seconds the bus frequency remains at 57.5Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 55 kW. At 5.9 seconds the bus frequency has recovered to 57.8 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 50 kW. At 6.7 seconds the bus frequency has recovered to 58.0 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 45 kW. At 7.3 seconds the bus frequency has recovered to 58.2 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 40 kW. At 8.1 seconds the bus frequency has recovered to 58.5 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 35 kW.

At 8.9 seconds the bus frequency has recovered to 58.7 Hz, and the remaining 5 kW of non-critical load is removed, bringing the total load to 30 kW. The bus frequency recovers above 59.5 Hz at 10.0 seconds although all non-critical load has been shed and a total of 30 kW of critical remain. The bus frequency continues to rise reaching its final stable operating point near 59.77 Hz with 50 kW of total load shed. Using the trended frequency, 5.73 Hz of frequency deviance lasting 10.0 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7.11. B1 30 kW Medium Sensitivity

In Event C3, an overload of approximately 30 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Medium Sensitivity level, which will cause it to react less quickly to an overload condition.

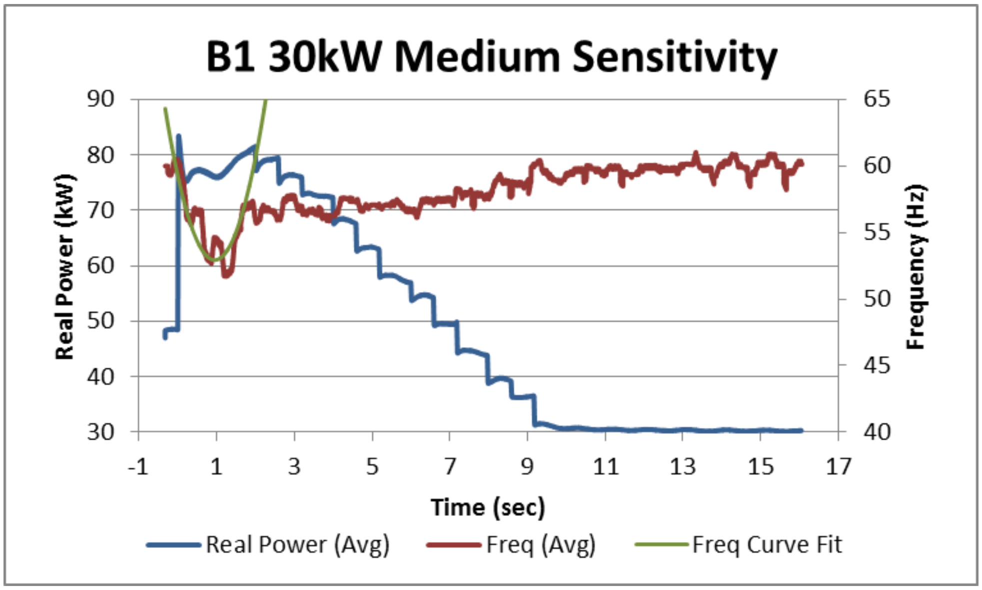

Figure 7.11.1: B1 30 kW Medium Sensitivity Real Power and Frequency

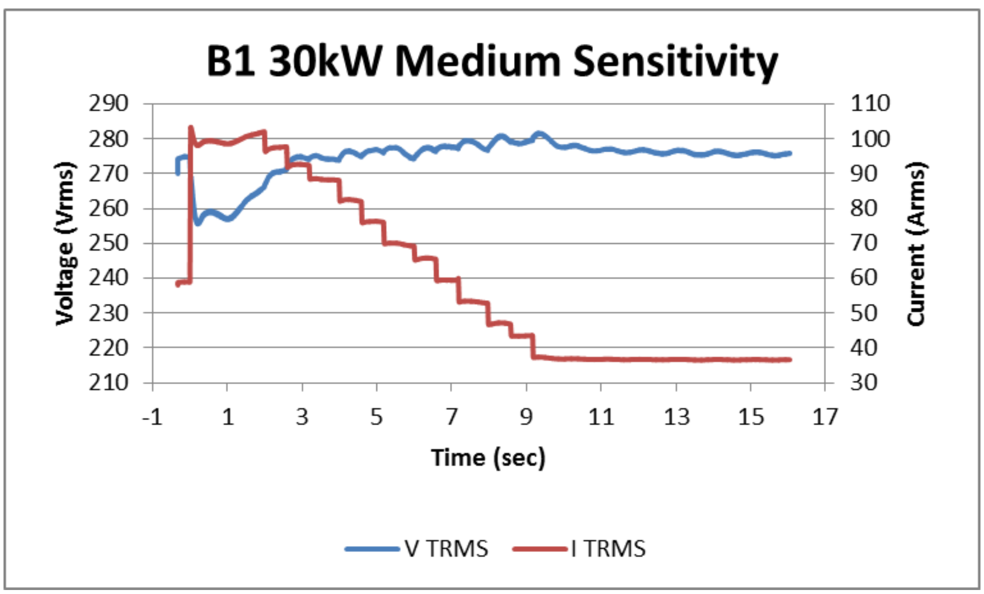

Figure 7.11.2: B1 30 kW Medium Sensitivity RMS Voltage and Current

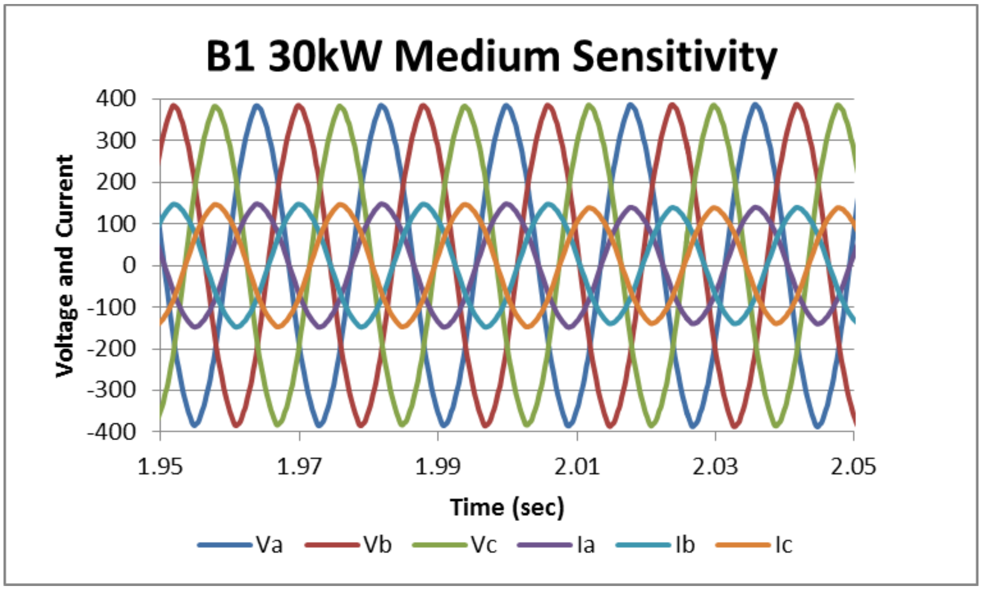

Figure 7.11.3: B1 30 kW Medium Sensitivity Waveform Voltage and Current

In Figure 7.11.1 above the initial load is approximately 48 kW and the bus frequency is approximately 59.78 Hz. At time 0 seconds, approximately 32 kW is added, bringing the total load to 81 kW. At 0.0 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.5 Hz at 0.1 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 2.0 seconds the bus frequency is 56.4 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.125 pu/s, dropping 3 kW of non-critical load, to approximately 78 kW. At 2.6 seconds the bus frequency, 56.6Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 3 kW of non-critical load, bringing the total load to 75kW.

At 3.2 seconds the bus frequency has recovered to 56.8 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 72 kW. At 4.0 seconds the bus frequency has recovered to 57.0 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 68 kW. At 4.6 seconds the bus frequency has recovered to 57.2 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 63 kW. At 5.2 seconds the bus frequency has recovered to 57.4 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 58 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated. At 6.0 seconds the bus frequency has recovered to 57.6 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 54 kW. At 6.5 seconds the bus frequency has recovered to 57.8 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 50 kW. At 7.2 seconds the bus frequency has recovered to 58.0 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 45 kW.

At 8.0 seconds the bus frequency has recovered to 58.2Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 40 kW. At 8.6 seconds the bus frequency has recovered to 58.4 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 36 kW. At 9.2 seconds the bus frequency has recovered to 58.6 Hz, and the remaining 5 kW of non-critical load is removed, bringing the total load to 31 kW. The bus frequency recovers above 59.5 Hz at 9.3 seconds although all non-critical load has been shed and a total of 31 kW of critical remain. The bus frequency continues to rise reaching its final stable operating point near 59.64 Hz with 50 kW of total load shed. Using the trended frequency, 5.73 Hz of frequency deviance lasting 9.3 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.

7.12. B1 30 kW Low Sensitivity

In Event C4, an overload of approximately 30 kW is placed on the islanded, inverter-based generator. Further in this test the Smart Load is set to a Low Sensitivity level, which will cause it to react least quickly to an overload condition.

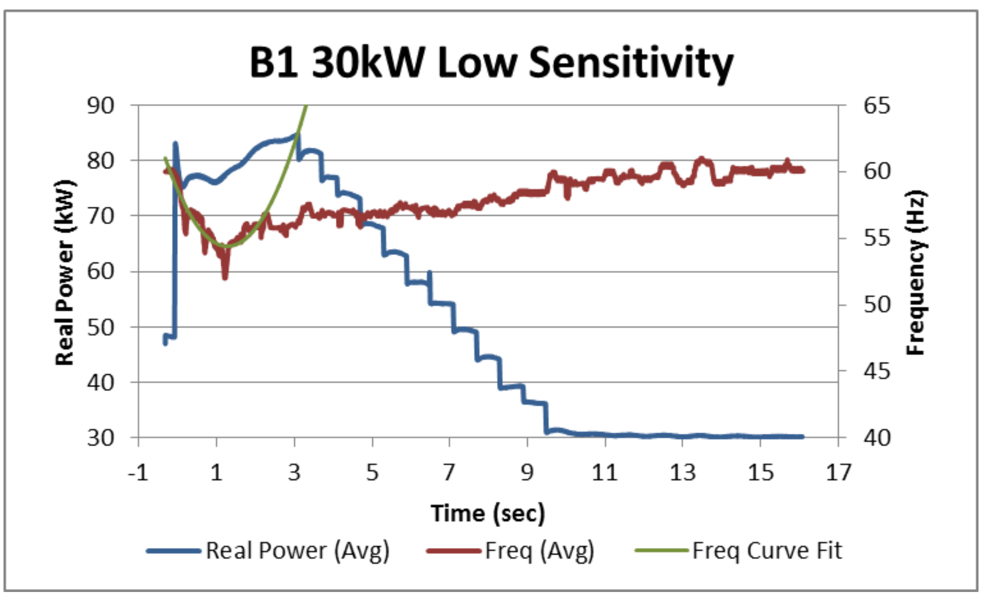

Figure 7.12.1: B1 30 kW Low Sensitivity Real Power and Frequency

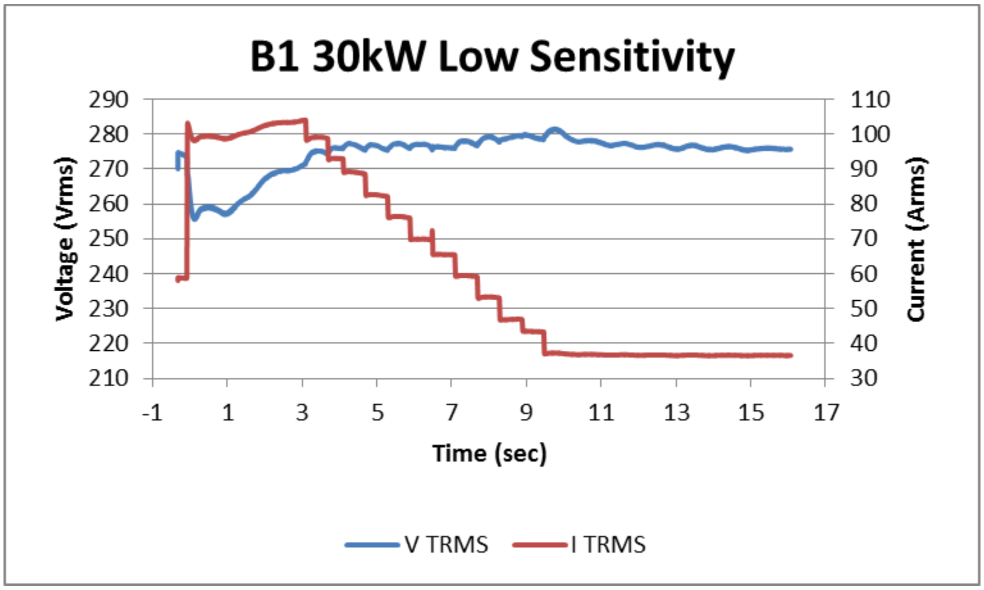

Figure 7.12.2: B1 30 kW Low Sensitivity RMS Voltage and Current

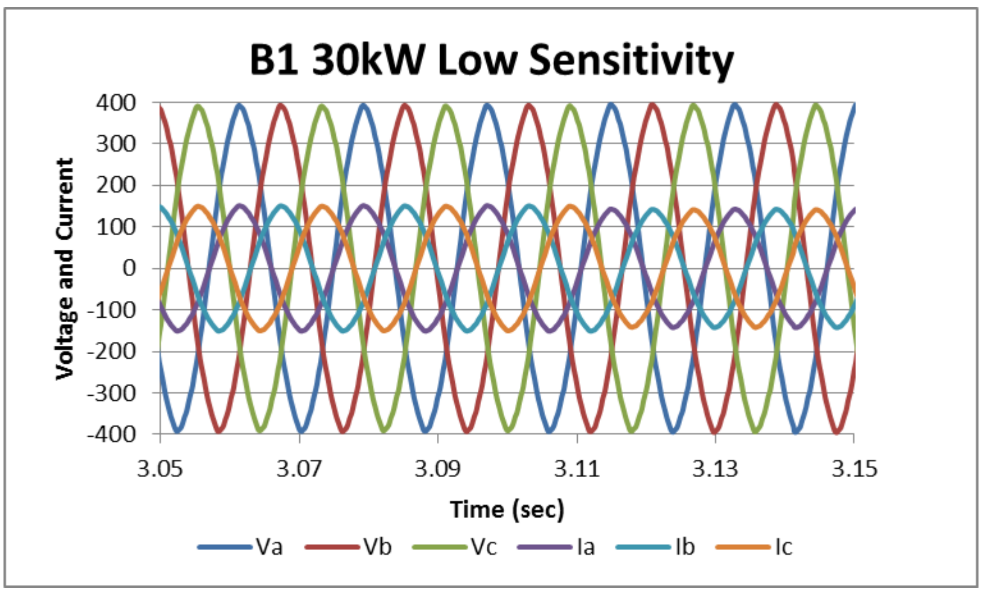

Figure 7.12.3: B1 30 kW Low Sensitivity Waveform Voltage and Current

In Figure 7.12.1 above the initial load is approximately 48 kW and the bus frequency is approximately 60.28 Hz. At time -0.1 seconds, approximately 35 kW is added, bringing the total load to 83 kW. At approximately -0.1 seconds the frequency has dropped below the Minimum Bus Frequency of 59.5 Hz and continues reaching the Load Shedding Frequency of 58.0 Hz at 0.1 seconds. At this point the Smart Load, Load Shedding Delay timer begins. At 3.1 seconds the bus frequency is 56.3 Hz, still below the Load Shedding Frequency, and the Load Shedding Delay timer has expired, beginning the load shedding process. The first step of non-critical load is removed at the rate dictated by the Load Shedding Rate, 0.143 pu/s, dropping 3 kW of non-critical load, to approximately 80 kW. At 3.7 seconds the bus frequency, 56.5Hz, is stable and its slope has flattened. Because it remains below the Minimum Bus Frequency the load shedding continues with an additional 4 kW of non-critical load, bringing the total load to 76kW.

At 4.1 seconds the bus frequency has recovered to 56.7 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 73 kW. At 4.7 seconds the bus frequency has recovered to 56.9 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 68 kW. At 5.3 seconds the bus frequency has recovered to 57.1 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 63 kW. At 5.9 seconds the bus frequency has reduced to 57.3 Hz, and an additional 3 kW of non-critical load is removed, bringing the total load to 60 kW. This load now falls below the Pmax set point, of 60 kW, the Pmax control has deactivated. At 6.5 seconds the bus frequency has recovered to 57.5 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 55 kW. At 7.1 seconds the bus frequency has recovered to 57.7 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 50 kW. At 7.7 seconds the bus frequency has recovered to 57.9 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 45 kW. At 8.3 seconds the bus frequency has recovered to 58.1, and an additional 5 kW of non-critical load is removed, bringing the total load to 40 kW.

At 8.9 seconds the bus frequency has recovered to 58.3 Hz, and an additional 4 kW of non-critical load is removed, bringing the total load to 36 kW. At 9.5 seconds the bus frequency has recovered to 58.5 Hz, and an additional 5 kW of non-critical load is removed, bringing the total load to 31 kW. The bus frequency recovers above 59.5 Hz at 9.5 seconds although all non-critical load has been shed and a total of 31 kW of critical remain. The bus frequency continues to rise reaching its final stable operating point near 59.50 Hz with 52 kW of total load shed. Using the trended frequency, 5.88 Hz of frequency deviance lasting 9.6 seconds was experienced during the overload event. The smart load has successfully protected the microgrid bus from source shutdown.