Residential Air Conditioner with VFD Test Report

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The author acknowledges the efforts of SCE Engineer Manuel Garcia who provided valuable contribution during the setup and testing of these units and Senior Engineer Richard Bravo for developing the initial device test procedures.

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1.0 EXECUTIVE SUMMARY

1.1 Introduction

System faults can sometimes occur on the electric grid due to a variety of environmental conditions and result in protective relays isolating problem areas such that voltage returns to normal conditions. Traditionally, the voltage recovers to nominal within a second after the fault is cleared, but there have been instances of delayed voltage recovery following faults on the electric system, especially during the summer season. These fault induced delayed voltage recovery (FIDVR) events have been attributed to air conditioner (A/C) units when their compressor motors stall as a result of the momentary low voltage. During this stalled condition, the compressors' consumption of reactive power radically increases which prevents system voltage from recovering immediately until the load trips itself off via internal thermal protection. Voltage recovery has been delayed for up to 50 seconds in some cases.

The Western Electricity Coordinating Council (WECC) has been continuously investigating FIDVR events and in 2006 its members from Bonneville Power Administration (BPA), Southern California Edison (SCE), and Electric Power Research Institute (EPRI) tested 27 residential split-phase A/C units to evaluate their dynamic performance. Among other performance characteristics, it was determined that these units typically stall between 60% and 70% nominal voltage well before they are disconnected by their power contactors at 53% voltage. It was also discovered that these single-phase compressor motors began stalling rather quickly, normally within 3 cycles. Ultimately, this A/C unit research was utilized by the Model Validation Working Group (MVWG) to develop and validate the A/C motor model.

1.2 Objective

The objective of this report is to assess the performance of several residential A/C units with variable frequency drive (VFD) technology during typical voltage and frequency deviations observed on the grid. These systems consist of an outdoor condensing unit along with one or more indoor air handler units for cooling individual areas in a residence, each with a controller printed circuit board (PCB). The advantage of these ductless split systems over conventional A/C units is that they are designed with inverter technology used to more accurately maintain temperature and reduce energy consumption. This is achieved by adjusting the rotation speed of the compressor to provide only enough cooling capacity to meet demand.

There has been little or no research executed on these types of units during dynamic conditions to determine whether or not they share the same stalling characteristics as conventional A/C devices during normal operation. Therefore the resulting test data may be used to support the validation of load models as well as the investigation of stalling solutions. The VFD A/C unit characteristics to be evaluated during testing include:

- Compressor stalling criteria (or lack thereof)
- Inrush currents during startup
- Controls protection/dropout capabilities
- Harmonics contribution
- Under/over-voltage performance
- Under/over-frequency performance
- Behavior during voltage/frequency oscillations
- Behavior during conservation voltage reduction

The following work is part of an integrated program of FIDVR research sponsored by the U.S. Department of Energy through the Lawrence Berkeley National Laboratory. The program is intended to promote national awareness, improve understanding of potential grid impacts, and identify appropriate steps to ensure the reliability of the power system.

1.3 Test Results Summary

Each of the VFD A/C units tested displayed similar shutdown and startup characteristics. Most of the load consumed by the compressor shuts down with rather short delay times, typically less than 5 cycles. Some of the units required an additional delay of 30 to 60 seconds or so for the outdoor fan to stop operating before going into standby mode. Once in standby mode, none of the VFD A/C units consumed more than 0.65 Amps.

Each unit also displayed relatively low inrush currents compared to conventional residential A/C units when starting up after nominal voltage has been established. The largest inrush current magnitude observed from these VFD A/C units was 11.3 Amps within 1.8 cycles (VFD A/C unit #1). Typically, VFD compressors would slowly ramp up over the course of roughly 20 to 50 seconds until the unit began consuming a constant steady state current value of no more than 5 Amps. However the VFD compressors were not limited this amount of load, but they would increase consumption periodically over the course of several minutes to meet temperature demand. Therefore, it was required that the unit continue running for several minutes before performing further testing to ensure the motor was more heavily loaded at approximately 80 degrees Fahrenheit room temperature. Based on this room temperature, each unit would operate at approximately 50% to 80% of its rated load.

No motor stalling occurred during any of the balanced and unbalanced under-voltage tests for all seven VFD A/C units. The compressor controls for the VFD A/C systems would always trip or drop out before compressor stalling could potentially take place. Also, data captured several seconds after the compressor was disconnected did not reveal restarting behavior and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor would only restart approximately several minutes after tripping/dropout occurred, outside the range of the data captured.

Even during cases where dropout did not happen and the compressor rode through all of the under-voltage sags down to 0% voltage, motor stalling still did not occur. These ride through scenarios typically occurred for those voltage transients with shorter duration times. The longest voltage sag duration time where compressor ride through occurred for all under-voltages was 6 cycles (for VFD A/C units #4 and #5).

The conditions required to cause dropout varied slightly for each VFD A/C unit and were greatly dependent on the voltage magnitude and sometimes the duration time of the voltage sag. The most common voltage magnitudes where dropout behavior takes place is between 50% and 60% nominal voltages among all seven VFD A/C units. Although there are a few exceptions, most tests revealed that compressor tripping occurs either at the end of the voltage sag or even up to 3 cycles after the voltage has recovered to steady state. One theory to explain these trip times is that the compressor is disconnected in response to the inrush current observed at the end of the voltage sag as it steps up to nominal. Another, less likely, explanation is that there may be logic in the controller PCB of the outdoor condensing unit that prevents disconnection of compressor load until voltage returns to nominal.

The following table provides the voltage magnitude and time required for tripping or dropout to occur for under-voltage transients (130, 12, and 3 cycles) that represent different switching times observed on the grid. “N/A” represents where dropout is not applicable and the unit rode through all voltage values (down to 0%). Additional times and details are provided for each unit in their individual sections of this report.

Unit	130 cycle Transients		12 cycle Transients		3 cycle Transients	
	$V_{trip / dropout}$ (%)	$t_{trip / dropout}$ (cyc)	$V_{trip / dropout}$ (%)	$t_{trip / dropout}$ (cyc)	$V_{trip / dropout}$ (%)	$t_{trip / dropout}$ (cyc)
VFD A/C #1	52%	15	55%	13.2	51%	3.6
VFD A/C #2	56%	7.8	55%	9	N/A	N/A
VFD A/C #3	58%	130.8	58%	12.6	59%	4.2
VFD A/C #4	69%	130.1	49%	12.9	N/A	N/A
VFD A/C #5	41%	130.8	20%	12.6	N/A	N/A
VFD A/C #6	81%	131.1	56%	12.2	N/A	N/A
VFD A/C #7	62%	129.6	60%	12	54%	4.2

Table 1.3.1 VFD A/C Units Under-voltage Tripping / Dropout Summary

With the exception of VFD A/C unit #3, none of the other units displayed over-voltage protection within the parameters of the over-voltage tests performed. In order to avoid damaging any voltage sensitive power electronic equipment inside the VFD A/C unit, each unit was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve, a curve developed to signify the tolerances of voltage sensitive loads. These tests included multiple voltage swells performed in 2% increments for up to 120% nominal. Only VFD A/C unit #3 displayed tripping behavior during balanced over-voltages, tripping at 112% nominal voltage in 1.2 cycles and at 118% nominal voltage in 0.6 cycles.

Additionally, none of the units displayed any frequency protection during multiple under and over-frequency transient tests within 58 Hz and 62 Hz. However two of units, VFD A/C #1 and #7, did trip during tests where frequency was ramped up to 70 Hz from 60 Hz. Both units tripped at approximately 67.7 Hz.

In general, the VFDs did an excellent job of managing the compressor motor speed and power consumption during a variety of voltages and frequency deviation tests. Real power remains relatively constant for each of the VFD A/C units during most of these tests. Reactive power consumption is not as predictable and varies differently for several units. Many of the devices also operate at high power factors, typically above 0.97, which may be a reason for the varied response of the moderately low reactive power load.

Conservation voltage reduction (CVR) will have little to no effect on motor loads managed using this VFD technology. Real power consumption is held nearly constant over the course of CVR for all of the units tested during the 1% incremental voltage steps.

2.0 EQUIPMENT SETUP & MEASUREMENTS

While testing the performance of the seven residential A/C units with VFD technology, the sinusoidal voltages and currents were measured at the main disconnect terminals (split-phase 240 V). These sinusoidal waveforms were used to calculate the RMS equivalent voltage/current values along with real power, reactive power, and frequency. Sinusoidal voltages and currents were also measured on all three phases of the VFD compressor to identify loading on the compressor before and during each test. In addition to these electrical measurements, an accelerometer was placed on the compressor motor to observe the mechanical vibration and serve as another indicator for when unit shuts down or if stalling would occur. Multi-meters with thermocouples were placed in the lab and at the supply fan of the indoor unit to verify and document temperature conditions.

VFD A/C #	Manufacturer	Outdoor P/N	Indoor P/N	Voltage	BTU	Refrigerant	SEER
1	Friedrich	MR36Y3J	MW36Y3J	230	33,000	R-410A	16.5
2	Carrier	38GVQ024-3	40GVQ024-3	230	24,000	R-410A	16
3	Lennox	MS8-HO-24P	MS8-HI-24P	230	24,000	R-410A	18
4	Goodman	MSH243E15MC	MSH243E15AX	230	24,000	R-410A	15
5	Klimaire	KSIO024-H219		230	24,000	R-410A	19
6	Panasonic	CU-KE36NKU	CS-KE36NKU	230	34,000	R-410A	16
7	LG	LSU360HV3	LSN360HV3	230	33,100	R-410A	16.1

Table 2.0.1 Residential VFD A/C Units Tested

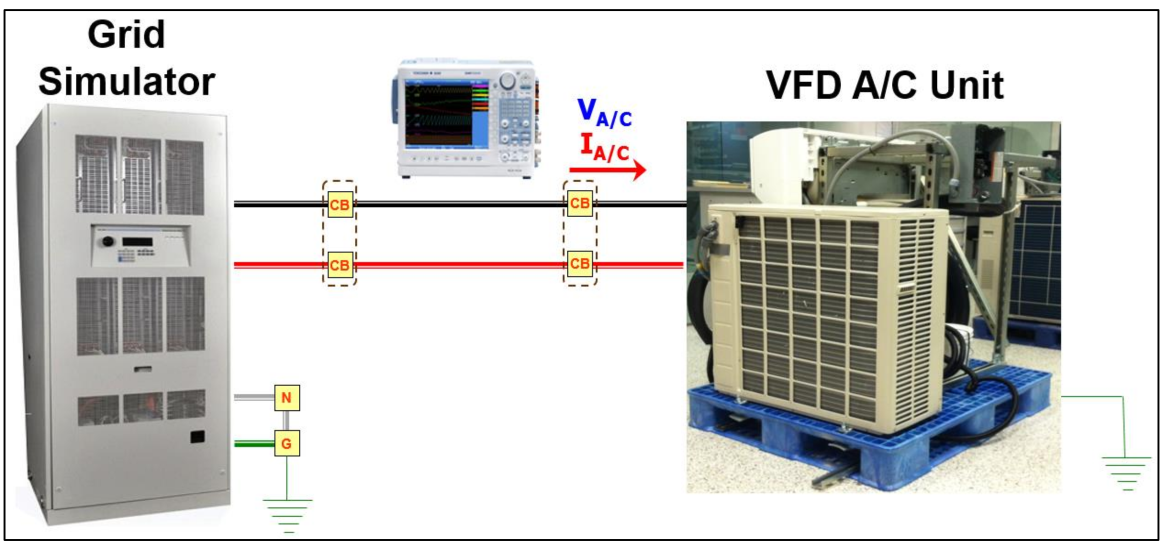

Figure 2.0.1 Split-phase VFD A/C Test Setup

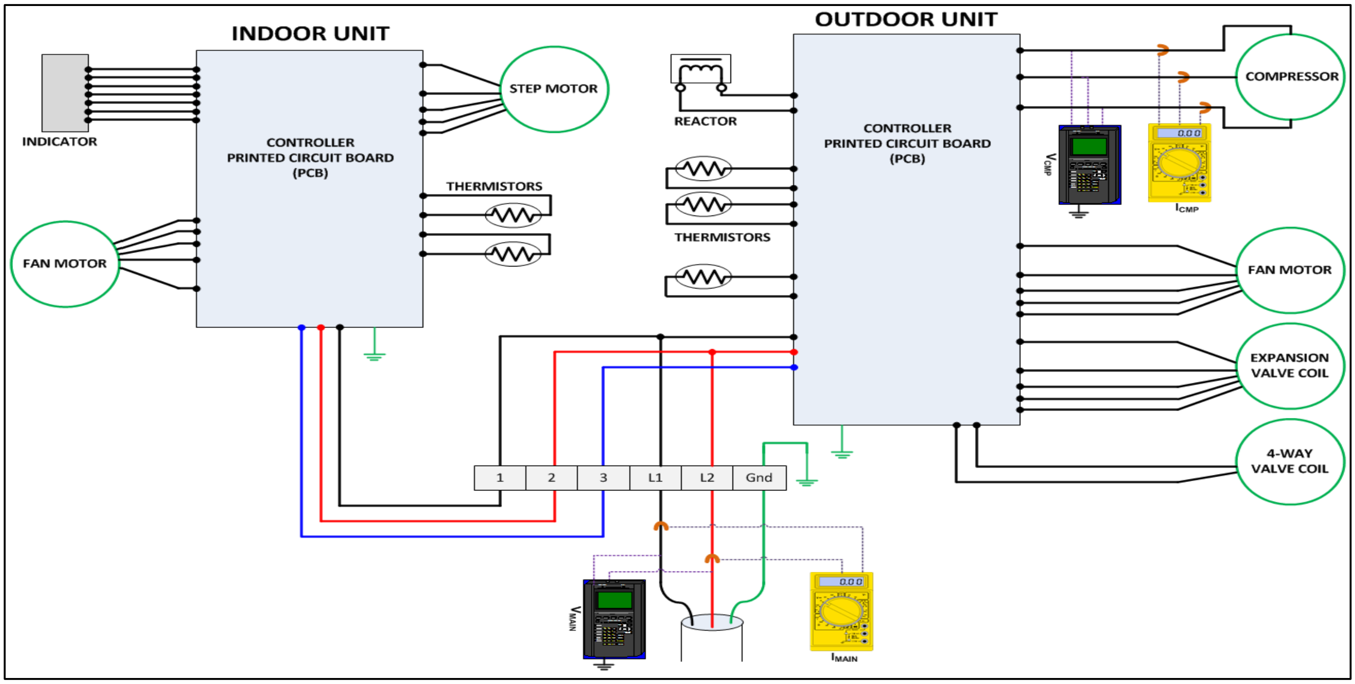

Figure 2.0.2 Typical VFD A/C Wiring Diagram

3.0 VFD AIR CONDITIONER #1 TEST RESULTS

The figure below shows a snapshot of VFD A/C unit #1 sinusoidal voltages and currents captured at the main terminals and compressor motor using a filter on the digital scope. Notice the distortion in the main currents compared to main voltages. The compressor is operating at approximately 290 Volts peak, 6.3 Amps peak, and 235 Hz at the observed loading condition. The specifications for the VFD A/C #1 components are provided in the table below.

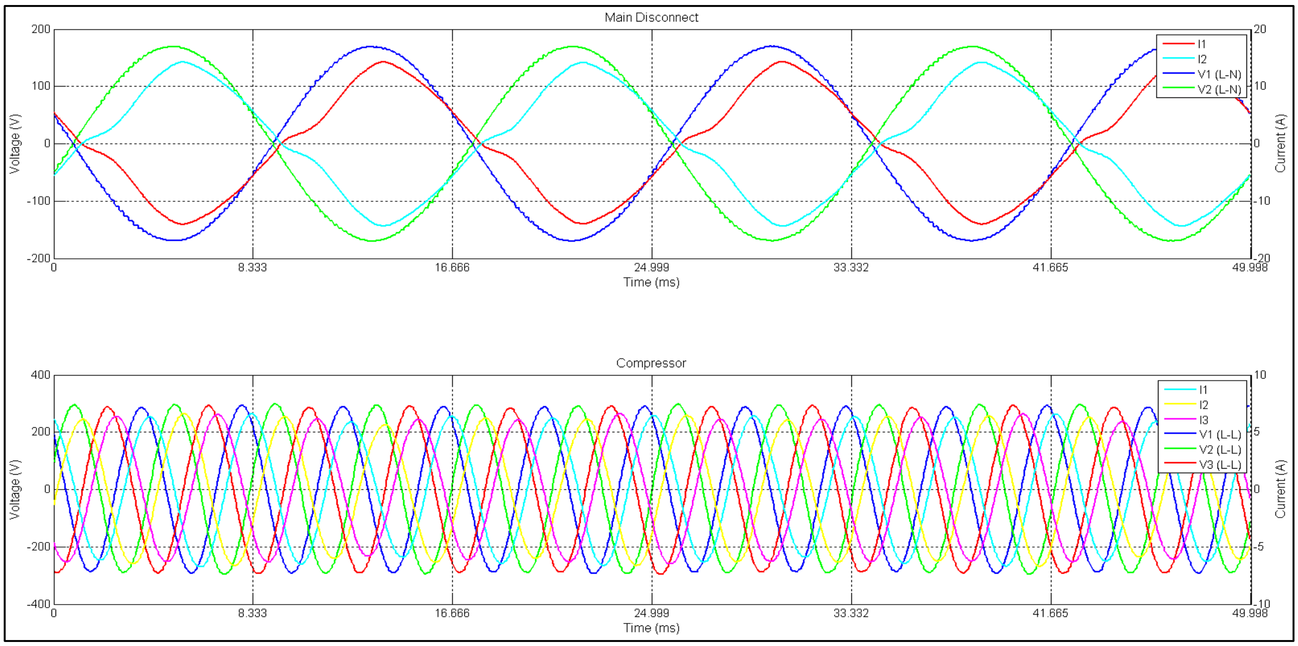

Figure 3.0.1 VFD A/C #1 Voltage and Current Waveforms

Manufacturer	Friedrich
Voltage (V)	230
Refrig.	R-410A
SEER	16.5
Compressor, Model #	CRSS C-6RZ146H1A
Compressor, RLA (Amps)	17.3
Compressor, LRA (Amps)	-
Outdoor Fan Motor, FLA (Amps)	0.25
Indoor Fan Motor, FLA (Amps)	0.5
Design Pressure High (PSI)	450
Design Pressure Low (PSI)	240

Table 3.0.1 VFD A/C #1 Specifications

3.1 Compressor Shutdown

VFD A/C #1 was shut down during normal operation using the programmable thermostat remote for the indoor blower unit. The figure below displays the measurements taken at the main terminal connections of the entire A/C unit.

The compressor and fans shut down almost immediately at the same time after adjusting the thermostat. The delay time is minuscule where current decreases from normal operation to standby within 2.4 cycles. While in standby mode, the device's power consumption is less than 0.6 Amps.

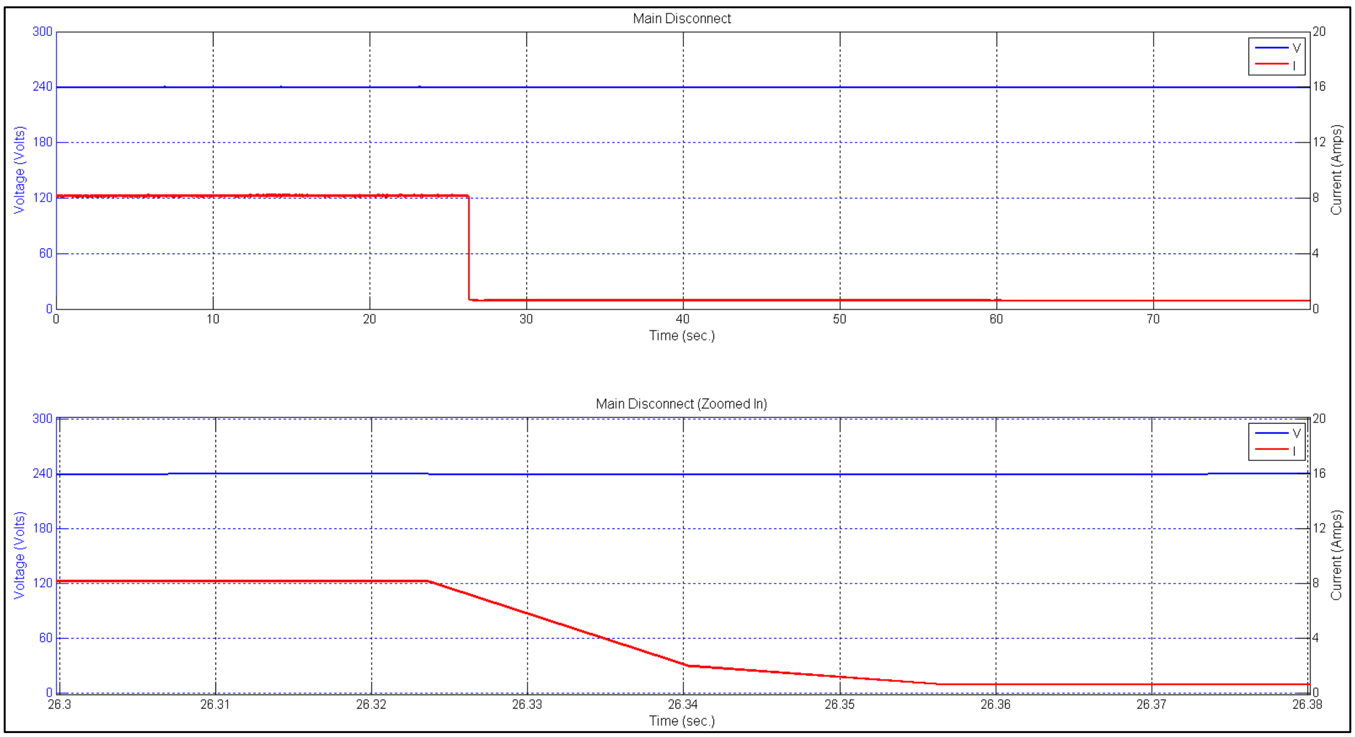

Figure 3.1.1 VFD A/C #1 Compressor Shutdown

3.2 Inrush Current

After starting up the VFD A/C unit via the programmable thermostat remote, the fan motor starts up first with an inrush current of approximately 11.3 Amps for a duration of 1.8 cycles. This is followed by the compressor slowly ramping up over the course of roughly 25 seconds until the unit is drawing 3.7 Amps as shown in the figure below. The indoor blower unit also experiences an inrush bringing total current to nearly 7 Amps within 3 cycles. The VFD compressor will increase in intervals over the course of several minutes to meet temperature demand until the unit is more heavily loaded. The room temperature was approximately 80 degrees Fahrenheit and the unit would typically operate near 9.7 Amps steady state.

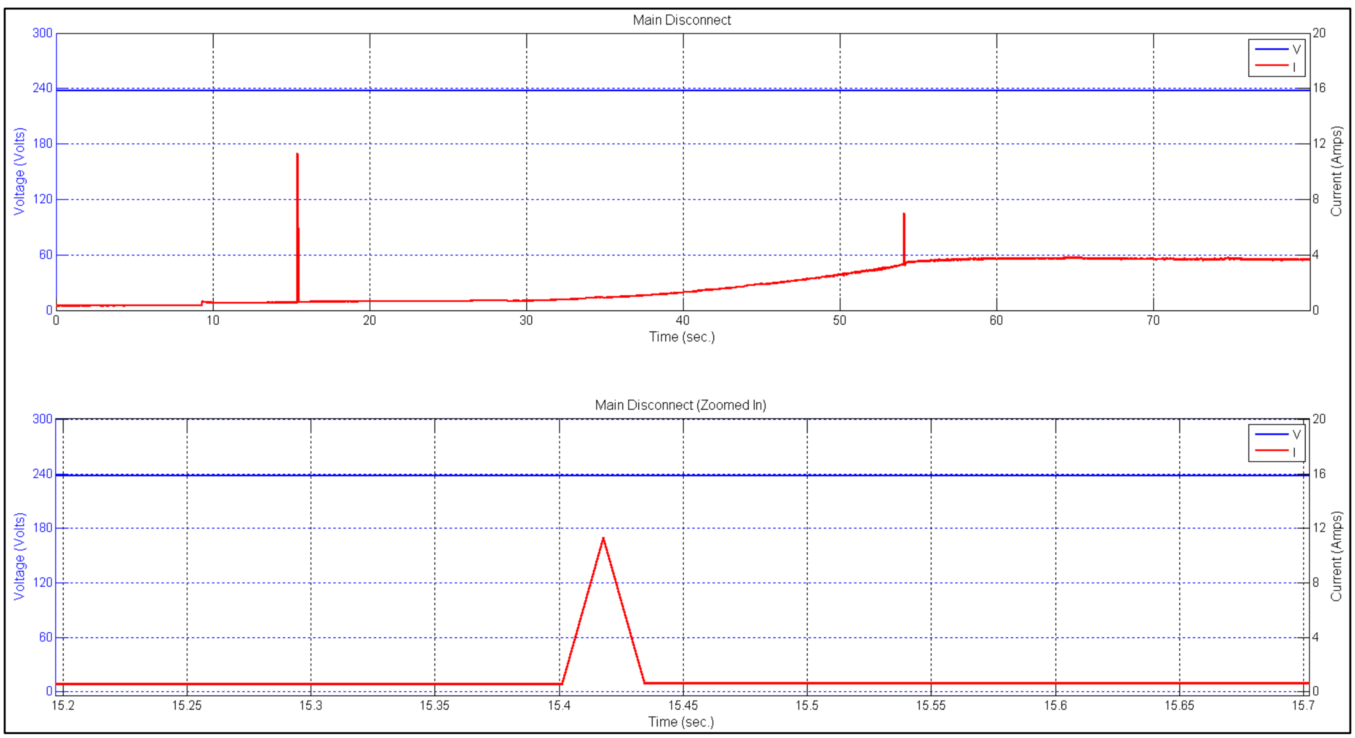

Figure 3.2.1 VFD A/C #1 Inrush Current

3.3 Balanced & Unbalanced Under-voltages

Performing balanced voltage sags on VFD A/C #1 in decrements of 10% revealed that the compressor is typically disconnected at 50% nominal voltage. Despite a few instances where the device rides through this voltage and does not trip until reaching 40% voltage, most voltage transients resulted in compressor tripping at the 50% voltage sags that had duration times of 3 to 130 cycles. Longer duration voltage sags (130 cycles) caused compressor tripping up to 18 cycles after the start of the voltage sag. However the remaining under-voltage tests in Table 3.3.1 consistently revealed compressor tripping at either at the end of the voltage sag or up to 1.4 cycles after voltage already recovered. This may be the result of the increasing spikes of inrush current at the end of each voltage sag or possibly the logic on the controller PCB is preventing load disconnection until voltage returns to nominal.

Data captured several seconds after the disconnection of the compressors did not reveal restarting behavior and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor would only restart several minutes after tripping occurred and there were no signs of stalling.

The only instance where the compressor did not trip and rode through all under-voltage sags (down to 0% voltage) occurred during transients that lasted only 1 cycle. However these 1 cycle tests were not as consistent as other under-voltage tests, causing the compressor to be tripped off at a variety of voltage magnitudes.

The following figure visually displays one of these balanced tests where the under-voltage sags have a duration time of 130 cycles. In this particular test, the compressor is observed being disconnected at 50% voltage after 18 cycles. The following table provides additional details regarding the compressor operation during a variety of balanced under-voltage transient tests including the voltage where the unit was tripped (V_{trip}) as well as the time it took for the unit controls to trip it offline after the voltage sag was initiated (t_{trip}).

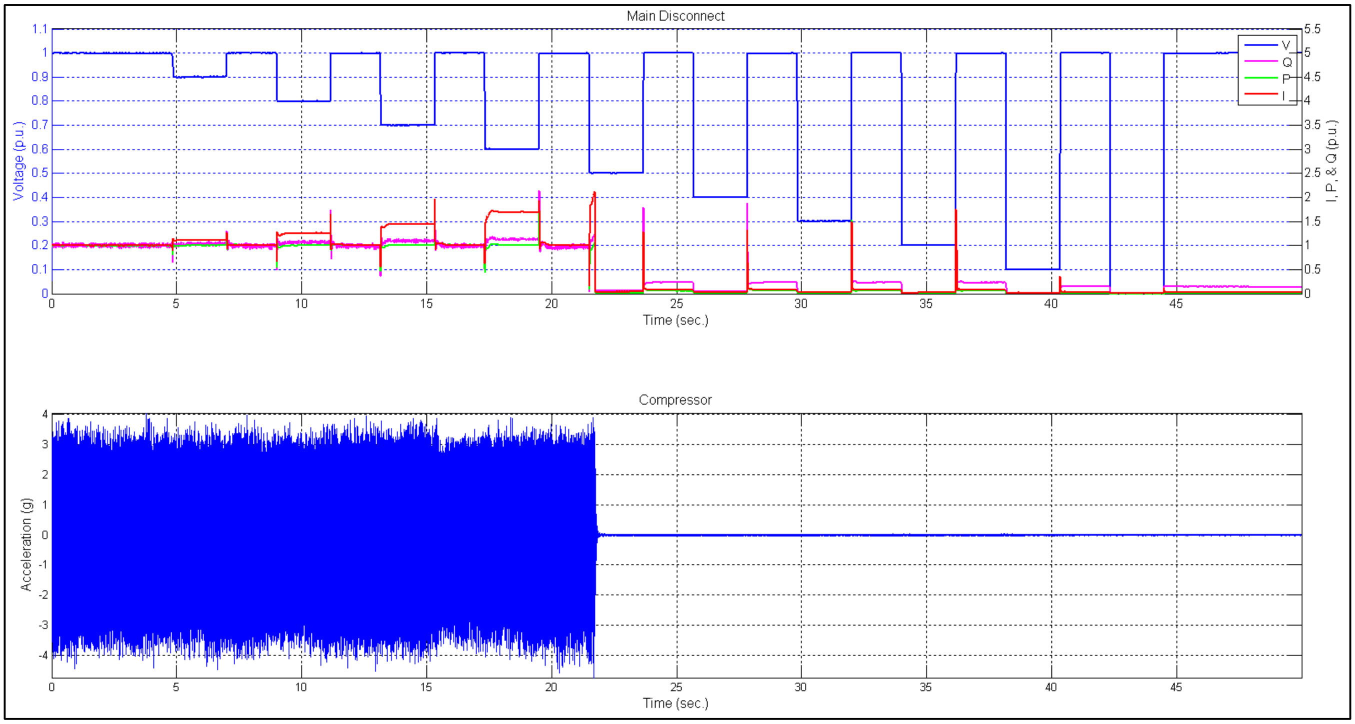

Figure 3.3.1 VFD A/C #1 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	50%	18
		50%	16.2
		50%	13.8
100%, 90%, 80%,... 0%	12	50%	11.4
		50%	10.8
		50%	12
100%, 90%, 80%,... 0%	9	40%	9
		50%	9
		50%	9
100%, 90%, 80%,... 0%	6	50%	6
		50%	7.2
		50%	6
100%, 90%, 80%,... 0%	3	40%	4.2
		50%	3
		50%	4.2
100%, 90%, 80%,... 0%	1	50%	2.4
		N/A	N/A
		30%	1.8

Table 3.3.1 VFD A/C #1 Balanced Under-voltages in 10% Decrements Results

Identifying the specific voltage where the compressors are disconnected and/or the controls dropped out requires additional balanced under-voltage tests in decrements of 1% nominal voltage. Several tests with different duration times showed that the compressor could begin tripping off for voltage sags as high as 55% and as low as 51% of nominal where the trip times typically occur at the end of the voltage sag or even up to 1.2 cycles after voltage recovers. This behavior may also be due to the inrush current as voltage returns to steady state or possibly a result of the controller PCB logic on the outdoor unit. The following table provides the details of the compressor disconnection behavior during these 1% voltage decrement tests.

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
60%, 59%, 58%,…	180	55%	179.4
60%, 59%, 58%,…	130	52%	15
60%, 59%, 58%,…	12	55%	13.2
60%, 59%, 58%,…	3	51%	3.6

Table 3.3.2 VFD A/C #1 Balanced Under-voltages in 1% Decrements Results

Unbalanced under-voltages on this VFD A/C unit resulted in compressor trip voltages and trip times similar to those observed during balanced under-voltage conditions with respect to the line-to-line voltage. Although the unit does not trip until the single line under-voltage sags with a duration of 3 to 130 cycles reach either 10% or 0% line-to-neutral when measuring one of the legs. Therefore the line-to-line trip voltages are 55% or 50% nominal voltage when measuring across both legs since one of the legs is being held at nominal voltage. These results suggest that the power electronic controls that operate the compressor of this particular VFD unit rely on the voltage potential across both lines. The 1 cycle voltage sags, which were performed to represent switching transients, did not cause any tripping behavior.

The following figure shows an example of these unbalanced cases (Line 1 under-voltages for 130 cycles). The following table provides the compressor disconnection behavior during unbalanced voltage transients observed at the main terminals of the VFD A/C unit. Notice that the shorter duration voltage sags (12 cycles and less) result in tripping at the end of the transient or up to 1.2 cycles after voltage recovers, similar to the behavior observed during balanced under-voltage tests.

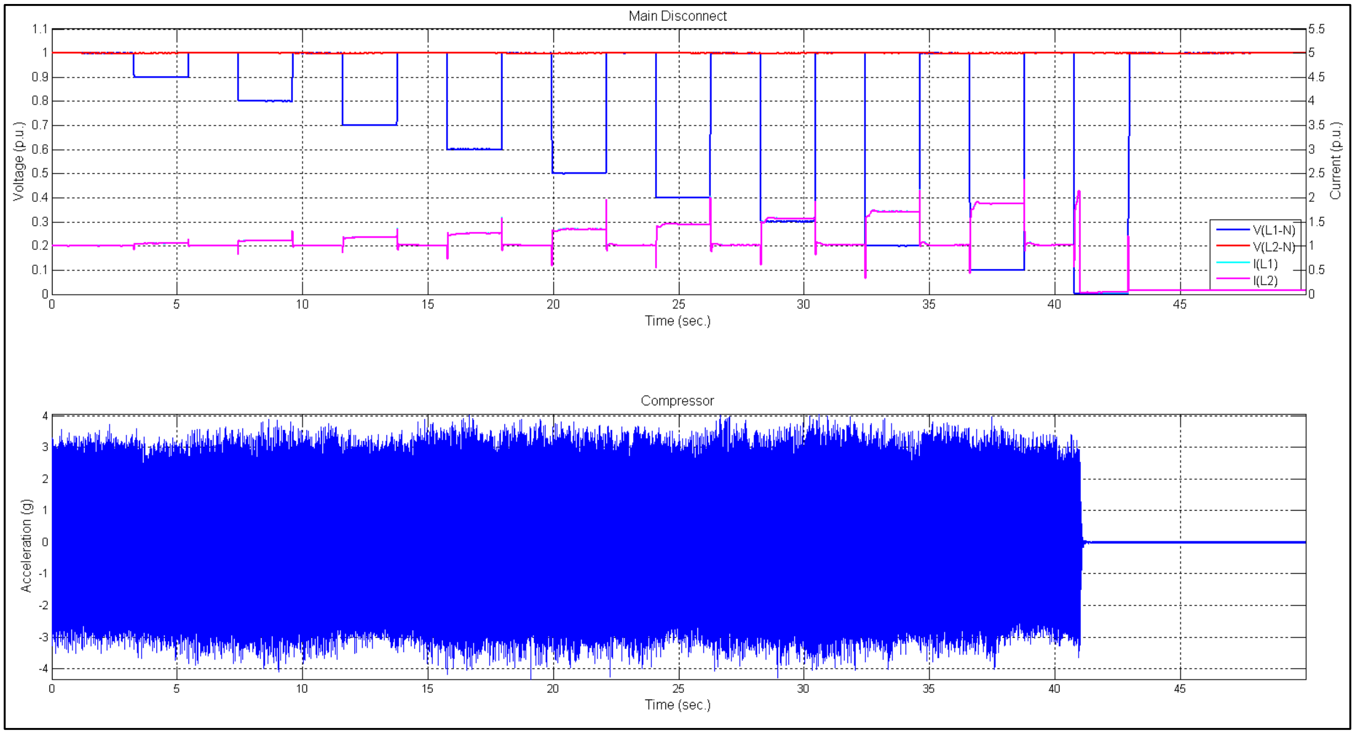

Figure 3.3.2 VFD A/C #1 Balanced Under-voltage Response (Line 1, 130 cycles)

Under-Voltage Transient			**Compressor**		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1	100%, 90%, 80%,... 0%	130	0%	50%	13.8
		12	10%	55%	12
		9	0%	50%	9.6
		6	10%	55%	6
		3	10%	55%	4.2
		1	N/A	N/A	N/A
L2	100%, 90%, 80%,... 0%	130	0%	50%	12
		12	10%	55%	12.6
		9	0%	50%	10.2
		6	10%	55%	6
		3	0%	50%	4.2
		1	N/A	N/A	N/A

Table 3.3.3 VFD A/C #1 Unbalanced Under-voltage Results

3.4 Balanced & Unbalanced Over-voltages

In order to avoid damaging any voltage sensitive power electronic equipment inside the VFD A/C unit, it was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve. These included multiple voltage swells performed in 2% increments for up to 120% nominal voltage to identify any tripping behavior. No over-voltage protection was observed during these tests and the VFD A/C unit rode through all of the voltage transients operating normally. The following figure and table display the details of this ride through performance.

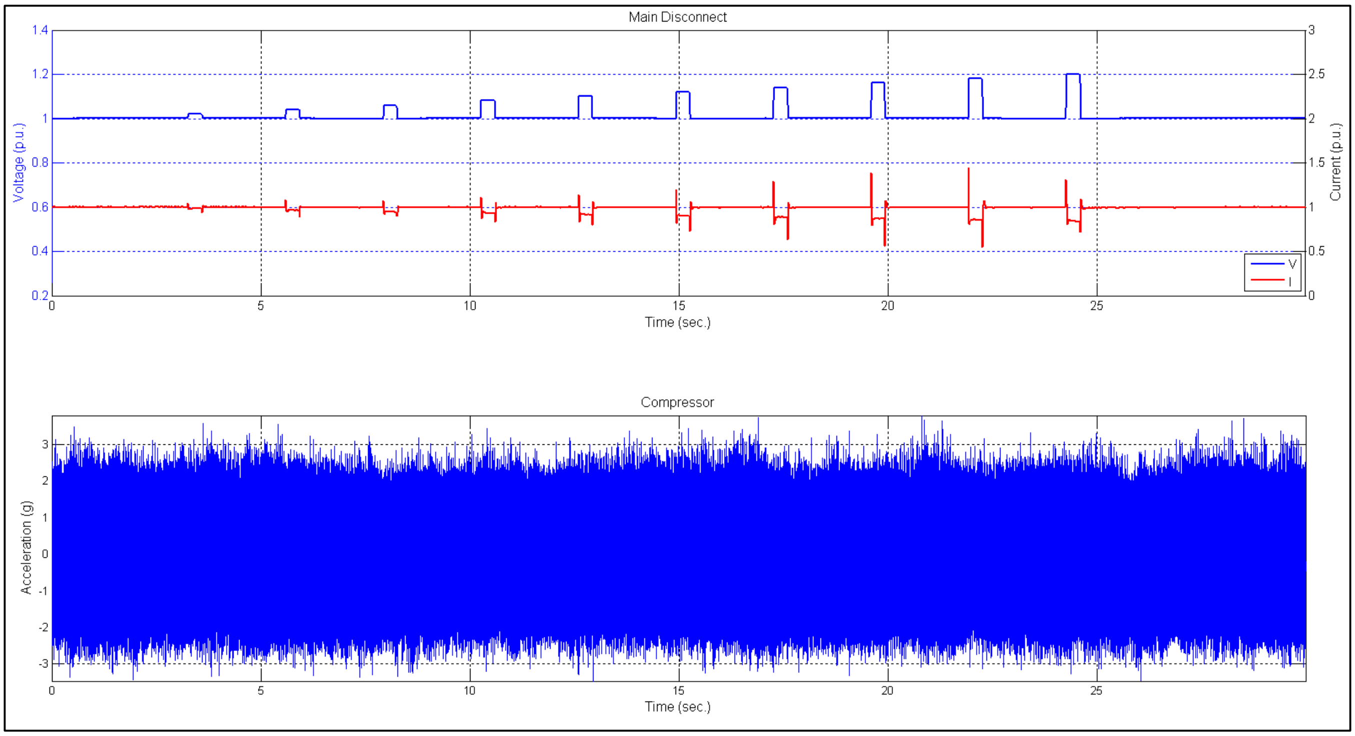

Figure 3.4.1 VFD AC #1 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		
Lines	Volt Range	Duration (cyc)	$V_{trip\ L\text{-}N}$ (%)	$V_{trip\ L1\text{-}L2}$ (%)	t_{trip} (cyc)
L1 & L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L1	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A

Table 3.4.1 VFD A/C #1 Balanced & Unbalanced Over-voltage Results

3.5 Voltage Oscillations

The following figure shows the performance of the VFD A/C unit during voltage oscillations between 100% and 90% nominal voltage for a variety of swing frequencies or oscillation rates.

Current oscillates in the opposite direction of voltage, up to 12% above nominal, to minimize any oscillations or deviations in real power. The consumption of real power remains relatively constant, within 2% of nominal, due the rapid change in current indicating that the VFD drive is attempting to keep the compressor motor speed constant. This near constant power response holds true for all voltage oscillation tests from 0.25 Hz to 2 Hz while voltage oscillates between 100% and 90%.

Reactive power consumption is very low since the power factor is greater than 0.99 for the device. Therefore any minor change in reactive load, even during steady state, results in drastic changes to the per unit values. As a result, reactive power was not included in the figure below.

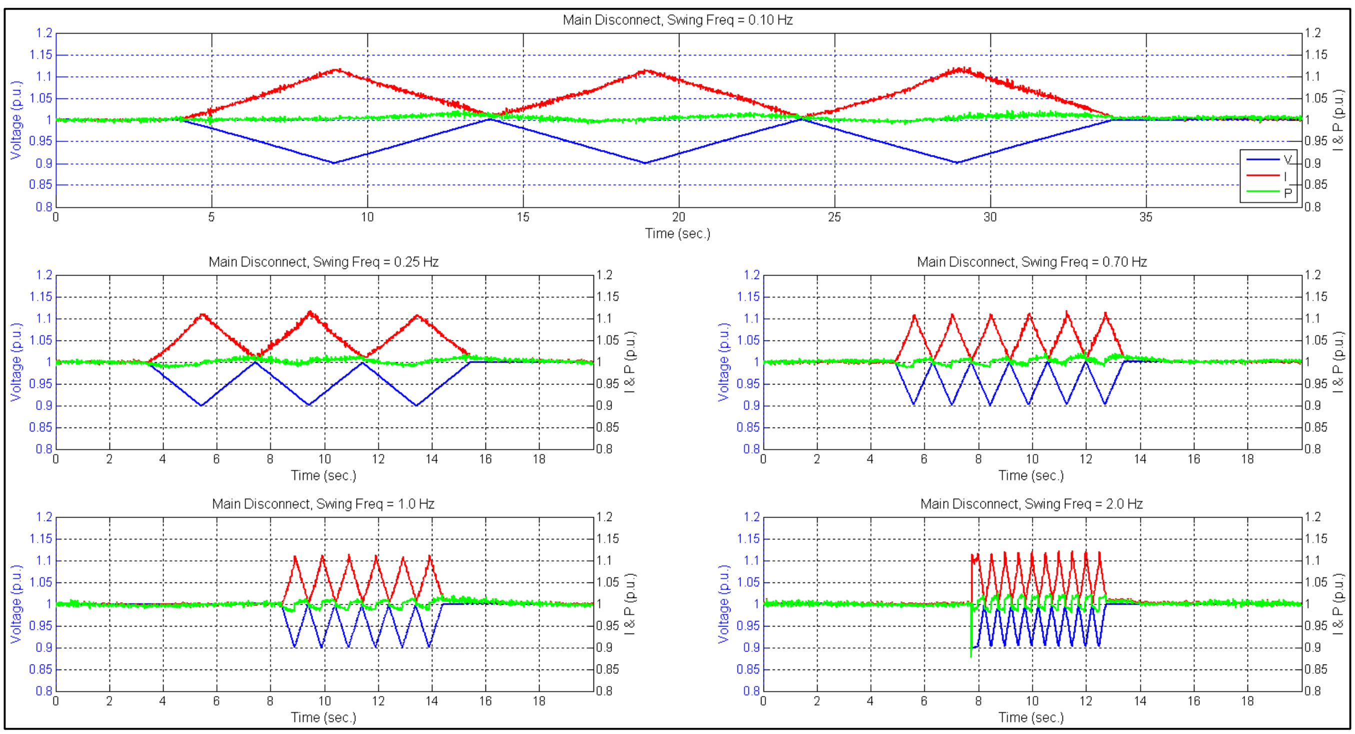

Figure 3.5.1 VFD AC #1 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

3.6 Under-frequency Events

After subjecting this VFD A/C unit to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection while operating between 60 Hz and 58 Hz. The device simply rides through these under-frequency conditions. The compressor motor frequency remains constant from the VFD despite changes in frequency at the unit's main terminals. The following figure and table identify the magnitude and duration of the frequency transient tests that were performed.

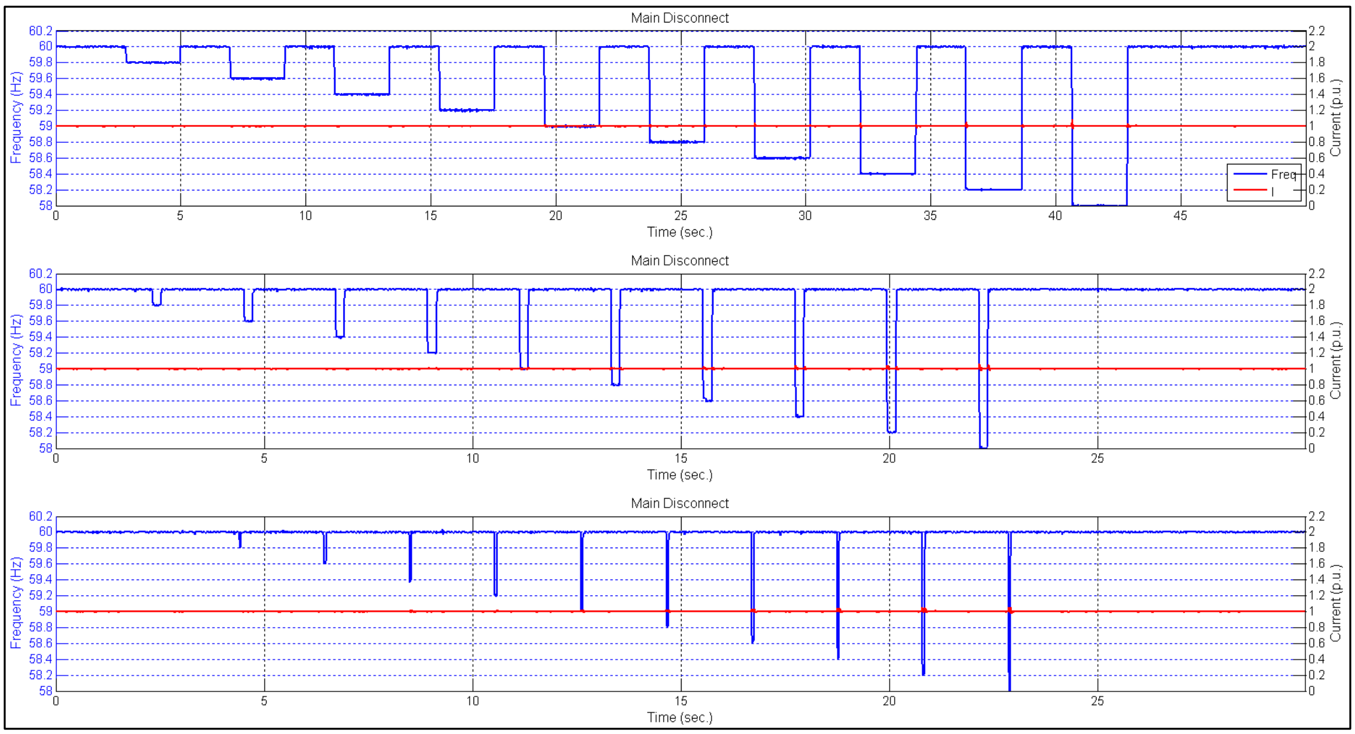

Figure 3.6.1 VFD A/C #1 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 3.6.1 VFD A/C #1 Under-frequency Test Results

3.7 Over-frequency Events

Similar to the under-frequency tests, the VFD A/C unit was subjected to over-frequency transients to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The compressor motor frequency remains constant from the VFD despite changes in frequency at the unit’s main terminals. The following figure and table identify the magnitude and duration of the specific over-frequency tests that were performed.

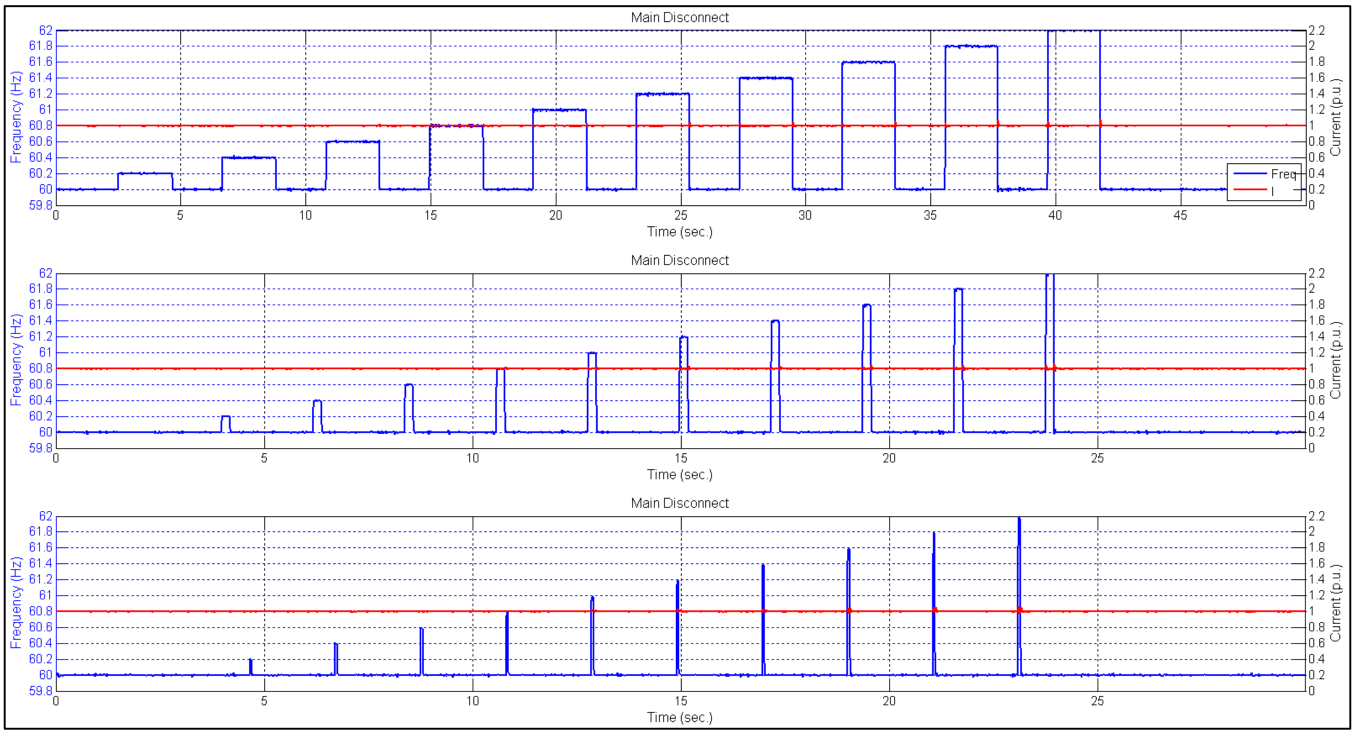

Figure 3.7.1 VFD A/C #1 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		**Compressor**	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 3.7.1 VFD A/C #1 Over-frequency Test Results

3.8 Frequency Oscillations

The following figure shows the performance of VFD A/C #1 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates (0.10, 0.25, 0.70, 1.0, and 2.0 Hz).

Current does not oscillate or deviate in response to frequency oscillations at the main terminals of the A/C unit. The active power consumption remains constant, within ±1% of nominal, along with current for all swing frequencies.

Reactive power was not included in the figure below because of its low consumption (power factor is greater than 0.99). Even minor deviations that naturally occur during steady state result in harsh changes to the per unit values plotted.

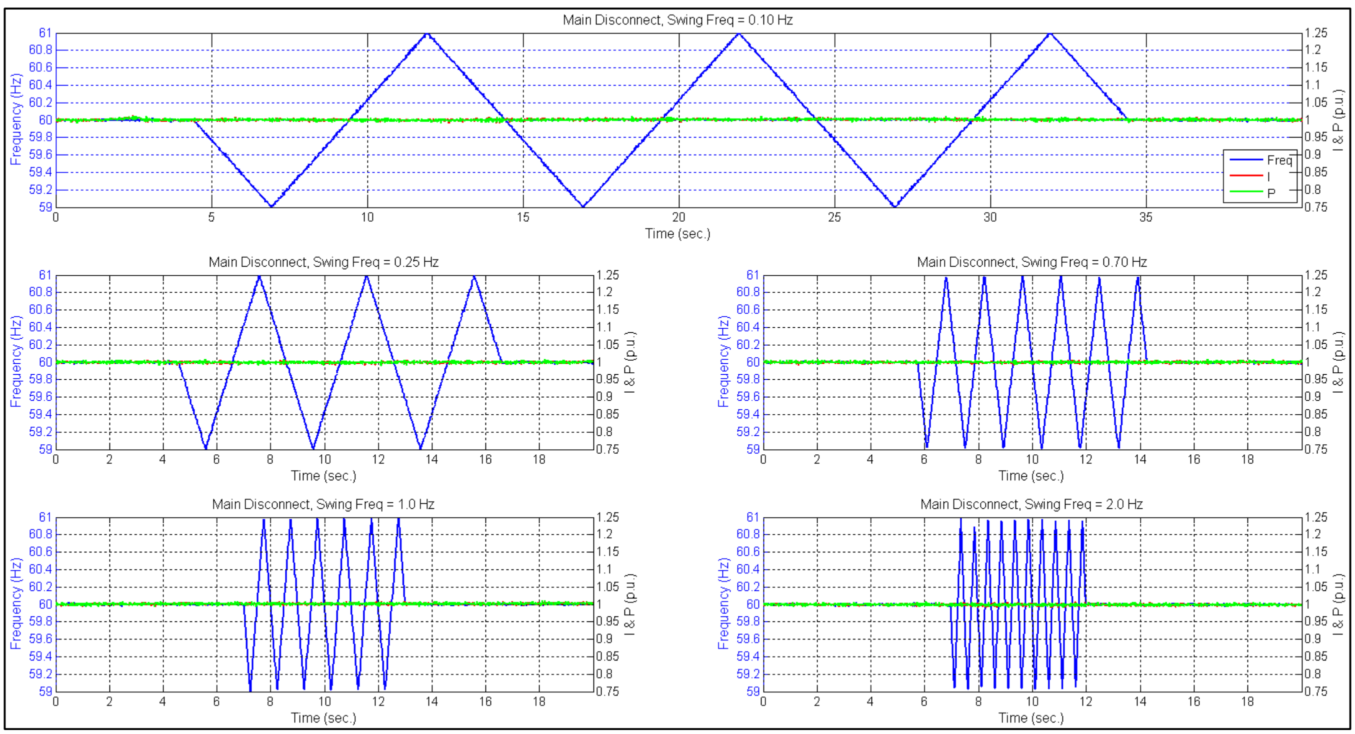

Figure 3.8.1 VFD A/C #1 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

3.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit tripped while ramping down to 50% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation (down to 60% nominal voltage).

Overall, the VFD is doing an excellent job maintaining constant power and a constant speed for the compressor motor despite the drastic change in voltage. Current ramps up to approximately 71% above nominal while maintaining near constant power. Real power only deviates within ±2% of steady state for the 8 second ramp test and within ±5% for the 2 second ramp test. Reactive power consumption is low, but ramps with the current to nearly 70% above it nominal value.

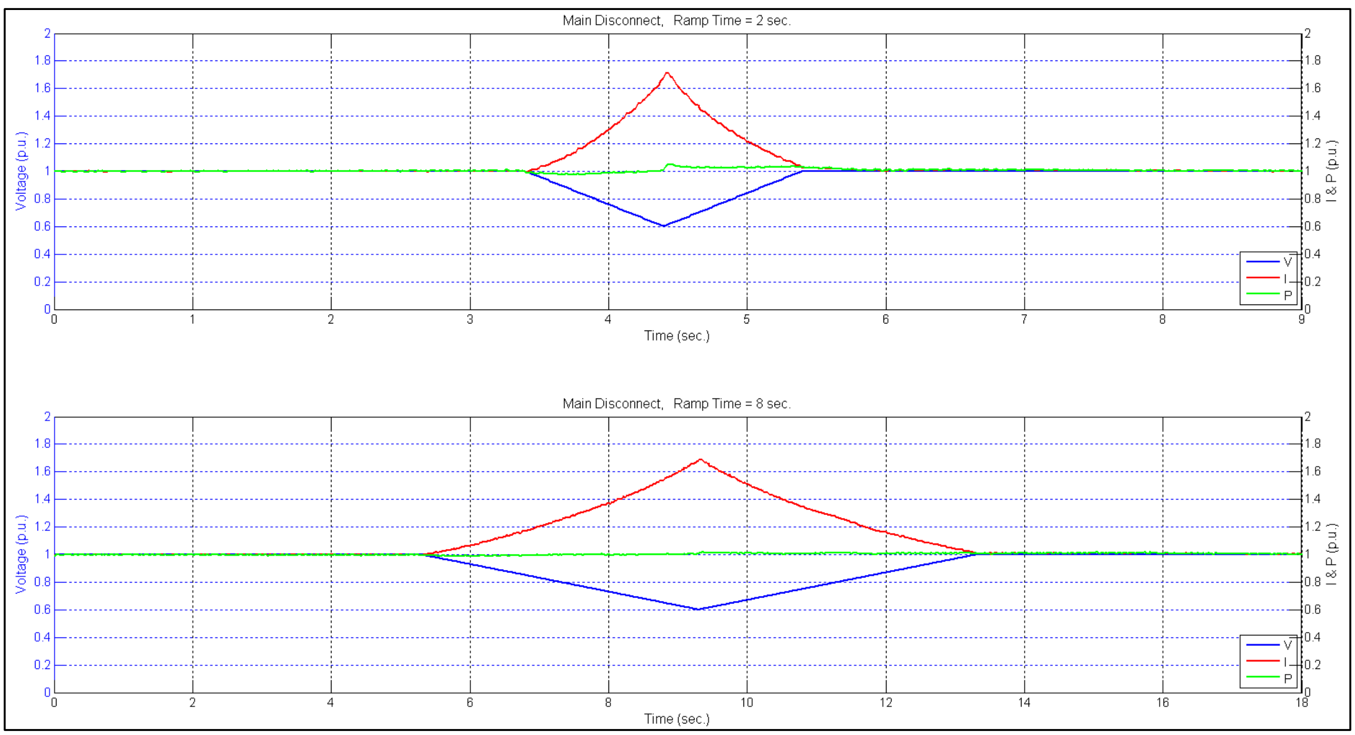

Figure 3.9.1 VFD A/C #1 Voltage Ramp Down to 60% (2 & 8 sec.)

Voltage was ramped up to 110% and back down steady state voltage at different ramp rates to demonstrate the load performance while operating at over-voltage values.

Similarly, the VFD maintains the speed and real power consumption of the compressor motor. Current is observed uniformly ramping down to nearly 10% below nominal, resulting in constant power load behavior. Real power consumption stays within ±1% of steady state. Little reactive power is consumed during normal operation, but it does ramp in the same direction as the current.

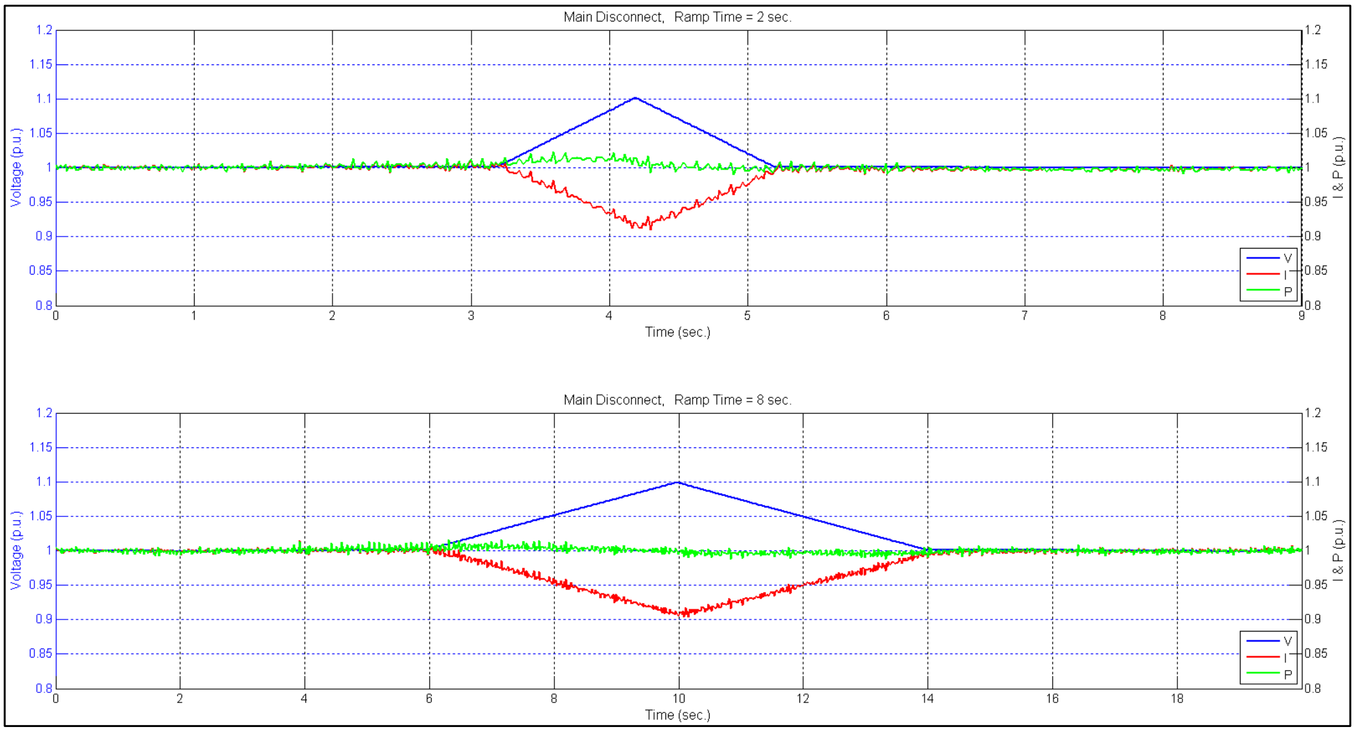

Figure 3.9.2 VFD A/C #1 Voltage Ramp Up to 110% (in 2 & 8 sec.)

3.10 Frequency Ramps

Frequency was ramped down to 50 Hz and back up to 60 Hz at different ramp rates to demonstrate the load performance while operating at lower frequency values as shown in the figure below.

Current and real power remain constant throughout the entire under-frequency ramp. Reactive power is relatively low (0.99 power factor) and therefore deviations in the per unit values are observed even during steady state.

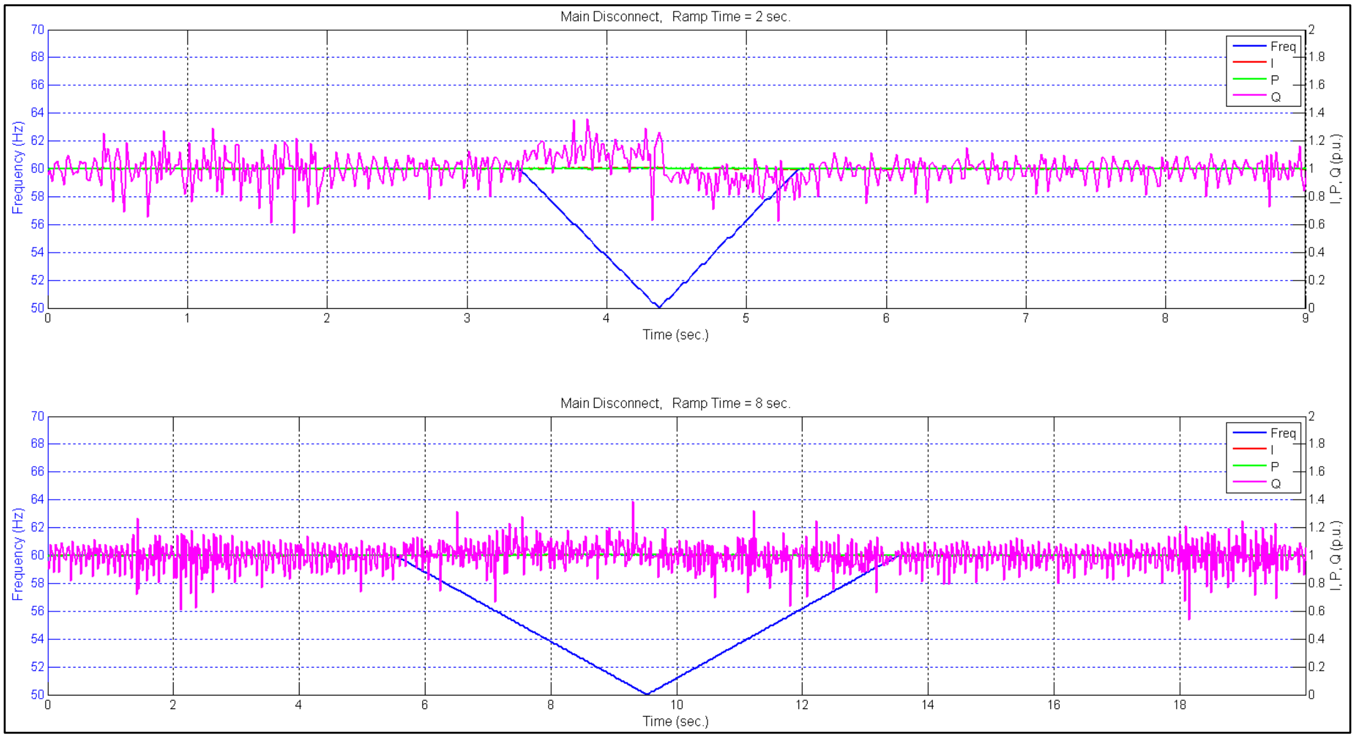

Figure 3.10.1 VFD A/C #1 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

Frequency was ramped up to 70 Hz and back down to 60 Hz at different ramp rates to demonstrate the load performance while operating at higher frequency values. However, VFD A/C #1 tripped at approximately 67.5 Hz and the test was redone ramping frequency up to 65 Hz as shown in the figure below.

Current stays constant at the beginning of the test until frequency reaches 64 Hz. At this point the current ramps up with frequency until peaking at 10% above nominal. Real power consumption is constant throughout the entire test. Reactive power, like current, begins ramping after frequency goes above 64 Hz and peaks at approximately 336% of nominal before ramping down. The device is operating at a power factor greater than 0.99 and therefore reactive power consumption is low.

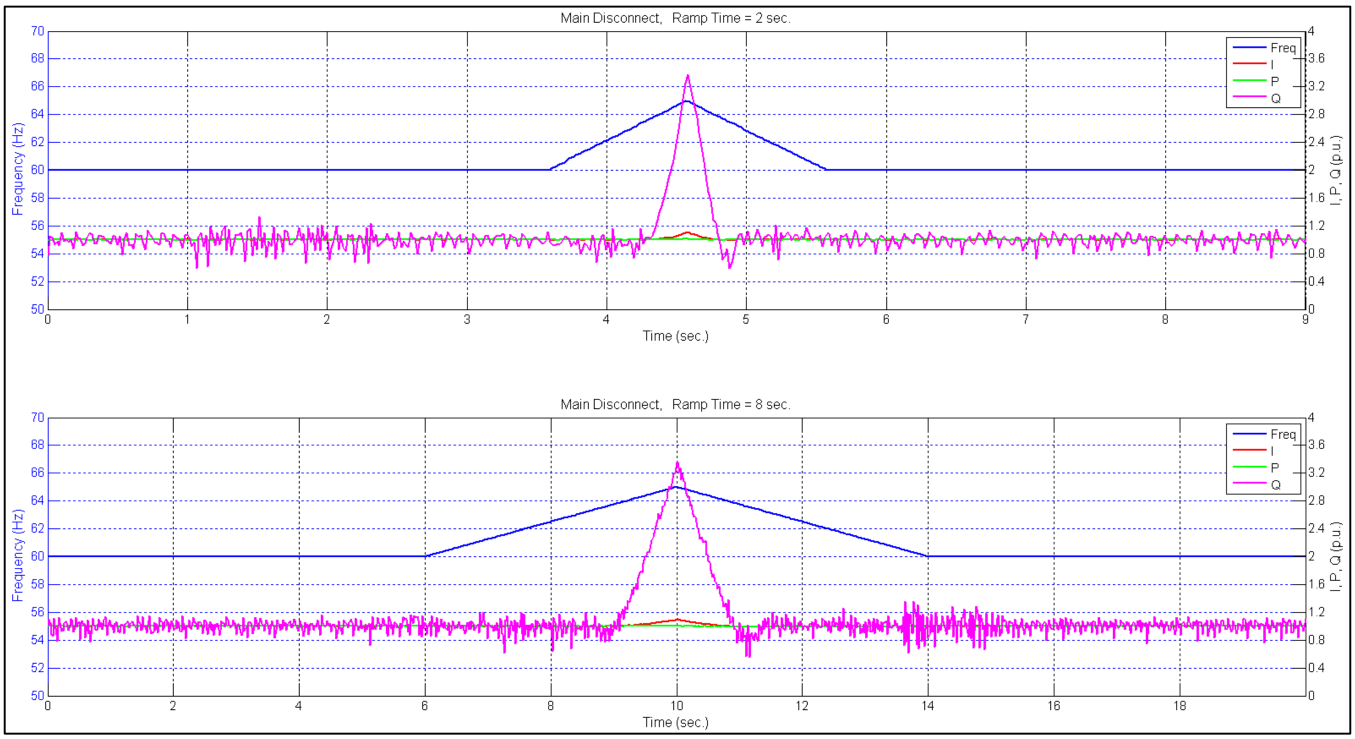

Figure 3.10.2 VFD A/C #1 Frequency Ramp Up to 65 Hz (in 2 & 8 sec.)

3.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times without scope filters to calculate the actual harmonic contribution of VFD A/C unit #1 to the grid. The total harmonic distortion of current was found to be almost 15% of the fundamental. The following table gives the total harmonic distortion calculations and the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)		
	$V_{(L1-L2)}$	$I_{(L1)}$	$I_{(L2)}$
1	0.95	14.76	14.86
2	0.95	14.71	14.81
3	0.95	14.71	14.81

Table 3.11.1 VFD A/C #1 Total Harmonic Distortion

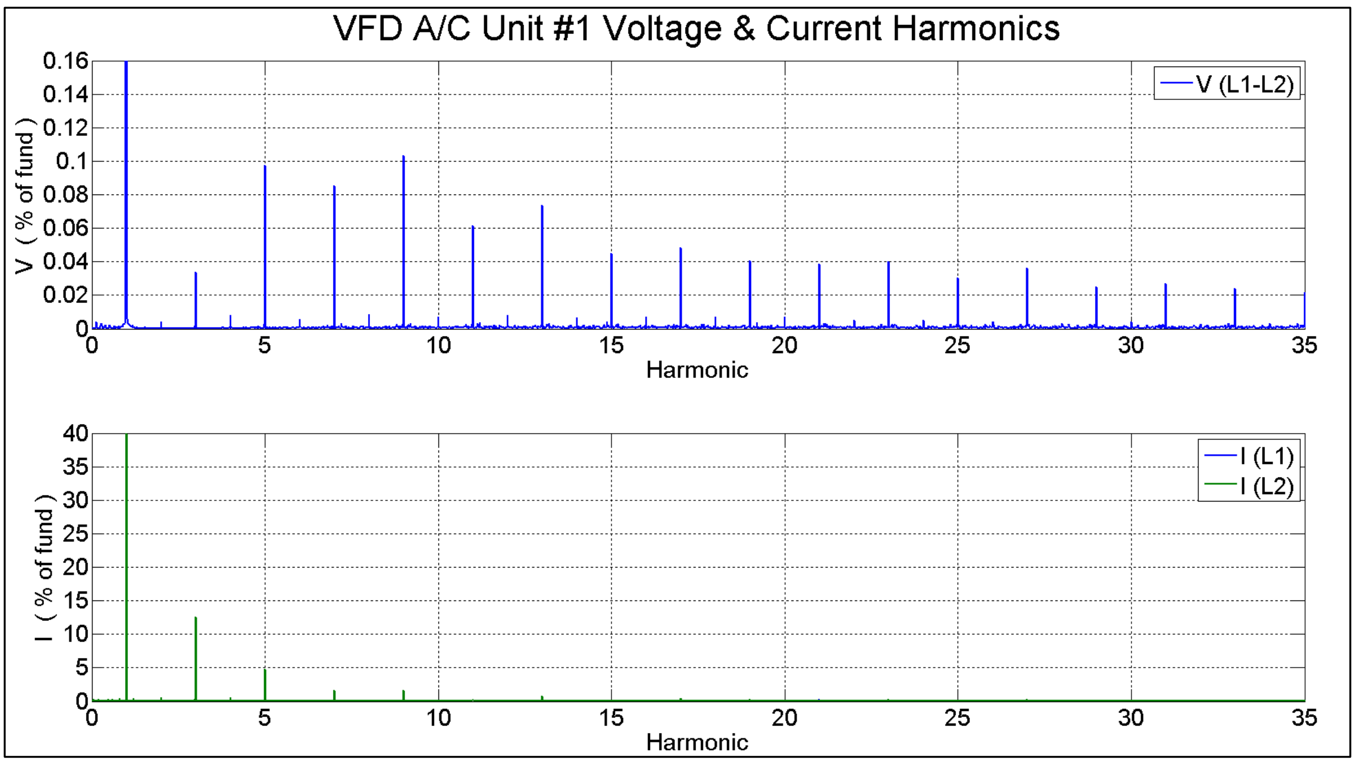

Figure 3.11.1 VFD A/C #1 Harmonics Contribution

3.12 Conservation Voltage Reduction

Voltage was decreased by 1% nominal voltage in 5 second intervals down to 90% before recovering back to steady state as shown in the figure below.

CVR will have little to no effect on power consumption for this type of A/C with VFD technology based on the following results. Current increases by approximately 1.2% of nominal current for every 1% decrease in nominal voltage over the course of the CVR test. This results in constant real power, within $\pm$2% of normal consumption. Reactive power does increase with current, but consumption is very low and difficult to plot in per unit values with the other electrical measurements.

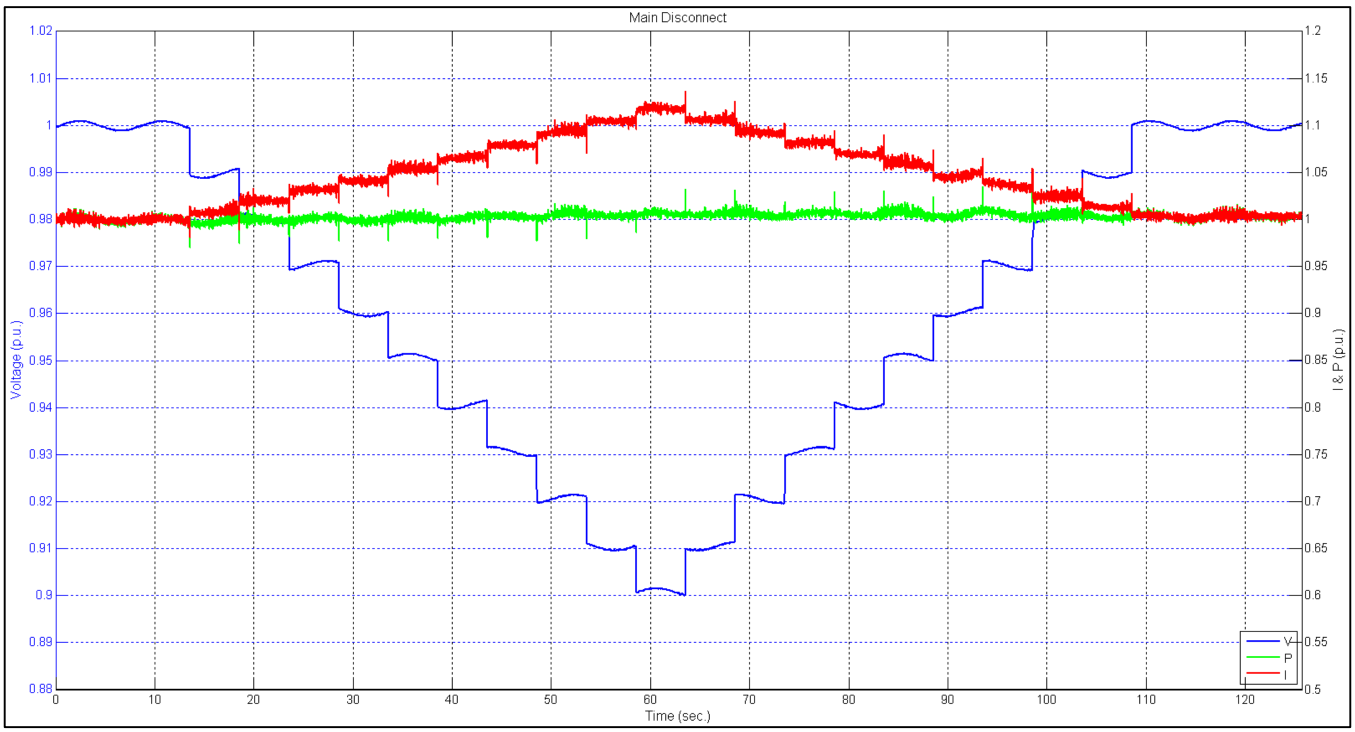

Figure 3.12.1 VFD A/C #1 CVR Response Down to 90% Voltage

Alternatively, the main terminal voltage at the VFD A/C unit was increased by 1% nominal voltage in 5 second intervals up to 105% before stepping back to steady state as shown in the figure below.

Again, CVR does not have a significant impact on the load power consumption. Current decreases by approximately 1% of its nominal value for every 1% increase in nominal voltage. Therefore real power remains at steady state consumption. Reactive power does decrease with current, but again is a very low value relative to the other measurements.

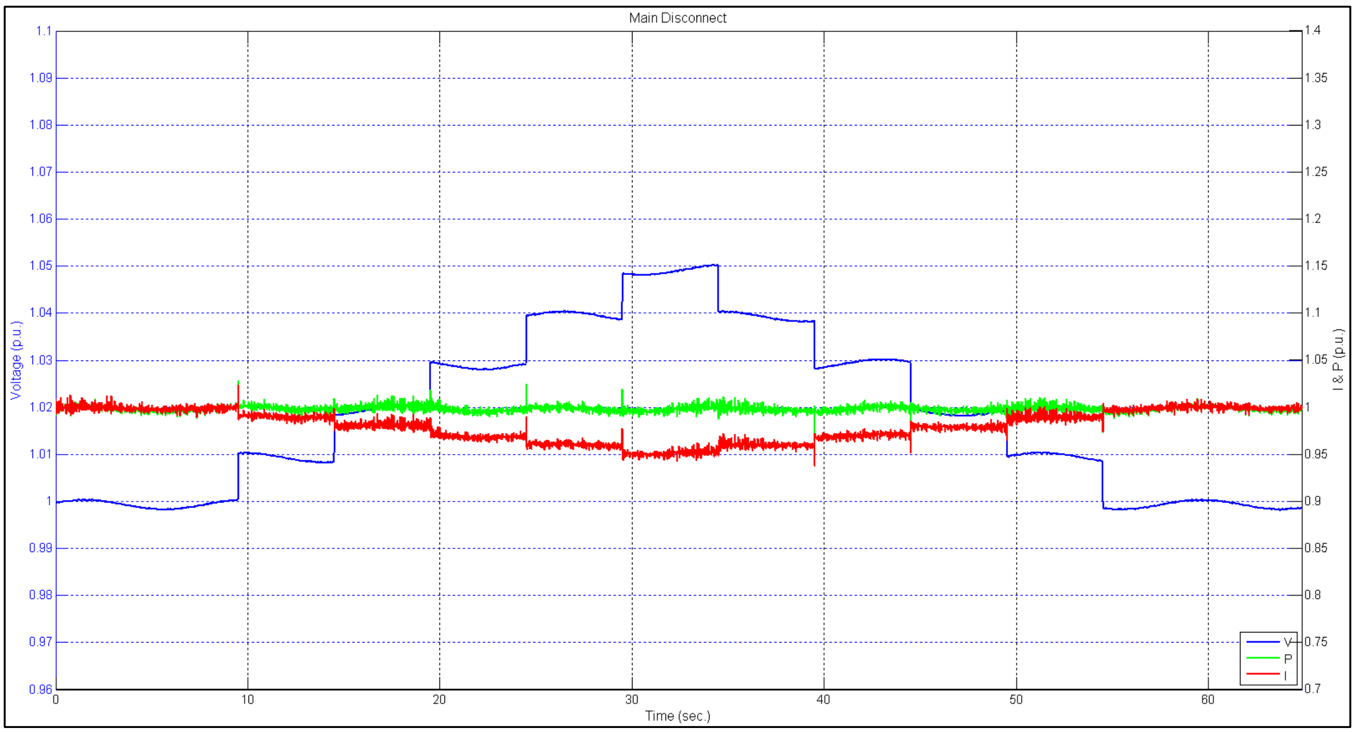

Figure 3.12.2 VFD A/C #1 CVR Response Up to 105% Voltage

4.0 VFD AIR CONDITIONER #2 TEST RESULTS

The figure below shows a snapshot of VFD A/C unit #2 sinusoidal voltages and currents captured at the main terminals and compressor motor using a filter on the digital scope. Notice the distortion in the main currents waveforms compared to the voltage waveforms. The compressor is operating at approximately 172 Volts peak, 9 Amps peak, and 160 Hz at the observed loading condition. The specifications for the VFD A/C #2 components are provided in the table below.

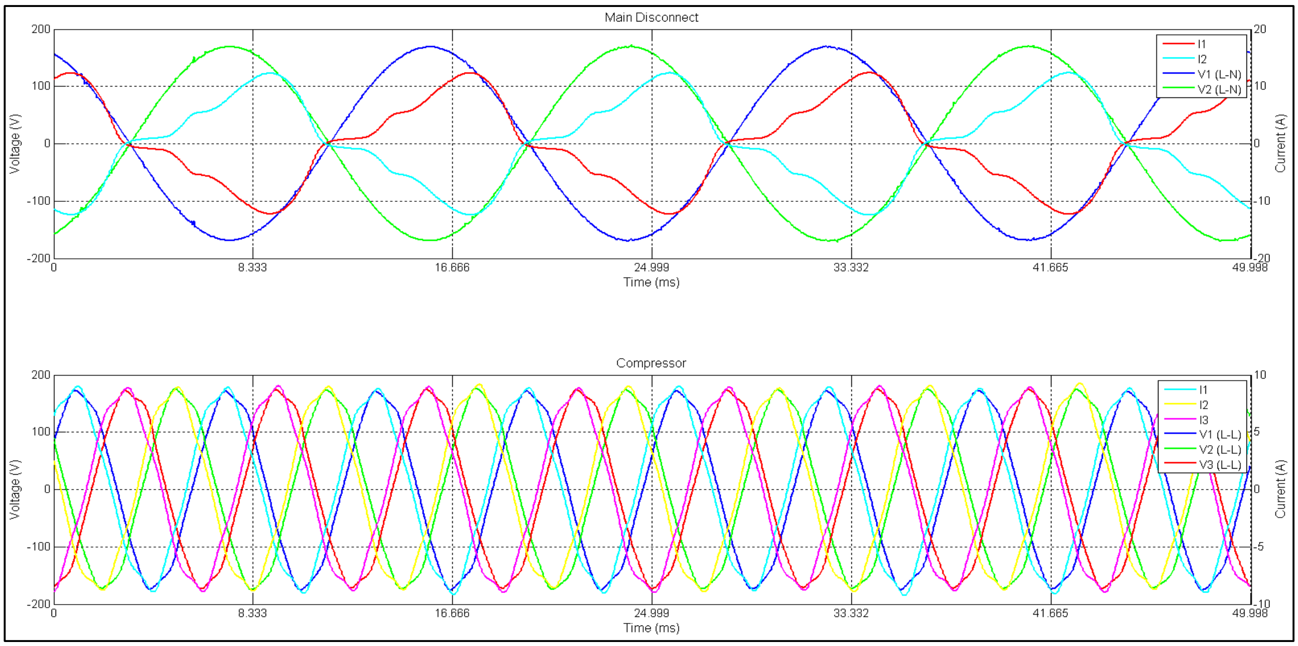

Figure 4.0.1 VFD A/C #2 Voltage and Current Waveforms

Manufacturer	Carrier
Voltage (V)	230
Refrig.	R-410A
SEER	16
Compressor, Model #	LG GJT240MBA
Compressor, RLA (Amps)	12.5
Compressor, LRA (Amps)	41
Outdoor Fan Motor, FLA (Amps)	0.62
Indoor Fan Motor, FLA (Amps)	0.45
Design Pressure High (PSI)	550
Design Pressure Low (PSI)	240

Table 4.0.1 VFD A/C #2 Specifications

4.1 Compressor Shutdown

VFD A/C #2 was shut down during normal operation using the programmable thermostat remote for the indoor blower unit. The figure below displays the measurements taken at the main terminal connections of the entire A/C unit.

The indoor unit fan shuts down immediately after adjusting the thermostat followed by the compressor starting to shut down within one second. The compressor current decreases rapidly within 3 cycles and slowly decays over the next 10 cycles. However, the outdoor unit fan continued operating for another 60 seconds before shutting down and the A/C unit entered standby mode. While in standby mode, the device's power consumption is less than 0.4 Amps.

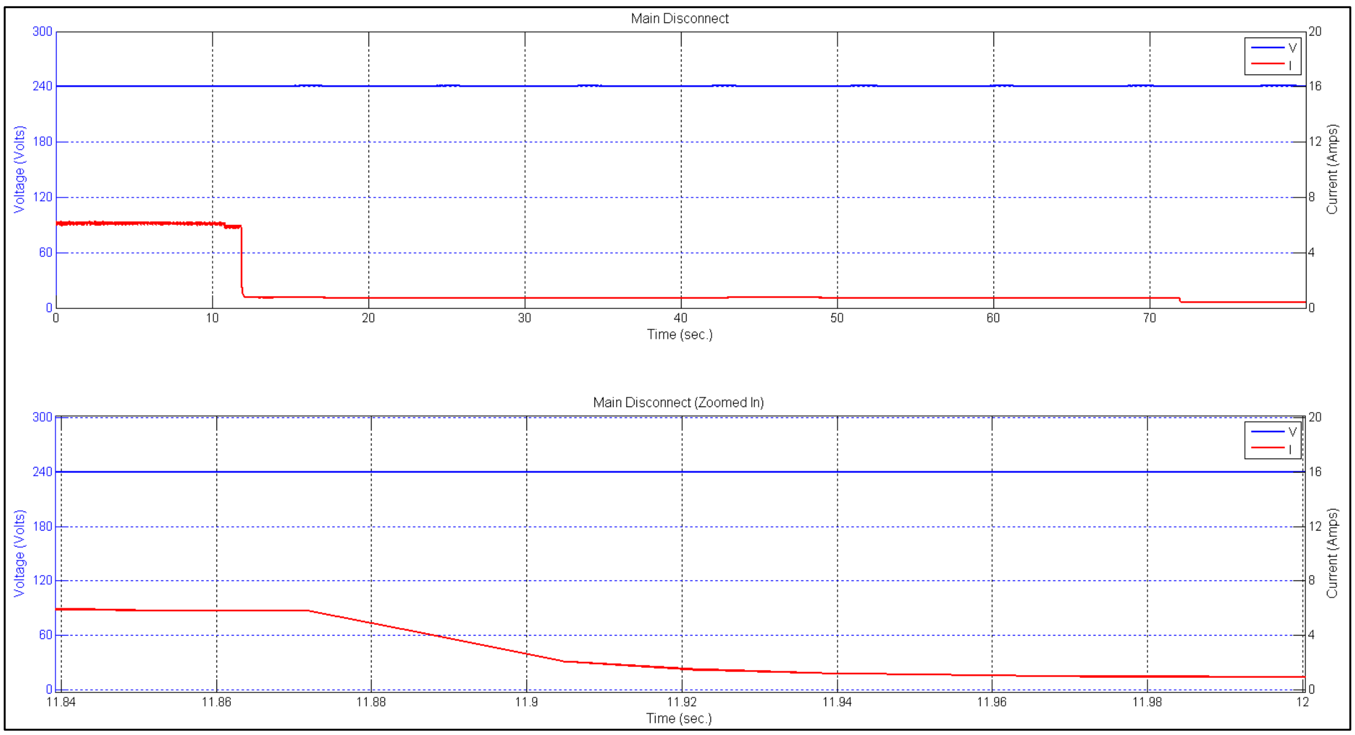

Figure 4.1.1 VFD A/C #2 Compressor Shutdown

4.2 Inrush Current

After starting up the VFD A/C unit via the programmable thermostat remote, the fan motors start up first with a maximum inrush current of 5.5 Amps in an 18 cycle window. This is followed by the compressor slowly ramping up over the course of roughly 45 seconds until the unit is drawing a minimum of 2.4 Amps. The VFD compressor will increase in intervals over the course of several minutes to meet temperature demand until the unit is more heavily loaded. The room temperature was approximately 80 degrees Fahrenheit and the unit would operate up to 7.2 Amps steady state.

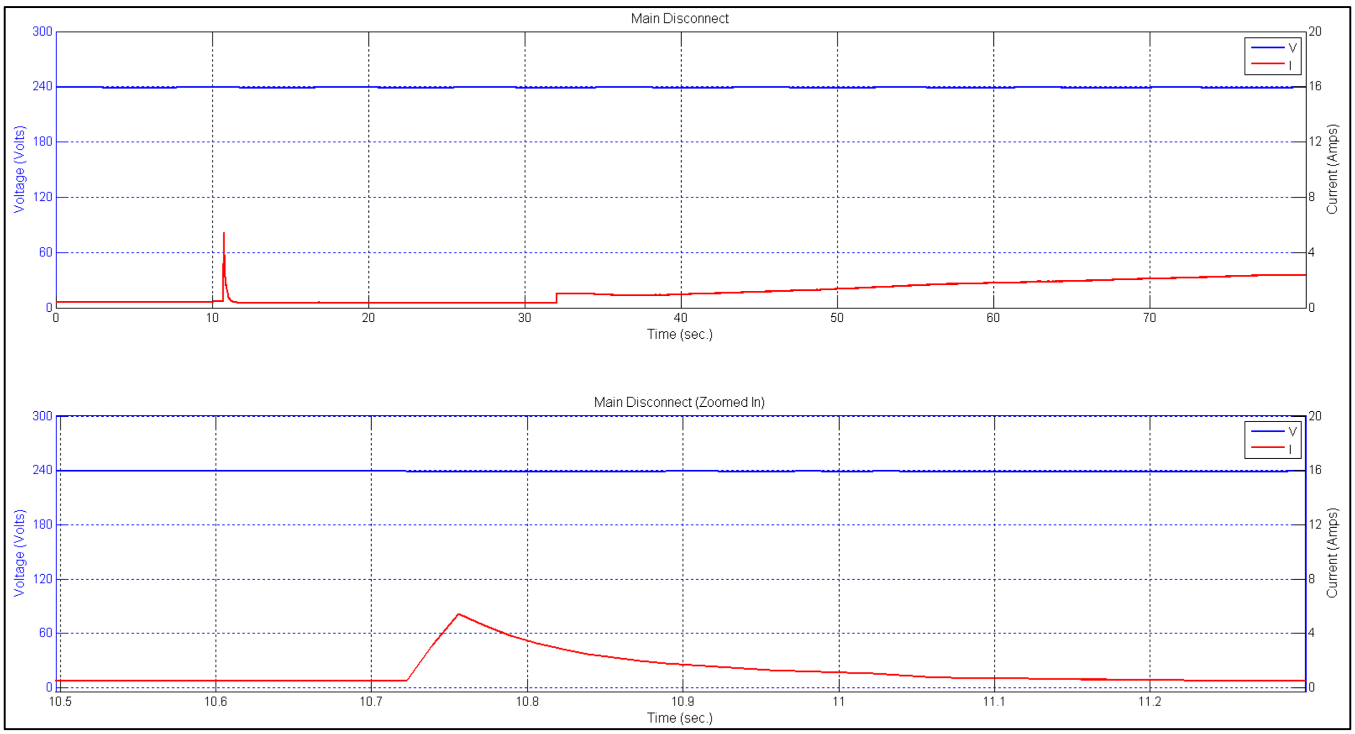

Figure 4.2.1 VFD A/C #2 Inrush Current

4.3 Balanced & Unbalanced Under-voltages

VFD A/C #2 was subjected to a series of balanced under-voltage sags in decrements of 10% to identify the conditions required to cause device dropout and tripping behavior. The unit was consistently observed disconnecting the compressor at 50% nominal voltage for sags with a duration of 6 to 130 cycles within 8.4 cycles after the start of the voltage sag. Table 4.3.1 shows that the 6 cycle transients were the only tests that resulted in the compressor shutting down after voltage already recovered to nominal.

Data captured several seconds after the disconnection of the compressors did not reveal restarting behavior and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor was only observed restarting several minutes after tripping occurred with no evidence of stalling behavior.

Voltage sags with a duration of 3 cycles and 1 cycle resulted in the compressor riding through all voltage magnitudes (down to 0% voltage) and continuing to operate normally. “N/A” or “not applicable” represents these ride through situations where there is no trip voltage or trip time available in the following tables.

The following figure visually displays one of the longer balanced tests where the under-voltage sags have a duration time of 130 cycles. The figure reveals that the compressor motor slows down slightly at 70% voltage and more significantly at 60% voltage before shutting down at 50% voltage within the first 2 cycles of the voltage sag. The current spikes take place when voltage steps from one magnitude to another are caused the compressor and fan motors. The real and reactive power profiles indicate a change in power factor at the beginning of the voltage sag that returns to normal before voltage recovers. The following table provides the voltage (V_{trip}) and time (t_{trip}) taken for the A/C unit’s controls to dropout and/or cause compressor tripping. The trip time is measured from the start of the voltage sag prior to the compressor shutting down.

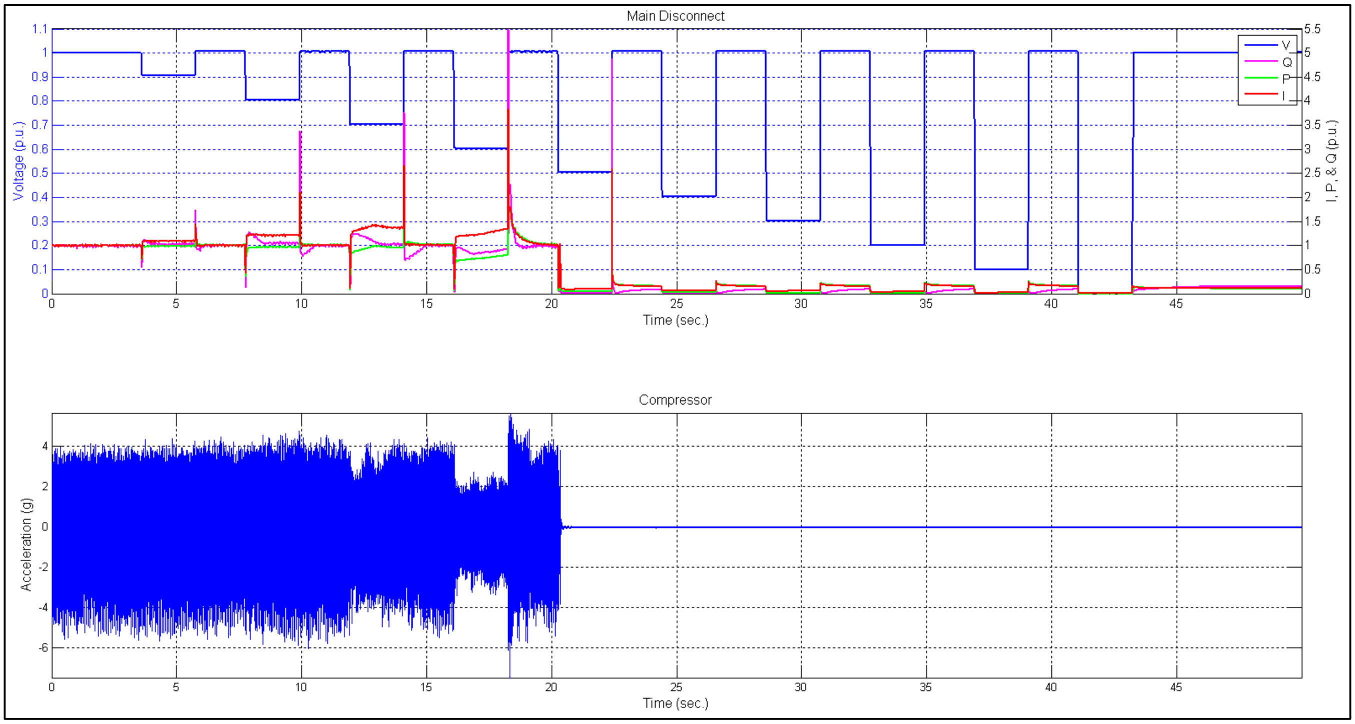

Figure 4.3.1 VFD A/C #2 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		**Compressor**	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	50%	1.2
		50%	1.2
		50%	1.2
100%, 90%, 80%,... 0%	12	50%	4.8
		50%	6
		50%	3.6
100%, 90%, 80%,... 0%	9	50%	5.4
		50%	4.8
		50%	7.2
100%, 90%, 80%,... 0%	6	50%	6.6
		50%	8.4
		50%	6.6
100%, 90%, 80%,... 0%	3	N/A	N/A
		N/A	N/A
		N/A	N/A
100%, 90%, 80%,... 0%	1	N/A	N/A
		N/A	N/A
		N/A	N/A

Table 4.3.1 VFD A/C #2 Balanced Under-voltages in 10% Decrements Results

Additional balanced under-voltage tests in decrements of 1% nominal voltage were performed to verify at which point do the controls drop out causing the compressor to be disconnected. Multiple tests suggested that the compressor would consistently be disconnected between 55% and 56% nominal voltage within 7.8 cycles after the start of the voltage sag. The following table provides the details of the compressor disconnection behavior during some these 1% voltage decrement tests.

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
60%, 59%, 58%,…	130	56%	7.8
60%, 59%, 58%,…	130	56%	7.8
60%, 59%, 58%,…	130	55%	7.2
60%, 59%, 58%,…	12	55%	7.8
60%, 59%, 58%,…	12	55%	9
60%, 59%, 58%,…	12	55%	9

Table 4.3.2 VFD A/C #2 Balanced Under-voltages in 1% Decrements Results

The results for the unbalanced under-voltages on this VFD A/C unit were consistent with the balanced under-voltage tests with respect to the line-to-line voltage at the main terminals. The unit has dropout and tripping behavior when one line drops to 10% or 0% nominal of line-neutral voltage and the other line stays at nominal voltage. This means that the line-to-line voltage measured across both legs is 55% or 50% of nominal. Therefore the controls at the PCB that operate the compressor of this VFD unit must be powered or stepped down using the line-to-line voltage. As expected based on the balanced under-voltage results, the 3 and 1 cycle duration unbalanced voltage sags of any magnitude did not cause any dropout/tripping behavior.

The following figure shows an example of these unbalanced cases (Line 1 under-voltages for 130 cycles) where the compressor shuts down at 10% nominal line-to-neutral voltage within the first 7.8 cycles of the voltage sag. The following table provides the compressor disconnection behavior during unbalanced voltage transients as observed at the main terminals of the VFD A/C unit, including the voltage magnitudes where disconnection occurs and how long it takes to disconnect after the voltage sag is initiated.

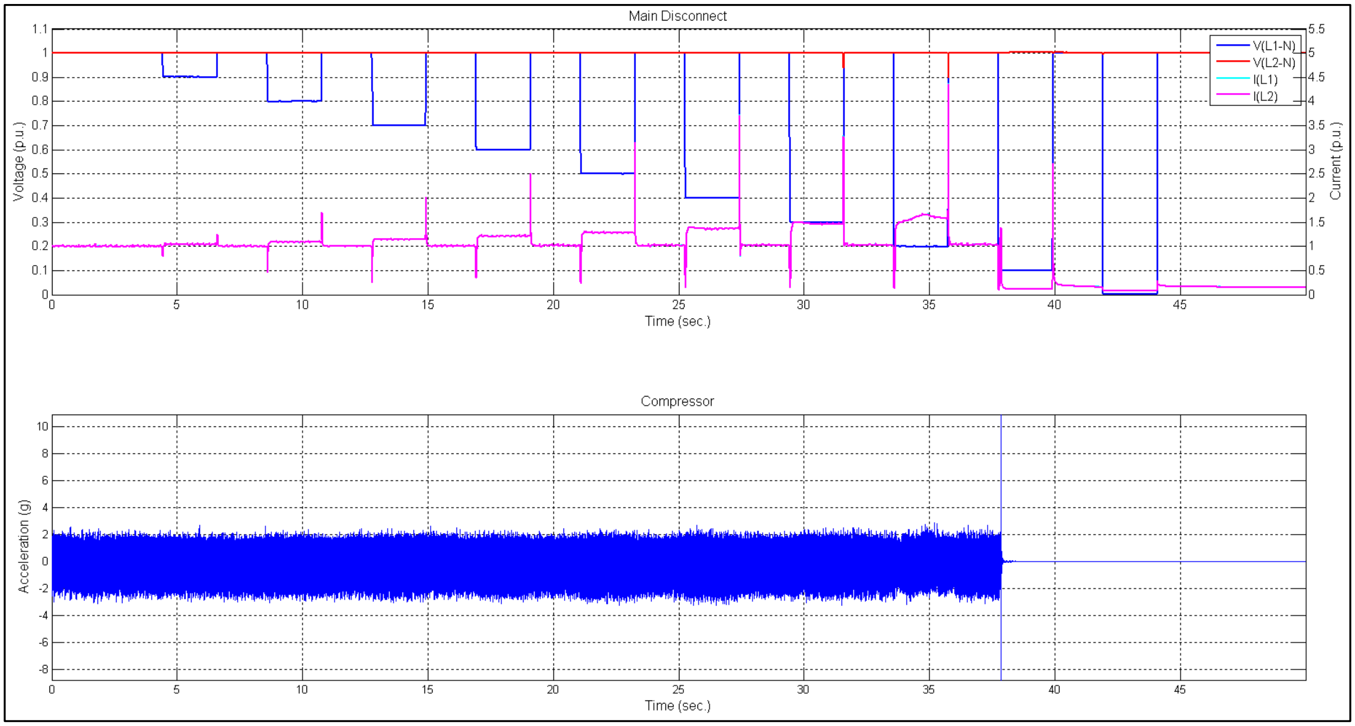

Figure 4.3.2 VFD A/C #2 Unbalanced Under-voltage Response (Line 1, 130 cycles)

Under-Voltage Transient			**Compressor**		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1	100%, 90%, 80%,... 0%	130	10%	55%	7.8
		6	N/A	N/A	N/A
		3	N/A	N/A	N/A
		1	N/A	N/A	N/A
L2	100%, 90%, 80%,... 0%	130	10%	55%	7.8
		6	0%	50%	5.4
		3	N/A	N/A	N/A
		1	N/A	N/A	N/A

Table 4.3.3 VFD A/C #2 Unbalanced Under-voltage Results

4.4 Balanced & Unbalanced Over-voltages

Multiple voltage swells were performed in 2% increments for up to 120% nominal voltage within the parameters of the ITIC (CBEMA) curve, a curve developed to identify the tolerances of voltage sensitive loads. No over-voltage protection was observed during these tests, only voltage ride-through. The following figure shows a sample over-voltage test and the following table specifies the tests performed.

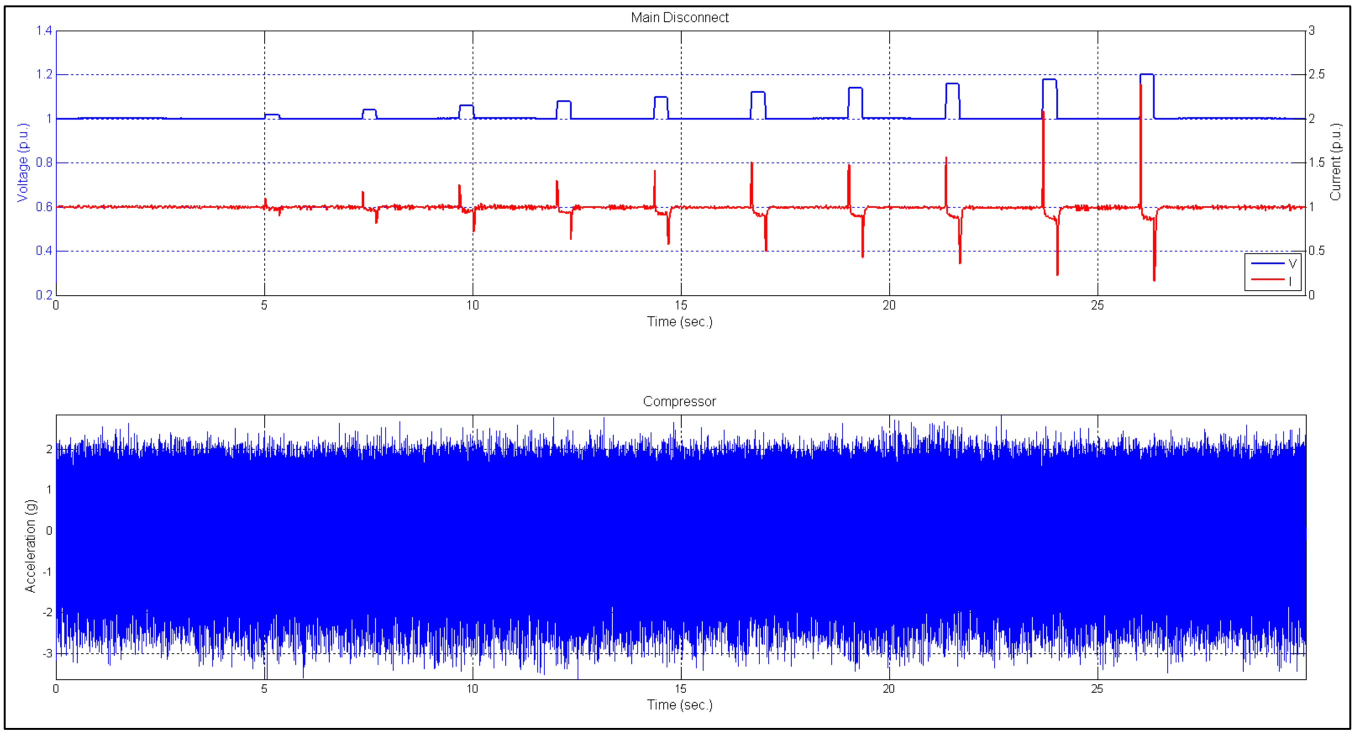

Figure 4.4.1 VFD AC #2 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1 & L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L1	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A

Table 4.4.1 VFD A/C #2 Balanced & Unbalanced Over-voltage Results

4.5 Voltage Oscillations

The following figure shows the performance of VFD A/C unit #2 during voltage oscillations between 100% and 90% nominal voltage for a variety of swing frequencies or oscillation rates.

Current oscillates in the opposite direction of voltage, up to 11% above nominal, to minimize any oscillations or deviations in real power for 0.10 Hz and 0.25 Hz oscillation rates. The current deviations become larger at faster oscillation rates (e.g. 14% above nominal at 2 Hz). As a result, real power remains within +3% of nominal at 0.10 Hz and 0.25 Hz with larger deviations occurring at faster oscillation rates.

Reactive power also oscillates opposite of voltage, up to +3% above nominal at 0.10 Hz. Similar to current and real power, deviations during oscillation become larger at higher swing frequencies or faster oscillation rates. Eventually reactive power deviates up to 16% from nominal for the 2 Hz oscillation test.

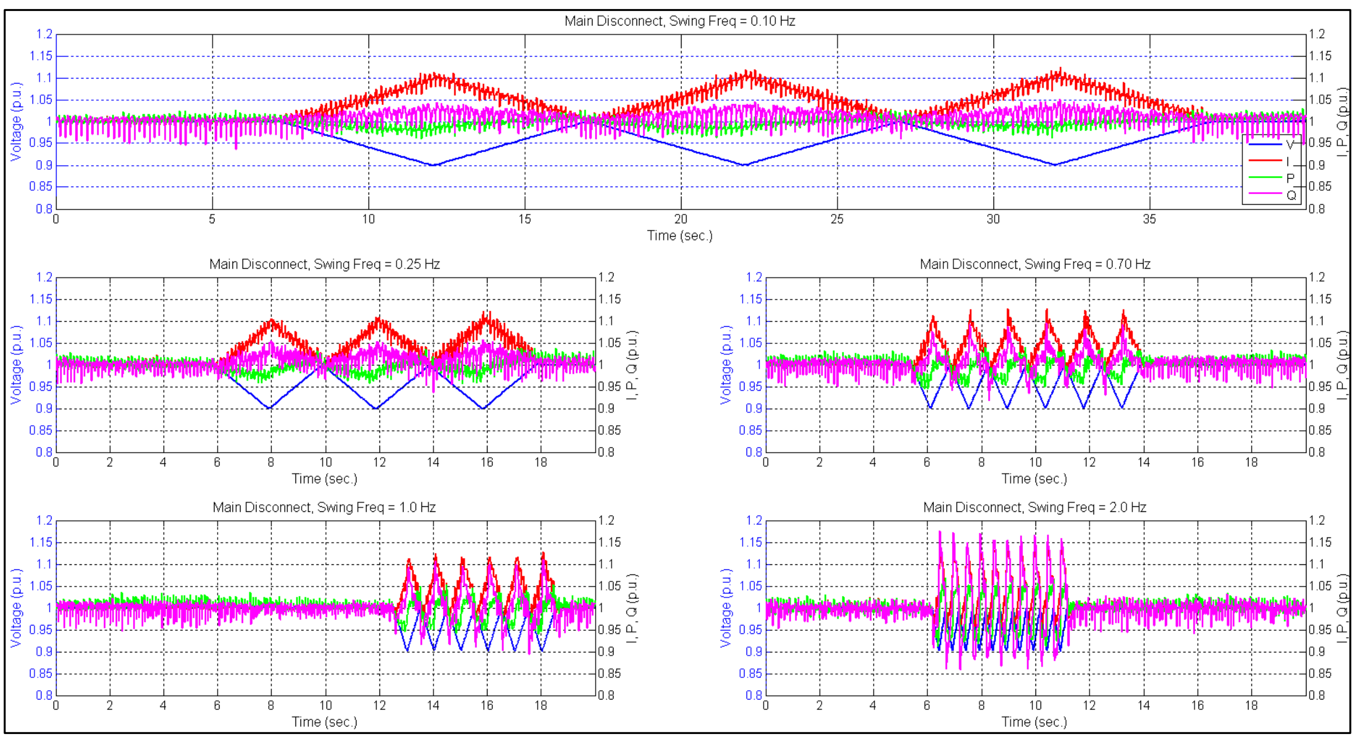

Figure 4.5.1 VFD AC #2 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

4.6 Under-frequency Events

After subjecting the VFD A/C unit to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection while operating between 60 Hz and 58 Hz. The device simply rides through these under-frequency conditions. The compressor motor frequency remains constant due to the VFD and maintains constant current consumption. The following figure and table identify the magnitude and duration of the frequency transient tests that were performed on VFD A/C #2.

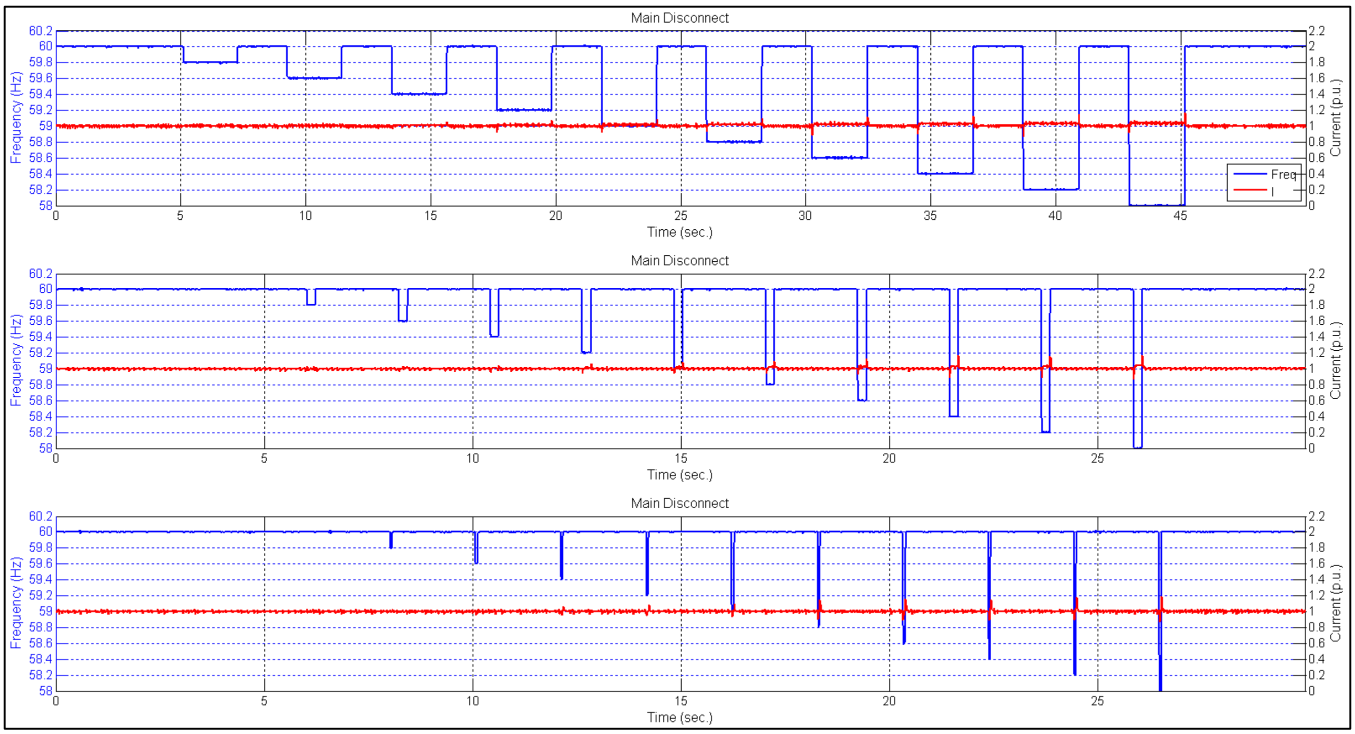

Figure 4.6.1 VFD A/C #2 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 4.6.1 VFD A/C #2 Under-frequency Test Results

4.7 Over-frequency Events

Similar to the under-frequency tests, the VFD A/C unit was subjected to over-frequency transients to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The compressor motor frequency remains constant from the VFD despite changes in frequency at the unit's main terminals. The following figure and table identify the magnitude and duration of the specific over-frequency tests that were performed on VFD A/C #2.

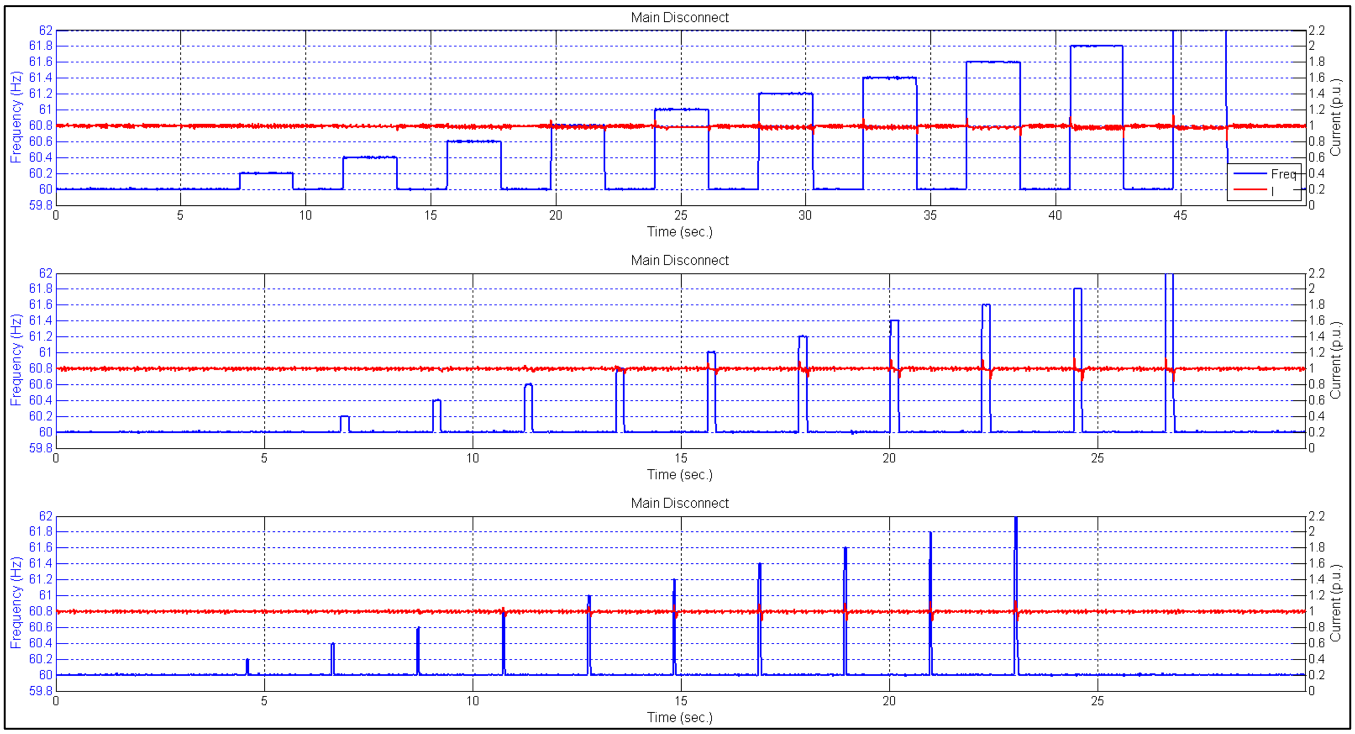

Figure 4.7.1 VFD A/C #2 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 4.7.1 VFD A/C #2 Over-frequency Test Results

4.8 Frequency Oscillations

The following figure shows the performance of VFD A/C #2 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates (0.10, 0.25, 0.70, 1.0, and 2.0 Hz).

Although the deviations from nominal become slightly larger for faster oscillation rates, current and real power measured at the main terminals of the VFD A/C unit remain relatively constant. Both remain within ±3% of their respective steady state values.

Reactive power oscillates in the opposite direction of voltage and deviations from nominal increase at faster oscillation rates. Reactive power consumption remains within ±14% of nominal.

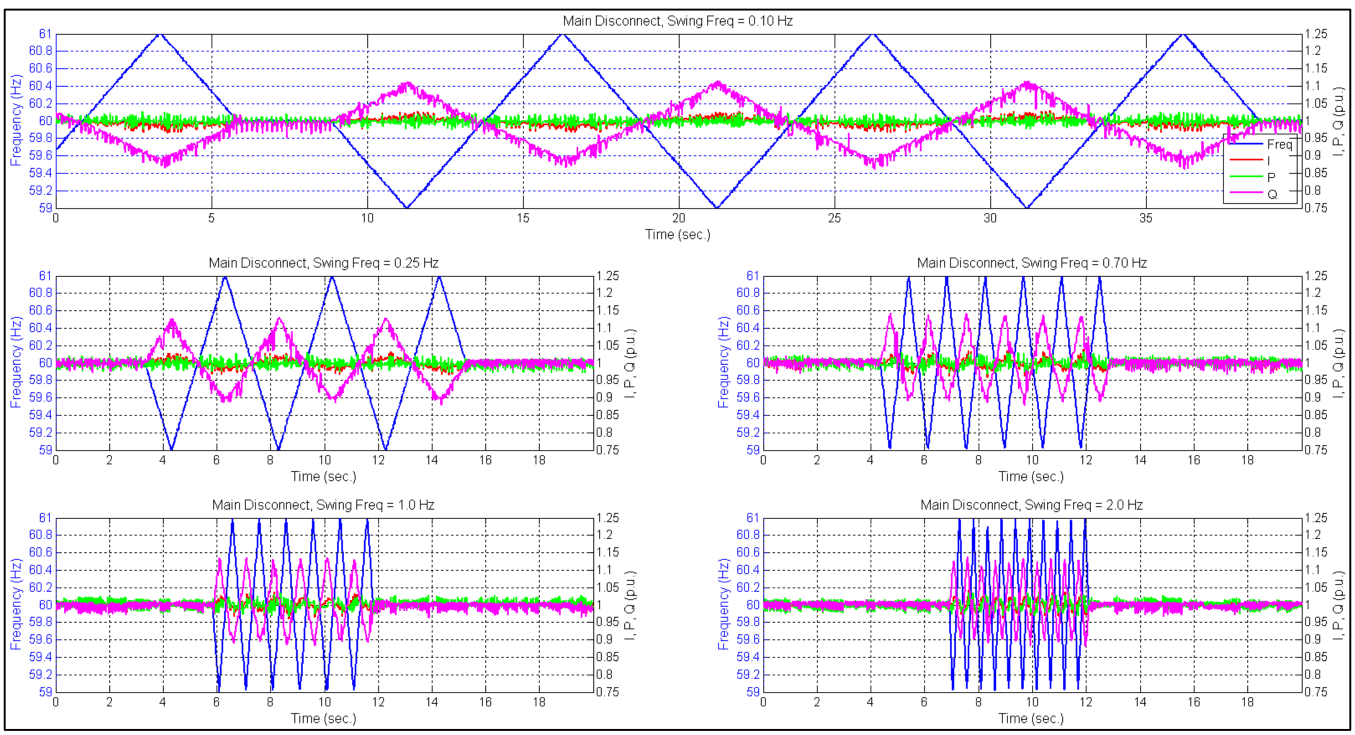

Figure 4.8.1 VFD A/C #2 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

4.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the VFD A/C unit tripped while ramping down to 50% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation (down to 60% nominal voltage).

Current ramps up to approximately 60% above nominal in response to the voltage ramp. Real power consumption decreases, deviating by 13% below steady state for the 8 second ramp test and below by 16% for the 2 second ramp test. Reactive power increases during the voltage ramp, up to 14% above steady state for the 8 second ramp test and 24% above steady state for the 2 second ramp test.

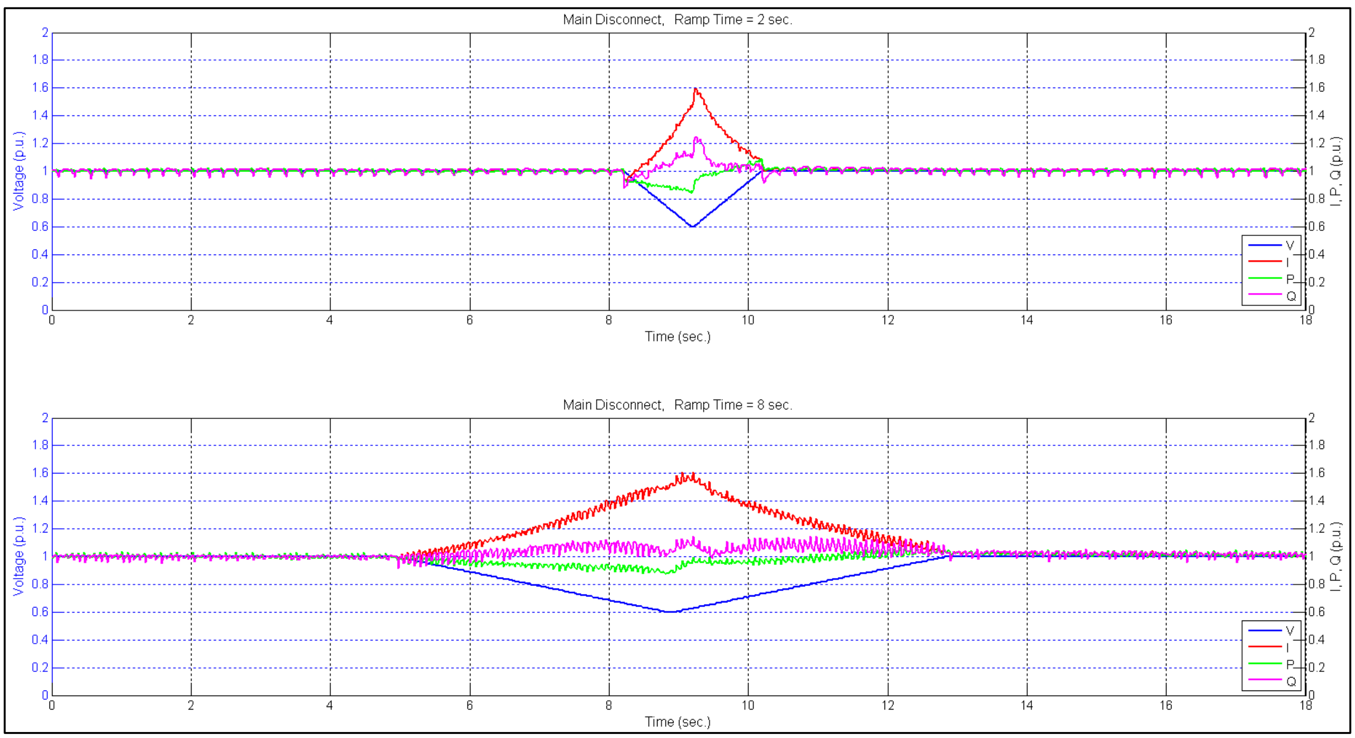

Figure 4.9.1 VFD A/C #2 Voltage Ramp Down to 60% (2 & 8 sec.)

Voltage was ramped up to 110% and back down steady state voltage at different ramp rates to demonstrate the load performance while operating at over-voltage values.

Current is observed ramping down to nearly 10% below nominal in response to the voltage ramp. Real power consumption increases slightly, up to 4% above steady state for the 8 second ramp test and up to 6% above steady state for the 2 second ramp test. Reactive power decreases with current, deviating by 4% below nominal during the 8 second ramp test and by 9% below nominal during the 2 second ramp test.

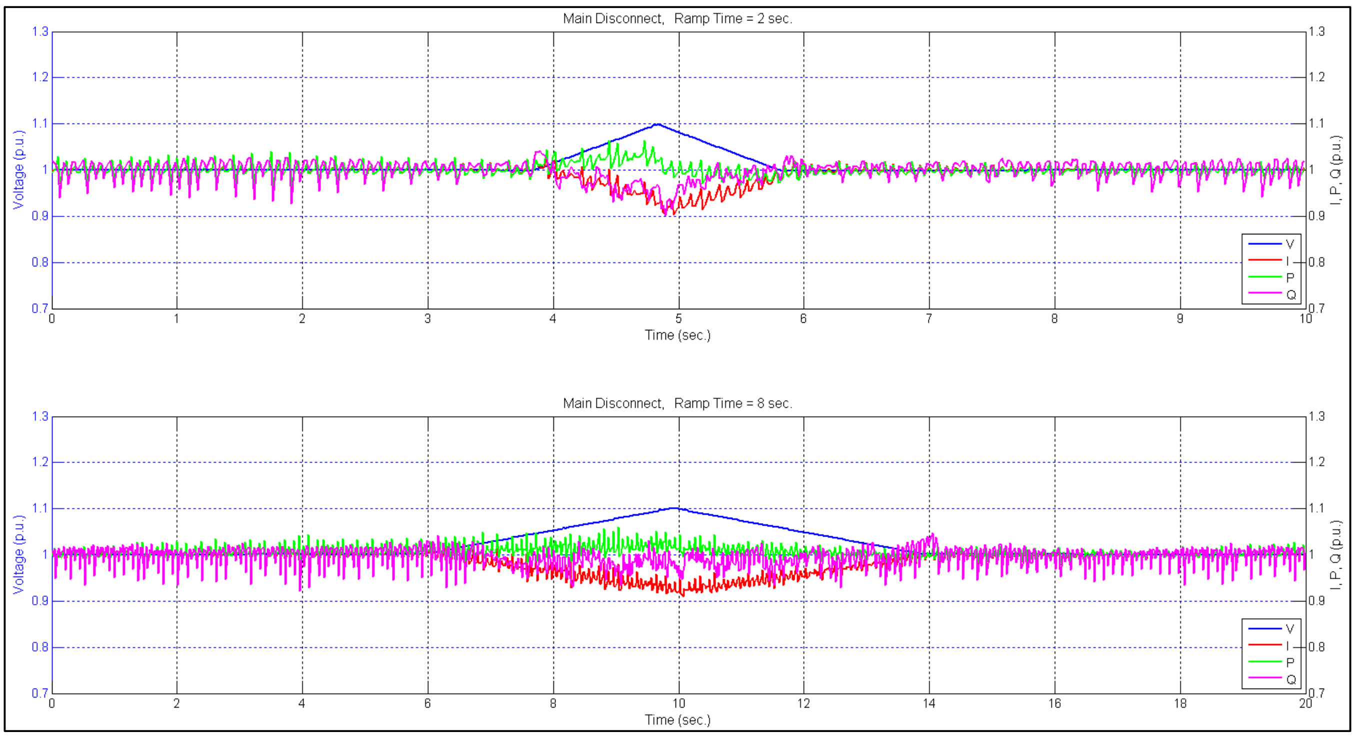

Figure 4.9.2 VFD A/C #2 Voltage Ramp Up to 110% (in 2 & 8 sec.)

4.10 Frequency Ramps

Frequency was ramped down to 50 Hz and back up to 60 Hz at different ramp rates to demonstrate the load performance while operating at lower frequency values as shown in the figure below.

The VFD does a good job maintaining constant speed on the compressor motor and holding real power consumption constant. Current slowly increases until it begins plateauing at approximately 12% above nominal as frequency falls below 54 Hz. Real power consumption remains constant throughout the entire under-frequency ramp (within ±3%). Reactive power experiences a dramatic increase as frequency begins ramping down and then the rate of change in reactive power consumption decreases at lower frequency values. Reactive power peaks at approximately 70% above nominal.

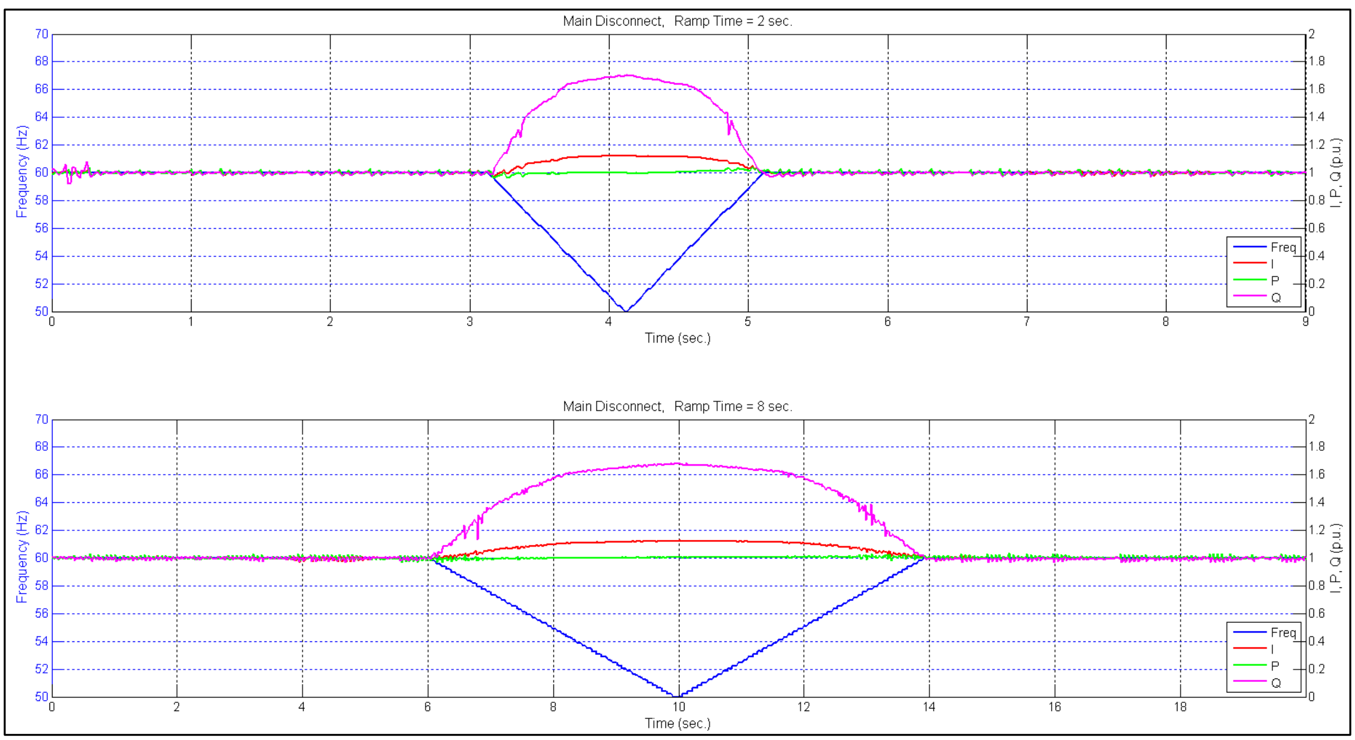

Figure 4.10.1 VFD A/C #2 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

Frequency was ramped up to 70 Hz and back down to 60 Hz at different ramp rates to demonstrate the load performance while operating at higher frequency values as shown in the figure below.

Similarly, the VFD maintains the speed and real power consumption of the compressor motor. Current and real power experience some deviation during the frequency ramp test, but remain within ±6% of their nominal values. Reactive power begins decreasing until reaching approximately 13% below nominal when the device is operating at 65 Hz. Reactive power then increases until reaching 7% below nominal at 70 Hz. Finally, the reactive power consumption follows this same behavior as frequency ramps back down to nominal.

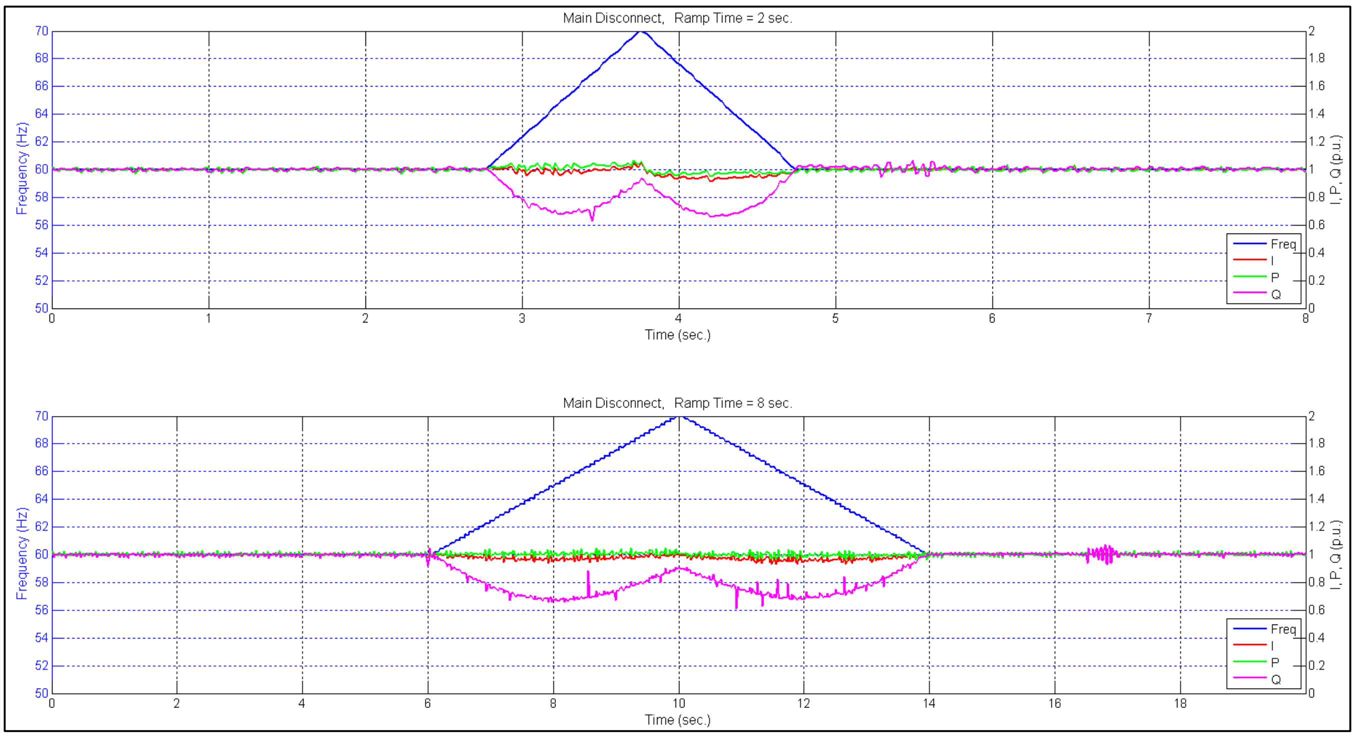

Figure 4.10.2 VFD A/C #2 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

4.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times without scope filters to calculate the actual harmonic contribution of VFD A/C unit #2 to the grid. The total harmonic distortion of current was significant and calculated to be just above 39% of the fundamental. The total harmonic distortion is not surprising based the distortion of current waveform seen in Figure 4.0.1. The following table gives the total harmonic distortion calculations and the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)		
	$V_{(L1-L2)}$	$I_{(L1)}$	$I_{(L2)}$
1	0.48	38.99	39.05
2	0.47	39.07	39.13
3	0.45	39.05	39.11

Table 4.11.1 VFD A/C #2 Total Harmonic Distortion

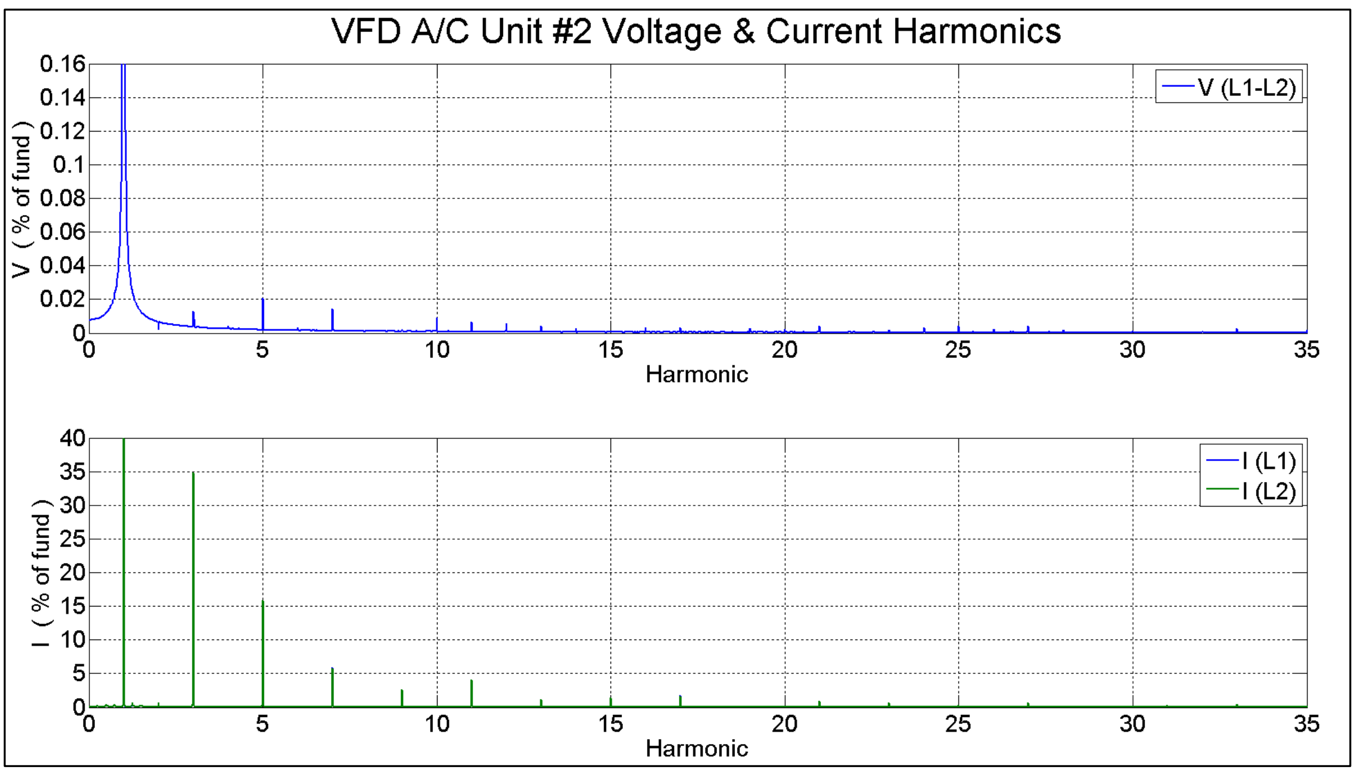

Figure 4.11.1 VFD A/C #2 Harmonics Contribution

4.12 Conservation Voltage Reduction

Voltage was decreased by 1% nominal voltage in 5 second intervals down to 90% before recovering back to steady state as shown in the figure below.

CVR will have little to no effect on real power consumption for this specific VFD A/C unit based on the following results. Current increases by approximately 1.1% of nominal current for every 1% decrease in nominal voltage. Real power remains relatively close to steady state over the course of the CVR test.

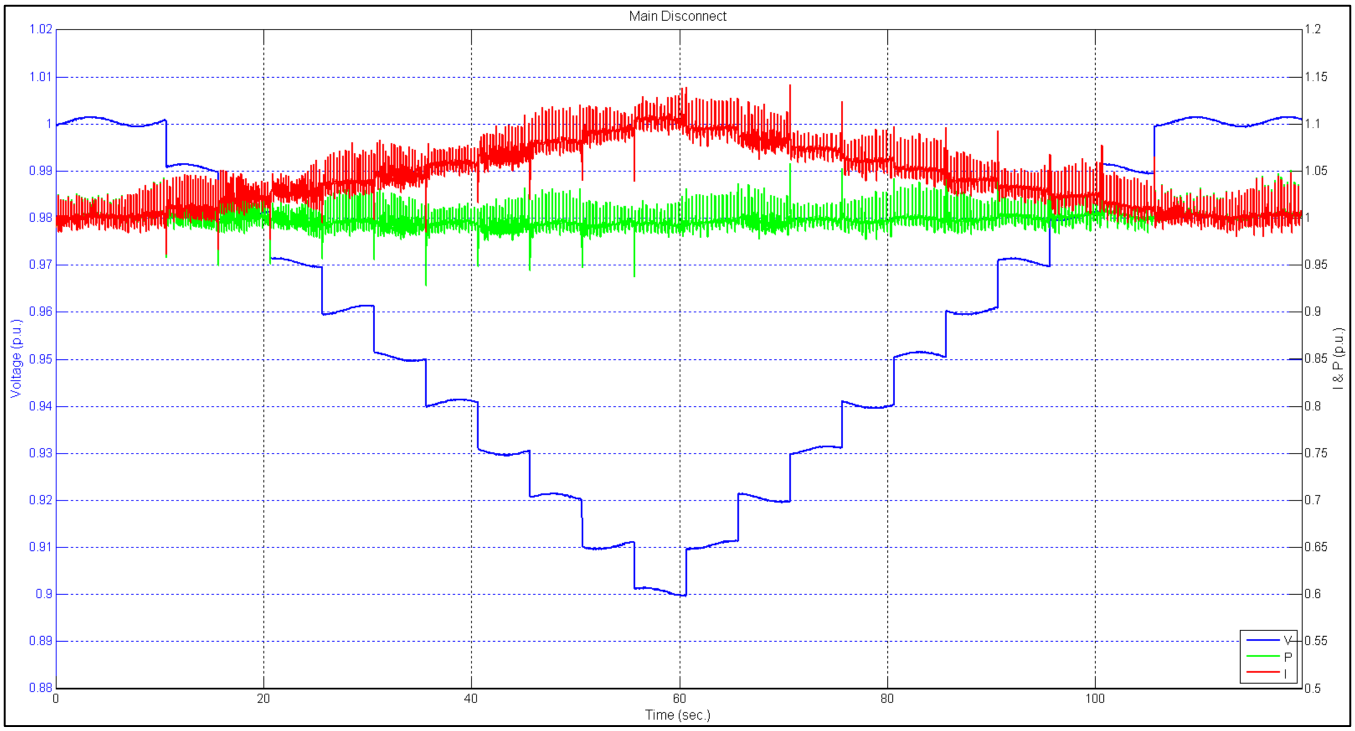

Figure 4.12.1 VFD A/C #2 CVR Response Down to 90% Voltage

Alternatively, the main terminal voltage at the VFD A/C unit was increased by 1% nominal voltage in 5 second intervals up to 105% before stepping back to steady state as shown in the figure below.

CVR does not have a significant impact on the VFD controlled load. Current decreases by approximately 0.8% of its nominal value for every 1% increase in nominal voltage. Therefore real power remains relatively close to steady state consumption.

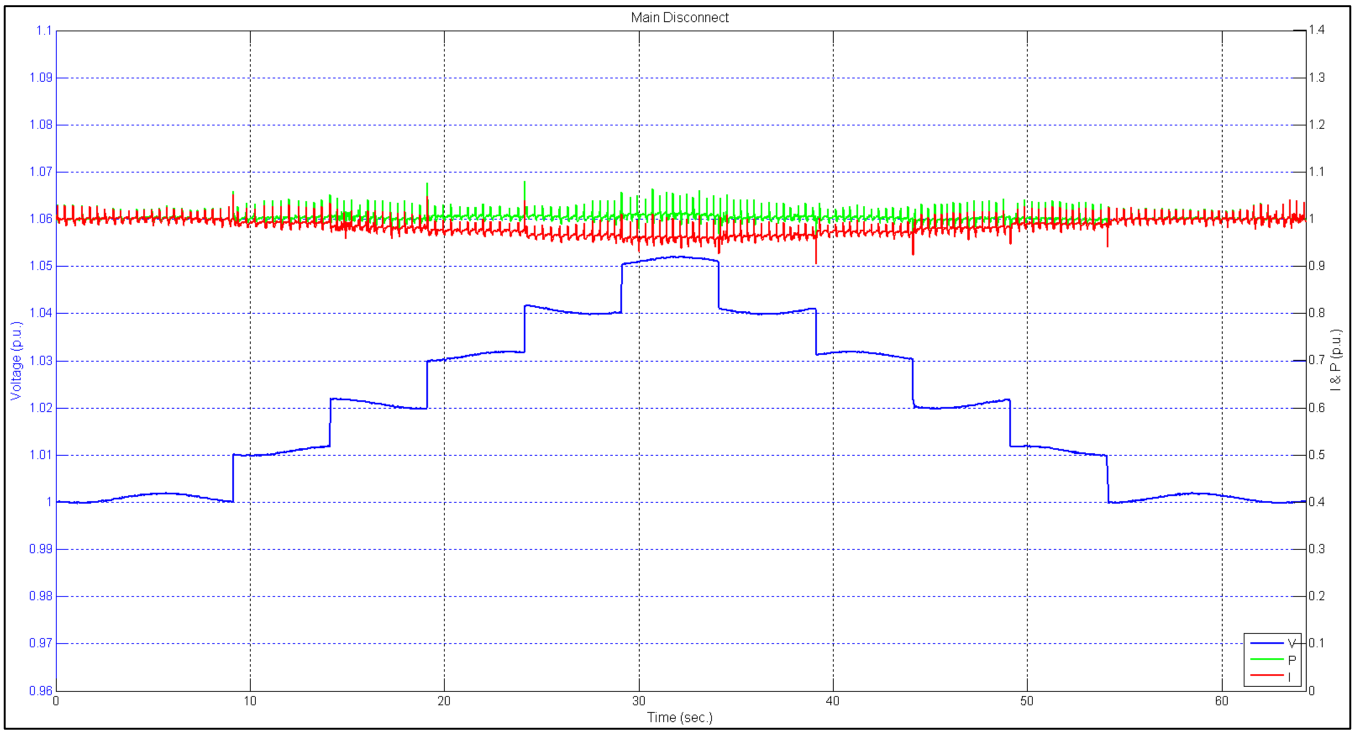

Figure 4.12.2 VFD A/C #2 CVR Response Up to 105% Voltage

5.0 VFD AIR CONDITIONER #3 TEST RESULTS

The figure below shows a snapshot of VFD A/C unit #3 sinusoidal voltages and currents captured at the main terminals and compressor motor using a filter on the digital scope. Notice the distortion in the main current waveforms compared to voltage waveforms. The compressor is shown operating at approximately 300 Volts peak, 3.8 Amps peak, and 227 Hz at the present loading condition. The specifications for the VFD A/C #3 components are provided in the table below.

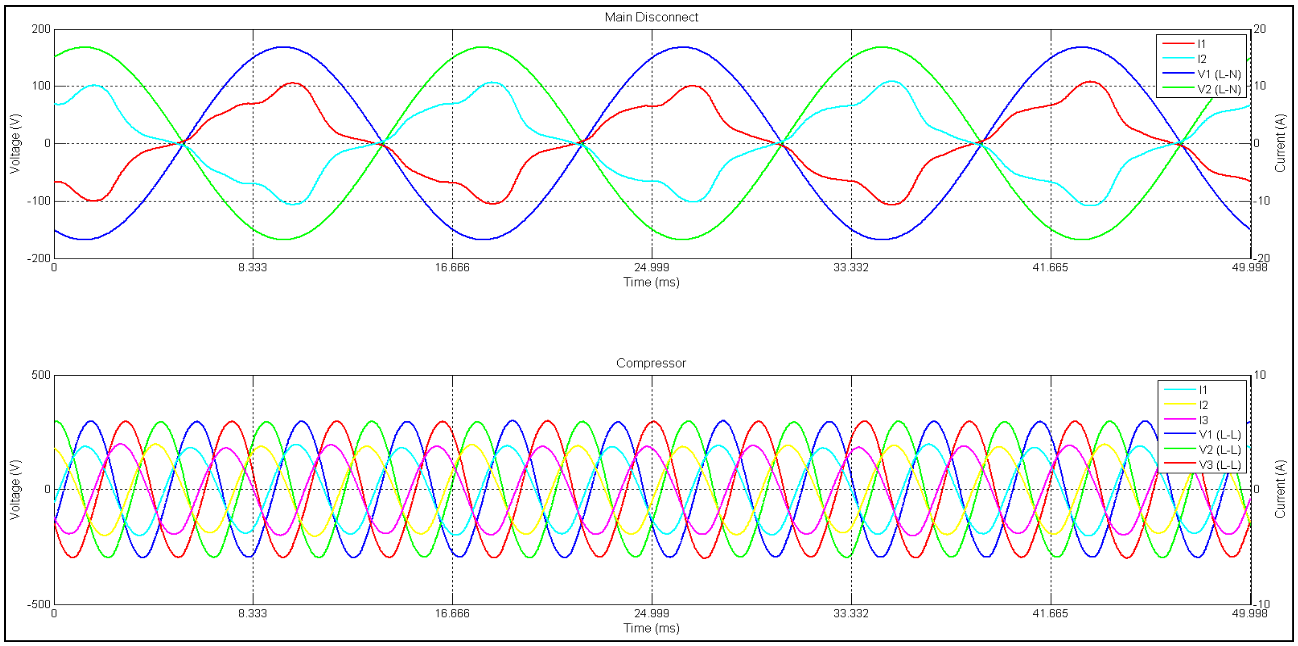

Figure 5.0.1 VFD A/C #3 Voltage and Current Waveforms

Manufacturer	Lennox
Voltage (V)	230
Refrig.	R-410A
SEER	18
Compressor, Model #	Mitsubishi SNB150FGAMC
Compressor, RLA (Amps)	11.04
Compressor, LRA (Amps)	-
Outdoor Fan Motor, FLA (Amps)	1.10
Indoor Fan Motor, FLA (Amps)	0.24
Design Pressure High (PSI)	550
Design Pressure Low (PSI)	240

Table 5.0.1 VFD A/C #3 Specifications

5.1 Compressor Shutdown

VFD A/C #3 was shut down during normal operation using the programmable thermostat remote for the indoor air handler unit. The figure below displays the measurements taken at the main terminal connections of the entire A/C unit.

The compressor and indoor fan shut down almost immediately at the same time after adjusting the thermostat. The current decreases rapidly such that the delay time is approximately 1.8 cycles. The outdoor unit fan continued operating for another 59 seconds before shutting down and the A/C unit entered standby mode. While in standby mode, the device's power consumption is approximately 0.3 Amps.

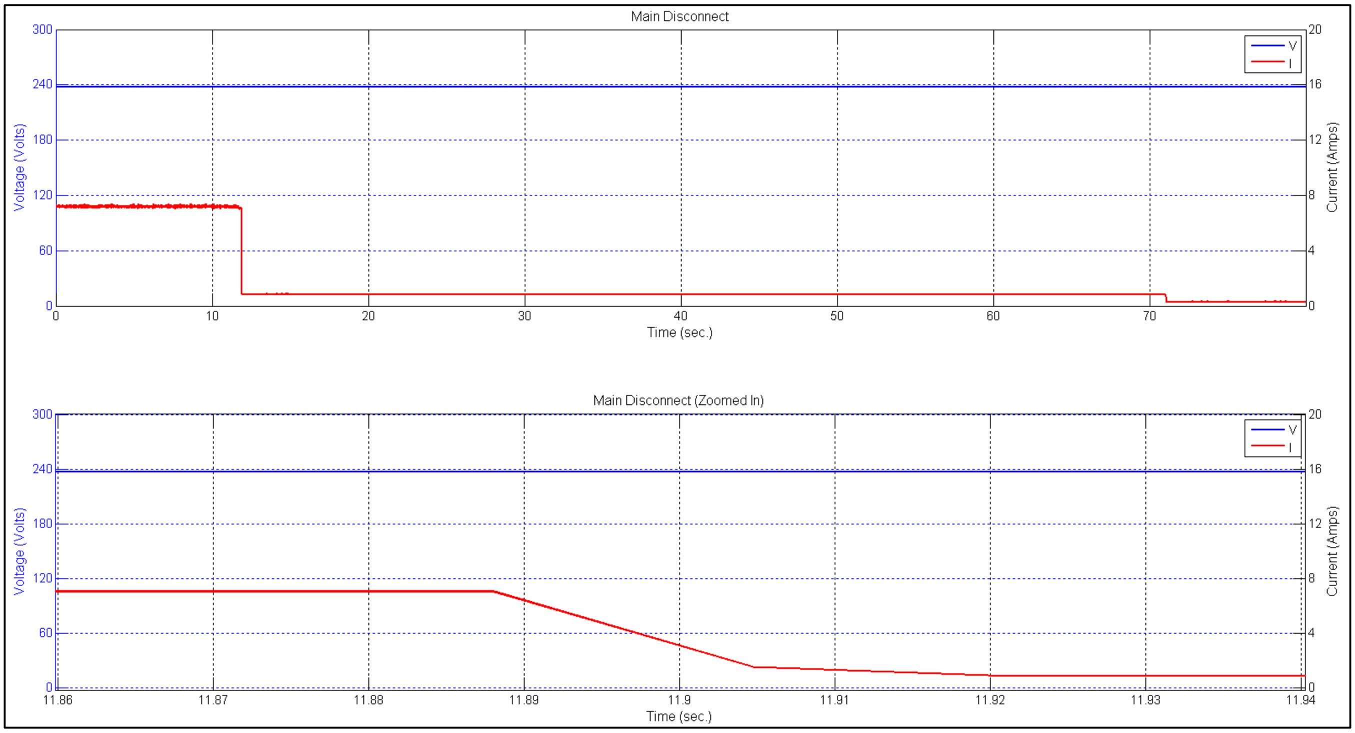

Figure 5.1.1 VFD A/C #3 Compressor Shutdown

5.2 Inrush Current

After starting up the VFD A/C unit via the programmable thermostat remote, there appears to be two successive inrush currents. The first inrush value peaks at 1.4 Amps for a duration of 3 cycles and the second peaks at 7.6 Amps before decaying over approximately 9 cycles. This is followed by the compressor slowly ramping up over the course of roughly 50 seconds until the unit is drawing 2.5 Amps. The VFD compressor will increase in intervals over the course of several minutes to meet temperature demand until the unit is more heavily loaded. The room temperature was approximately 77 degrees Fahrenheit and the unit would typically operate near 6 to 7.1 Amps steady state.

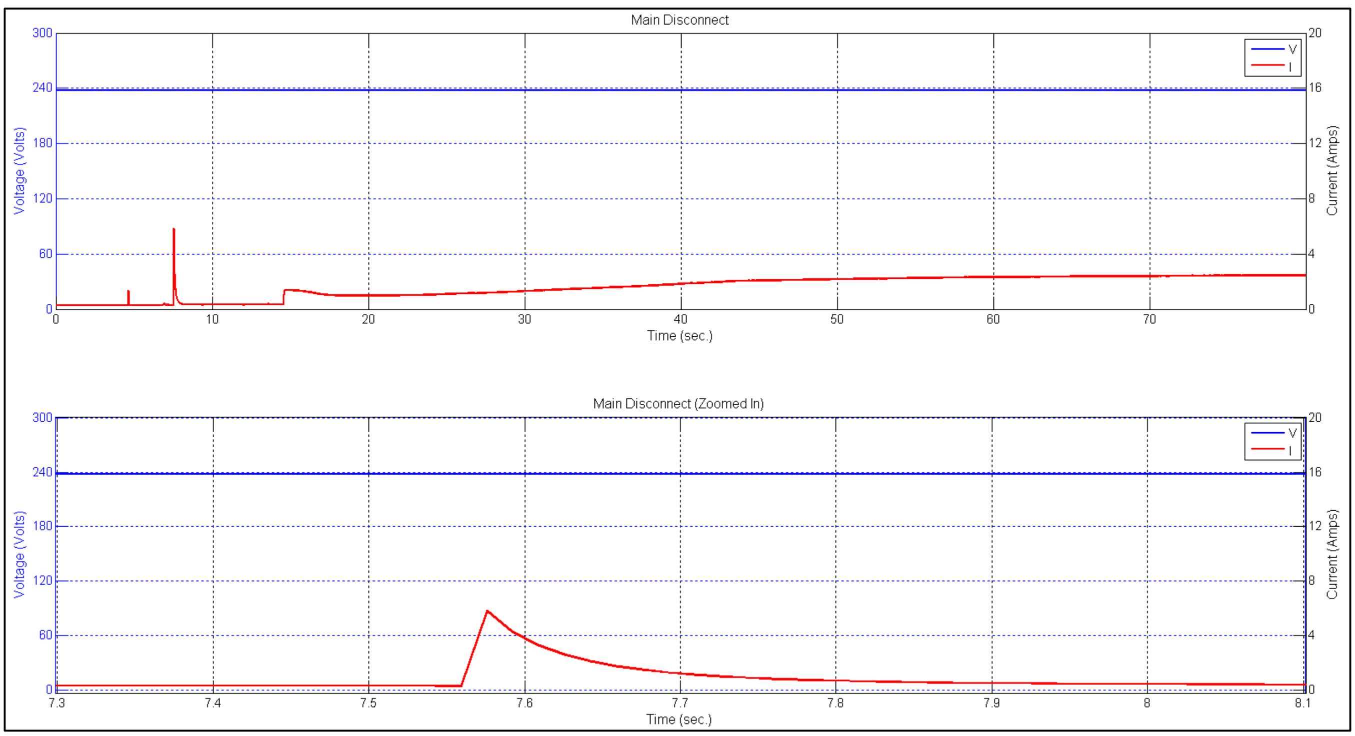

Figure 5.2.1 VFD A/C #3 Inrush Current

5.3 Balanced & Unbalanced Under-voltages

After performing under-voltages on VFD A/C #3 in decrements of 10%, the compressor is observed typically disconnecting at either 50% or 60% nominal voltage for voltage sags with a duration of 6 to 130 cycles. The 3 cycle tests were not as consistent as others displaying tripping behavior at various voltage magnitudes and the 1 cycle tests were much more consistent, resulting in tripping at 30% nominal voltage.

As shown in Table 5.3.1 every time the compressor was disconnected, it occurred as voltage was recovering from a sag or up to 1.2 cycles after voltage already recovered. A theory is that this tripping behavior may be caused by increasing inrush currents observed at the end of each voltage sag. Another, less likely, possibility is that the logic in the controller PCB is preventing load disconnection until voltage returns to nominal. None of the voltage sags resulted in voltage ride through for all magnitudes down to 0% voltage and no stalling behavior was observed during any of these tests.

Data captured several seconds after the disconnection of the compressors did not reveal restarting behavior and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor would only restart several minutes after tripping occurred.

The following figure visually displays one of these balanced tests where the under-voltage sags have a duration time of 130 cycles. The compressor is observed being disconnected immediately after voltage recovers from a 50% voltage sag. The following table provides additional details regarding the compressor operation during the various balanced under-voltage transient tests including the voltage where the unit was tripped (V_{trip}) as well as the time it took for the unit controls to trip it offline (t_{trip}), measuring from the start of the voltage sag.

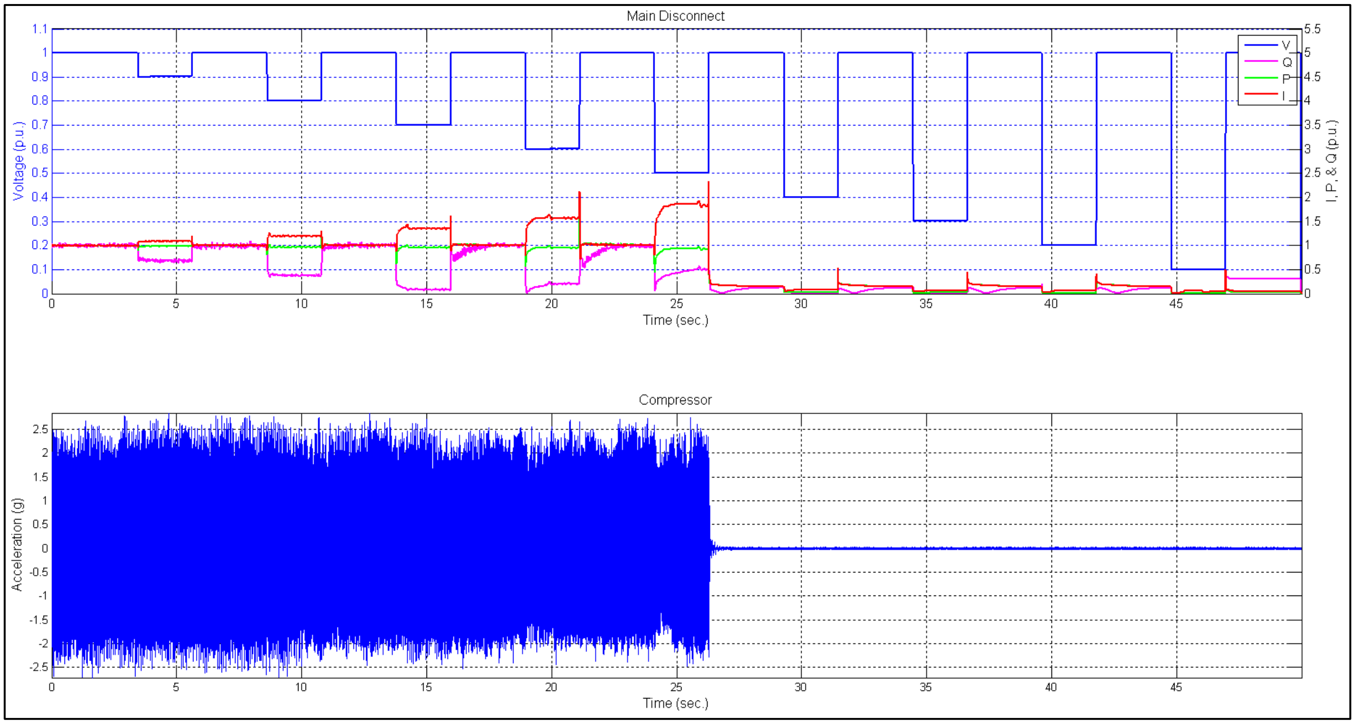

Figure 5.3.1 VFD A/C #3 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	50%	130.8
		50%	130.8
		50%	130.8
100%, 90%, 80%,... 0%	12	60%	13.2
		50%	13.2
		50%	13.2
100%, 90%, 80%,... 0%	9	60%	10.2
		50%	9
		60%	9.6
100%, 90%, 80%,... 0%	6	50%	7.2
		60%	6.6
		60%	6.8
100%, 90%, 80%,... 0%	3	60%	3.2
		40%	3.6
		50%	4
100%, 90%, 80%,... 0%	1	30%	1.8
		30%	1.8
		30%	1.8

Table 5.3.1 VFD A/C #3 Balanced Under-voltages in 10% Decrements Results

Identifying the specific voltage where the compressors are disconnected and/or the controls dropped out requires additional balanced under-voltage tests in decrements of 1% nominal voltage. Several tests with duration times from 3 to 130 cycles revealed that the compressor could begin tripping off for voltage sags between 59% and 58% nominal voltage and again occurred after voltage already recovered, likely due to the inrush current at the end of the voltage sag or possibly the logic of the controller PCB on the outdoor unit. Switching transients (represented using 1 cycle) showed tripping at 23% nominal voltage after voltage recovers. The following table provides the details of the compressor disconnection behavior during each of these 1% voltage decrement tests.

Under-Voltage Transient		**Compressor**	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
60%, 59%, 58%, …	130	58%	130.8
60%, 59%, 58%, …	12	58%	12.6
60%, 59%, 58%, …	3	59%	4.2
60%, 59%, 58%, …	1	23%	1.8

Table 5.3.2 VFD A/C #3 Balanced Under-voltages in 1% Decrements Results

Unlike other units, VFD A/C #3 compressor trip voltages and trip times for unbalanced under-voltage tests were not as consistent with their balanced under-voltage counterparts. There are several cases where the unit trips off at either 20% or 0% line-to-neutral on one line, which means the line-to-line values are 60% or 50% nominal voltage which is where tripping occurred for balanced conditions. However there are other cases where the unit appears more sensitive to tripping at slightly higher voltages (30% line-to-neutral or 65% line-to-line nominal voltage). The switching transients or 1 cycle voltage sags, rode through all unbalanced under-voltages as expected since the lowest voltage magnitude possible is 50% line-to-line nominal voltage during these unbalanced tests.

The following figure shows an example of these unbalanced cases (Line 2 under-voltages for 130 cycles) where the compressor shut down at 30% line-to-neutral nominal voltage just as the voltage sag is recovering. The following table provides the compressor disconnection behavior during unbalanced voltage transients observed at the main terminals of the VFD A/C unit. Similar to the balanced under-voltage tests, unbalanced voltage tests also result in the compressor disconnecting at the very end of the voltage sag or up to 1.8 cycles after voltage has already recovered to steady state.

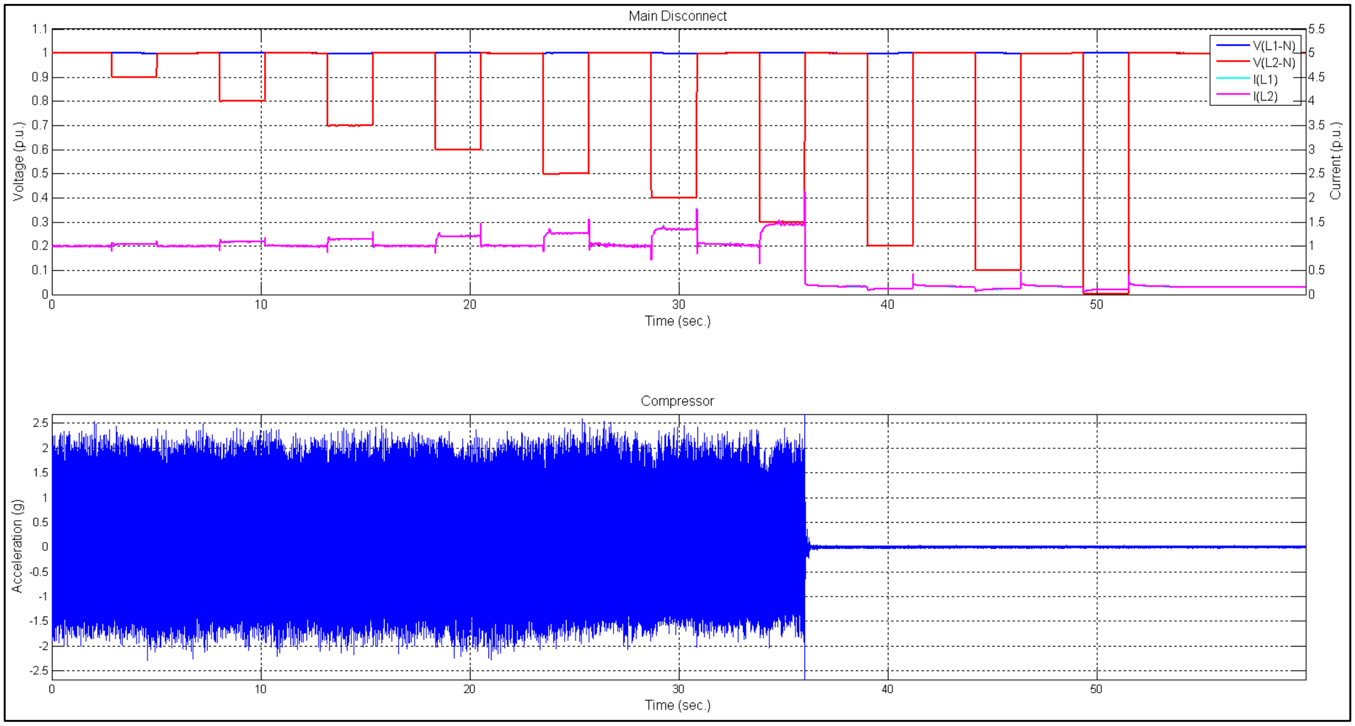

Figure 5.3.2 VFD A/C #3 Unbalanced Under-voltage Response (Line 2, 130 cycles)

Under-Voltage Transient			Compressor		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1	100%, 90%, 80%,... 0%	130	30%	65%	131.8
		12	0%	50%	13.2
		6	20%	60%	6.6
		3	30%	65%	4.2
		1	N/A	N/A	N/A
L2	100%, 90%, 80%,... 0%	130	30%	65%	129.6
		12	20%	60%	13.2
		6	30%	65%	7.2
		3	0%	50%	4.2
		1	N/A	N/A	N/A

Table 5.3.3 VFD A/C #3 Unbalanced Under-voltage Results

5.4 Balanced & Unbalanced Over-voltages

VFD A/C #3 was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve. These included multiple voltage swells performed in 2% increments for up to 120% nominal voltage to identify any tripping behavior. During balanced conditions, the VFD A/C unit tripped at 112% nominal voltage in the first 1.2 cycles of the voltage swell and tripped at 118% nominal voltage after 0.6 cycles of the voltage swell. However the unit did ride through all of the unbalanced over-voltage transients while operating normally.

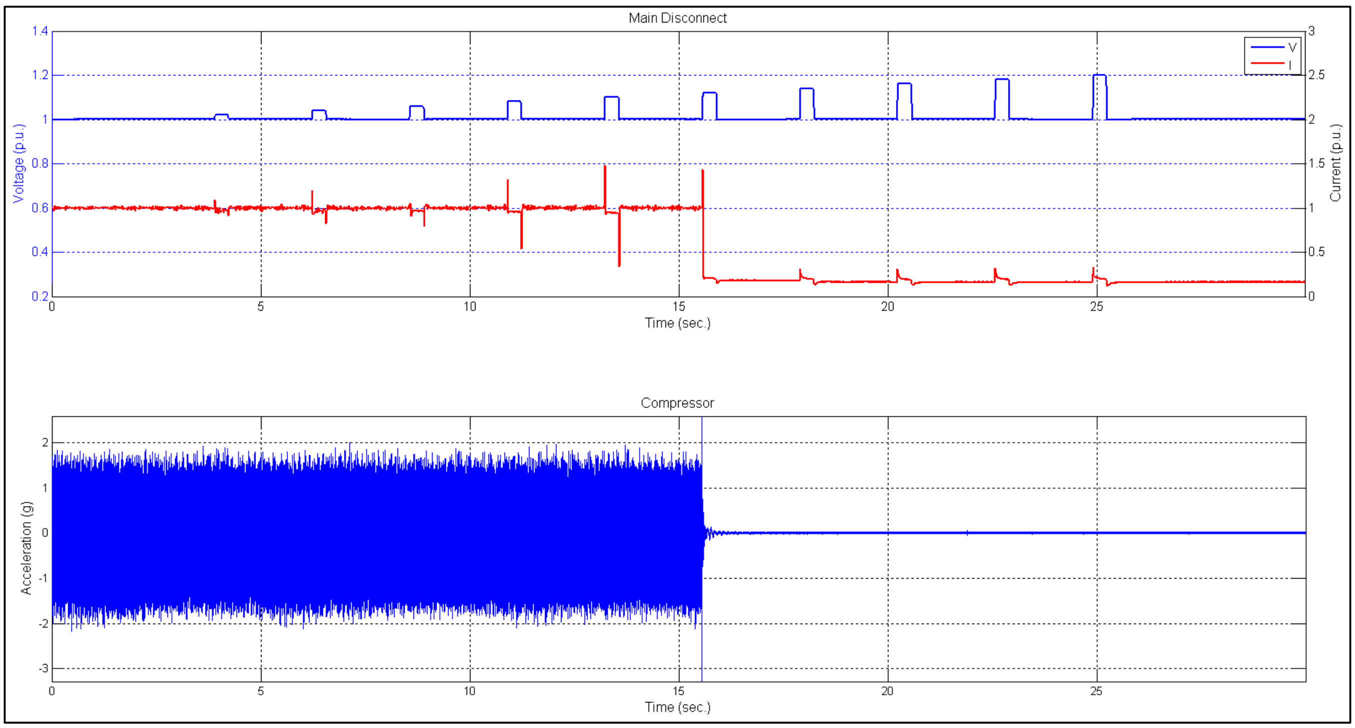

Figure 5.4.1 VFD AC #3 Balanced Over-voltage Response (20 cycles)

Lines	Volt Range	Duration (cyc)	$V_{trip\ L\text{-}N}$ (%)	$V_{trip\ L1\text{-}L2}$ (%)	t_{trip} (cyc)
L1 & L2	100%, 102%, 104%,... 120%	20	112%	112%	1.2
		3	112%	112%	1.2
		1	118%	118%	0.6
L1	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A

Table 5.4.1 VFD A/C #3 Balanced & Unbalanced Over-voltage Results

5.5 Voltage Oscillations

The following figure shows the performance of VFD A/C #3 during voltage oscillations between 100% and 90% nominal voltage for a variety of swing frequencies or oscillation rates.

Current oscillates in the opposite direction of voltage, up to 10% above nominal, to minimize any oscillations or deviations in real power. The consumption of real power remains relatively constant, within 3% of nominal, due the rapid change in current and the VFD drive is attempting to keep the motor speed constant. This near constant power response holds true for all voltage oscillations from 0.25 Hz to 2 Hz.

Reactive power consumption is very low since the power factor is greater than 0.99 for the device. Therefore any minor change in reactive load, even during steady state, results in drastic changes to the per unit values. As a result, reactive power was not included in the figure below.

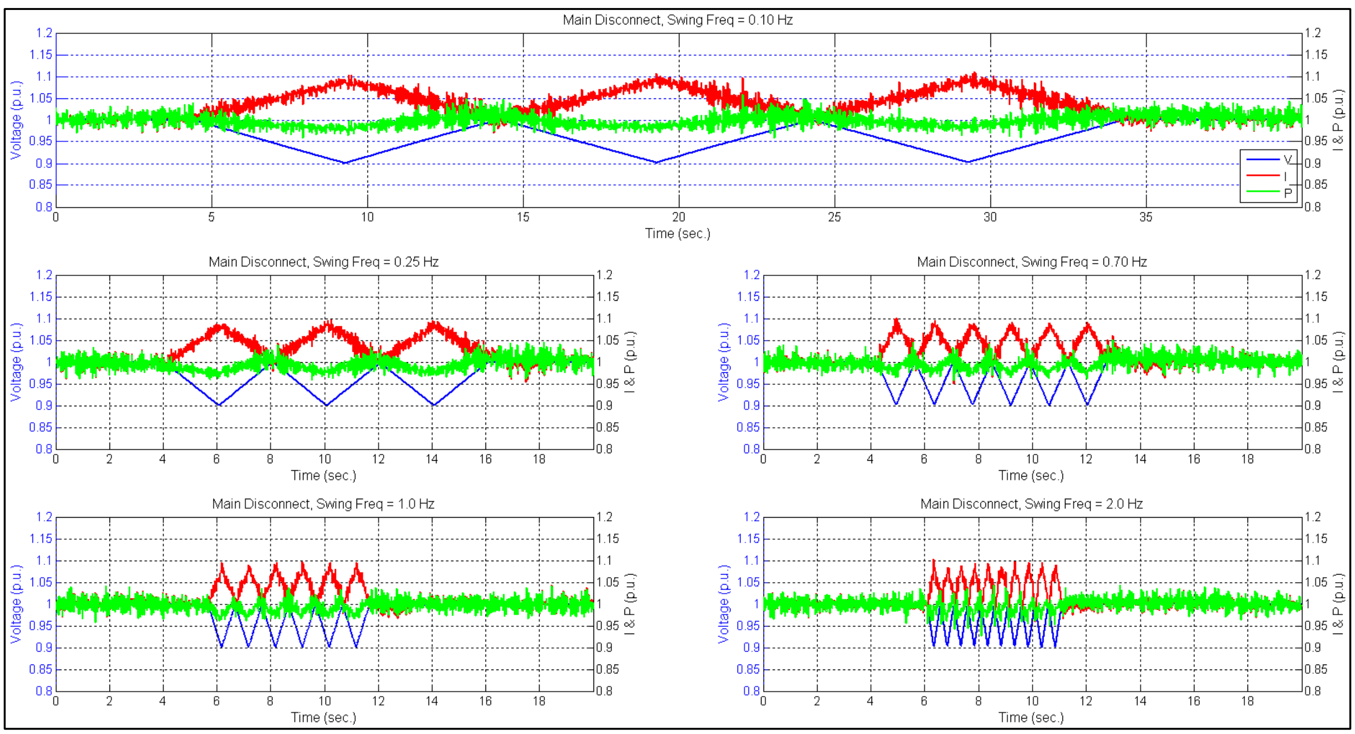

Figure 5.5.1 VFD AC #3 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

5.6 Under-frequency Events

After subjecting VFD A/C #3 to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection while operating between 60 Hz and 58 Hz. The device simply rides through these under-frequency conditions. Current remains constant suggesting that the VFD is keeping the motor frequency constant. The following figure and table identify the magnitude and duration of the frequency transient tests that were performed.

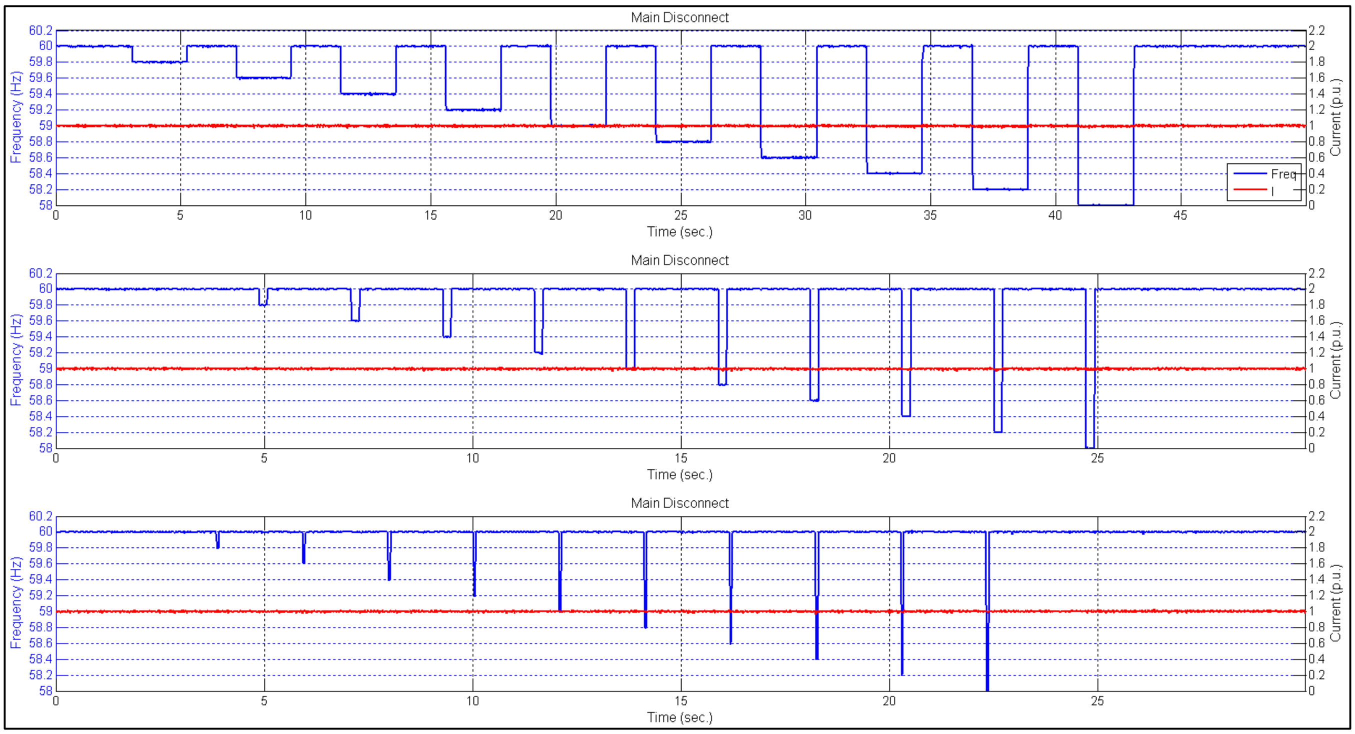

Figure 5.6.1 VFD A/C #3 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		**Compressor**	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 5.6.1 VFD A/C #3 Under-frequency Test Results

5.7 Over-frequency Events

Similar to the under-frequency tests, VFD A/C #3 was subjected to over-frequency transients to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The compressor motor frequency remains constant from the VFD despite changes in frequency at the unit's main terminals. The following figure and table identify the magnitude and duration of the specific over-frequency tests that were performed.

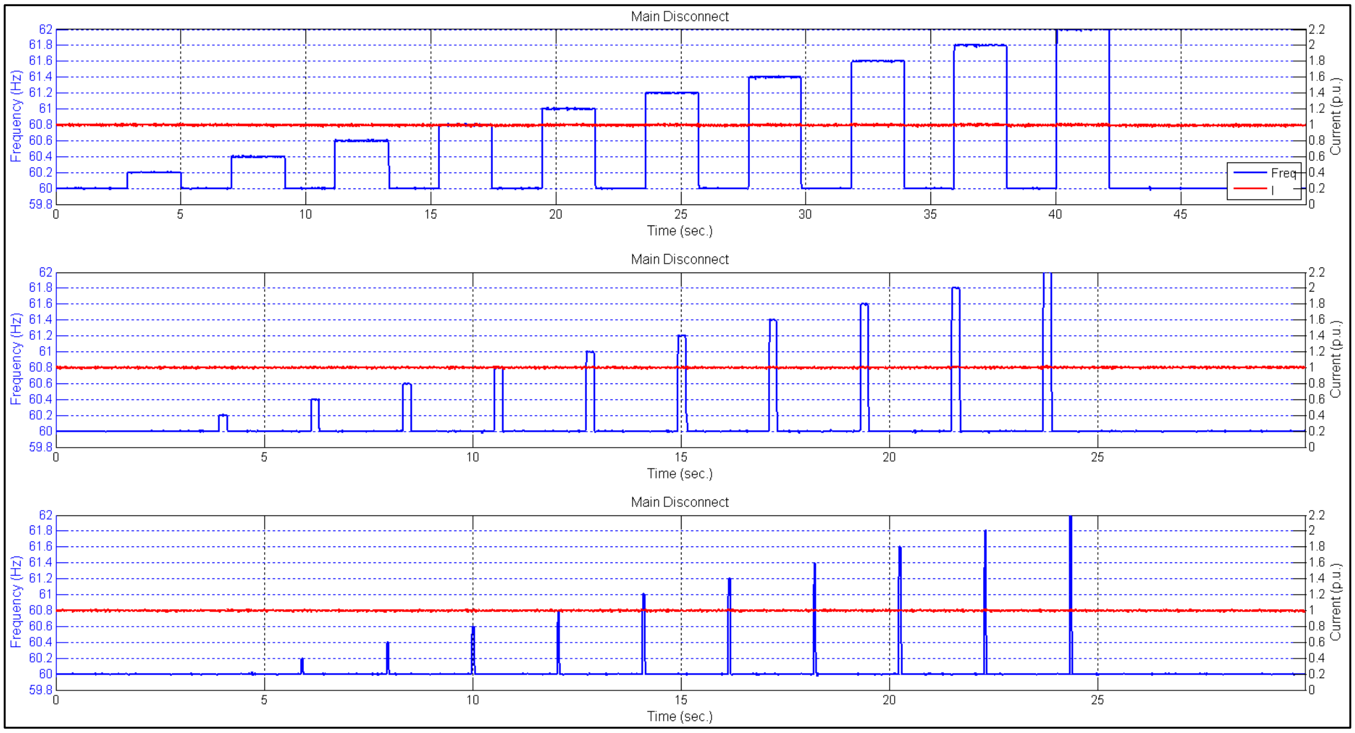

Figure 5.7.1 VFD A/C #3 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 5.7.1 VFD A/C #3 Over-frequency Test Results

5.8 Frequency Oscillations

The following figure shows the performance of VFD A/C #3 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates (0.10, 0.25, 0.70, 1.0, and 2.0 Hz).

The response of the load suggests that the VFD is effectively maintaining frequency at the compressor motor. The main current does not oscillate or deviate in response to frequency oscillations at the main terminals of the A/C unit. The active power consumption remains constant, within <u>+</u>1% of its steady state value along with current for all swing frequencies.

Reactive power was not included in the figure below because of its low consumption (power factor is greater than 0.99). Even minor deviations that naturally occur during steady state result in harsh changes to the per unit values plotted.

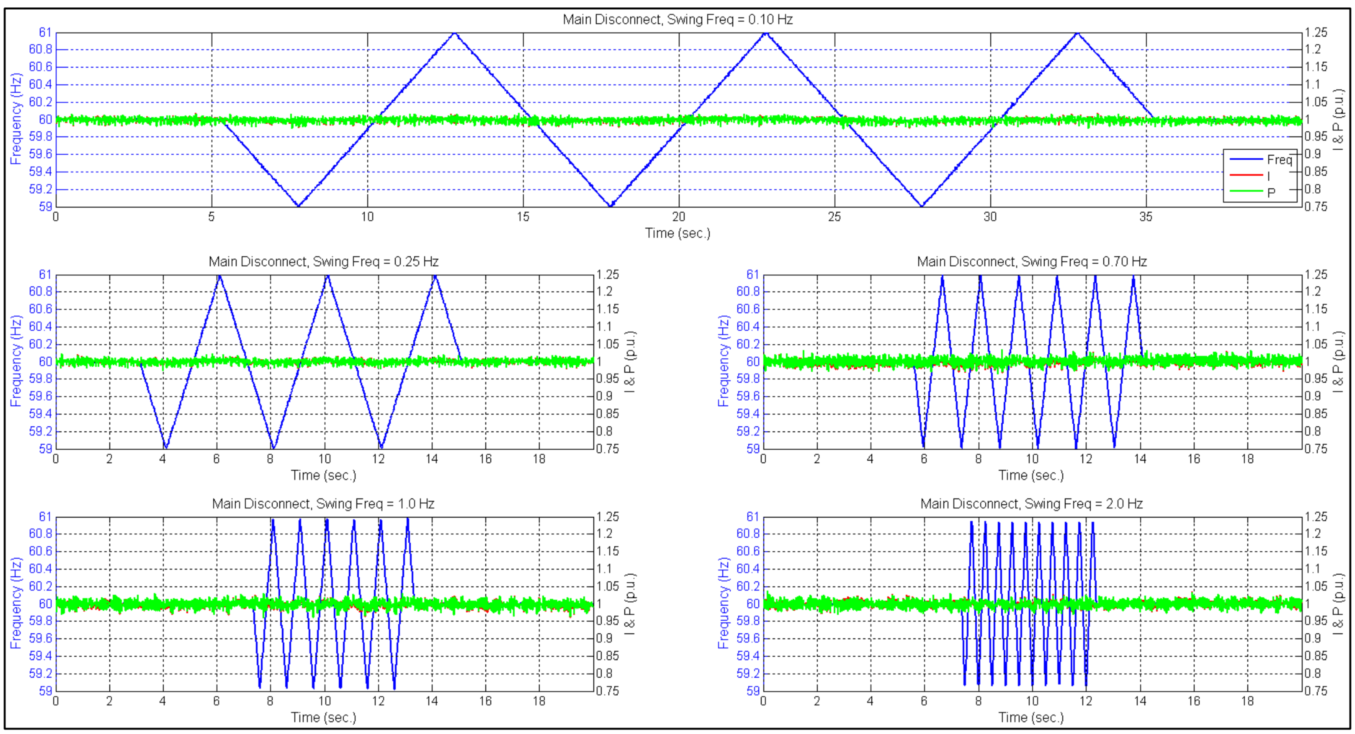

Figure 5.8.1 VFD A/C #3 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

5.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit tripped while ramping down to 50% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation (down to 60% nominal voltage).

The VFD is attempting to maintain a constant speed at the compressor motor. Current ramps up to approximately 53% above nominal while voltage ramps down to 40% below nominal. Real power consumption is steadily reduced to as low as 8% below nominal for both ramp tests. Reactive power consumption is low due to the large power factor, but it ramps down to nearly 0% of its nominal value.

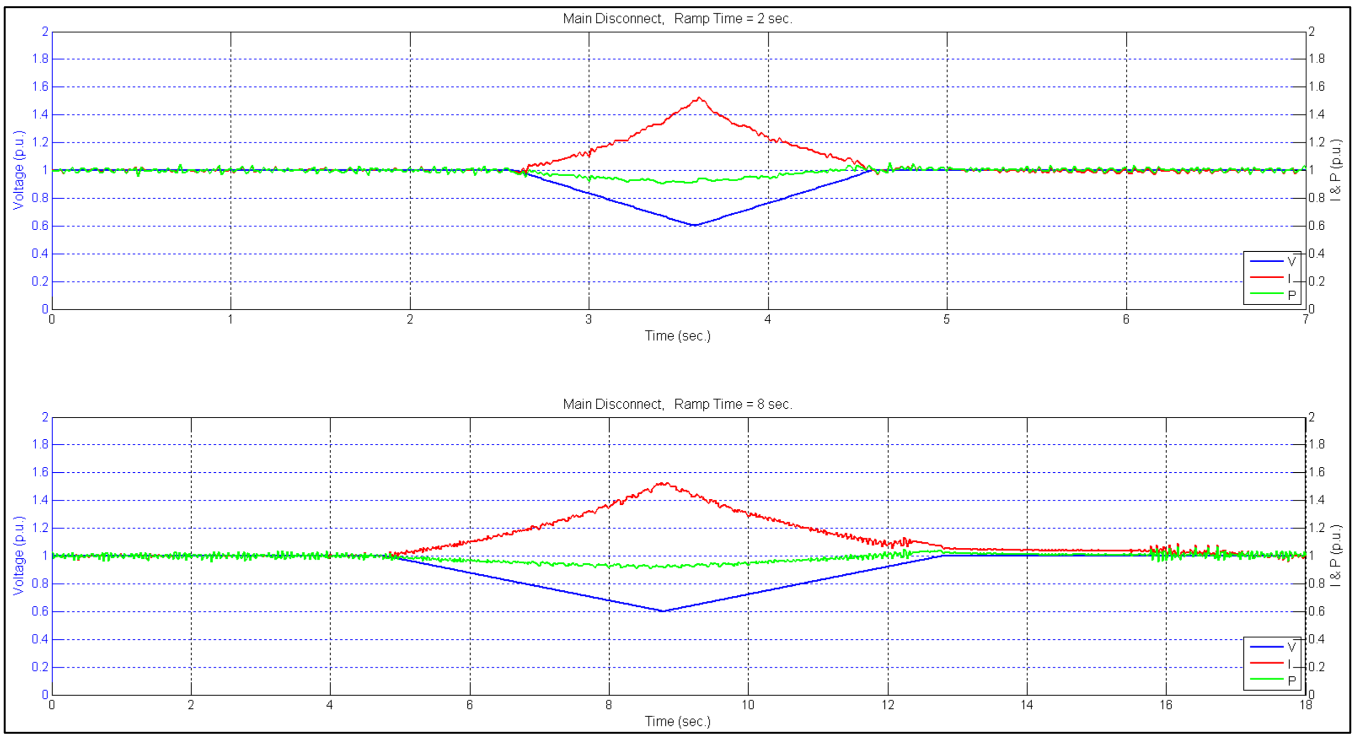

Figure 5.9.1 VFD A/C #3 Voltage Ramp Down to 60% (2 & 8 sec.)

Voltage was ramped up to 110% and back down steady state voltage at different ramp rates to demonstrate the load performance while operating at over-voltage values.

Current and real power appear to oscillate during this test due the changing shape of the current sinusoidal waveform towards the peak of the voltage ramp. Current is slowly reduced down to nearly 6% below nominal for the 2 second ramp test and 8% below nominal for the 8 second ramp test in response to voltage. Real power consumption steadily increases to approximately 5% above steady state. Little reactive power is consumed during normal operation and therefore was not plotted.

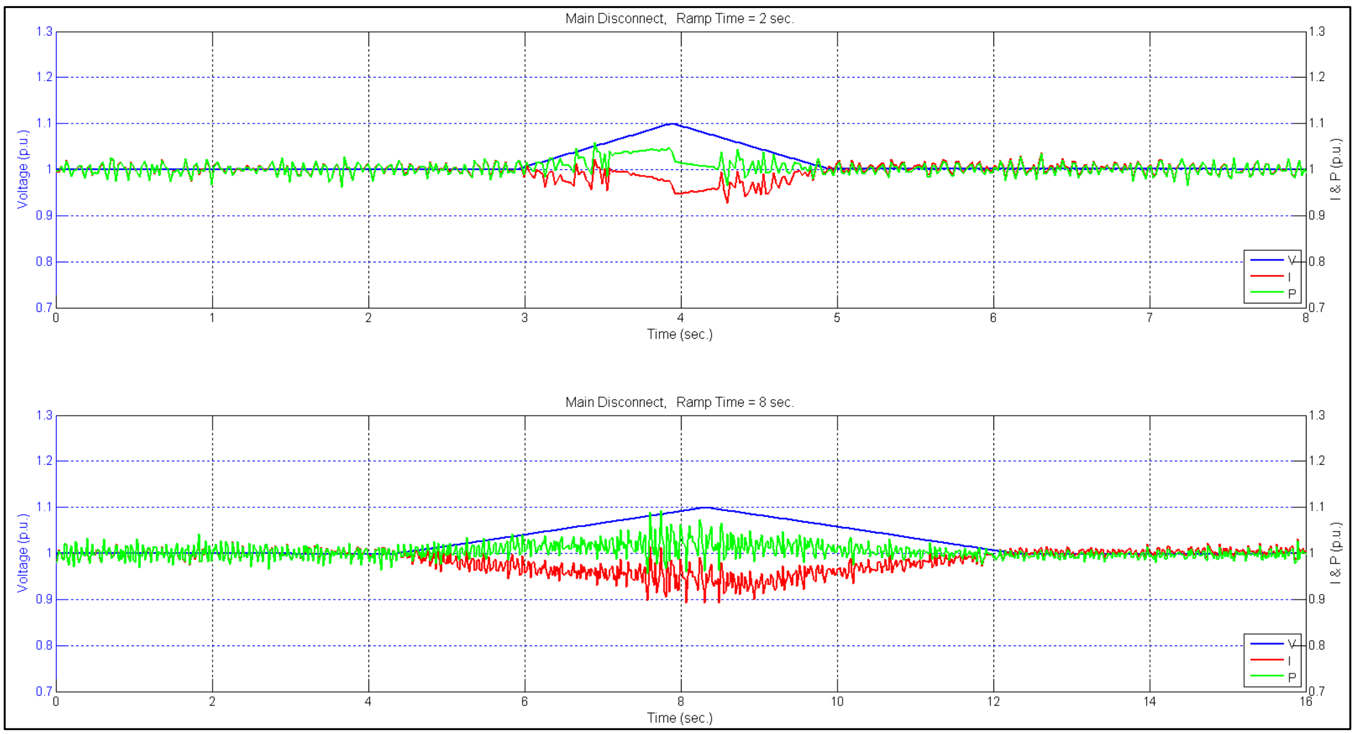

Figure 5.9.2 VFD A/C #3 Voltage Ramp Up to 110% (in 2 & 8 sec.)

5.10 Frequency Ramps

Frequency was ramped down to 50 Hz and back up to 60 Hz at different ramp rates to demonstrate the load performance while operating at lower frequency values as shown in the figure below.

Current and real power remain relatively constant throughout the entire under-frequency ramp, but there is a slight reduction in consumption by approximately 4% of nominal. Overall, the VFD helps the compressor motor maintain frequency and constant current. Reactive power does not follow a linear response in relation to frequency, but does deviate as low as 20% below steady state.

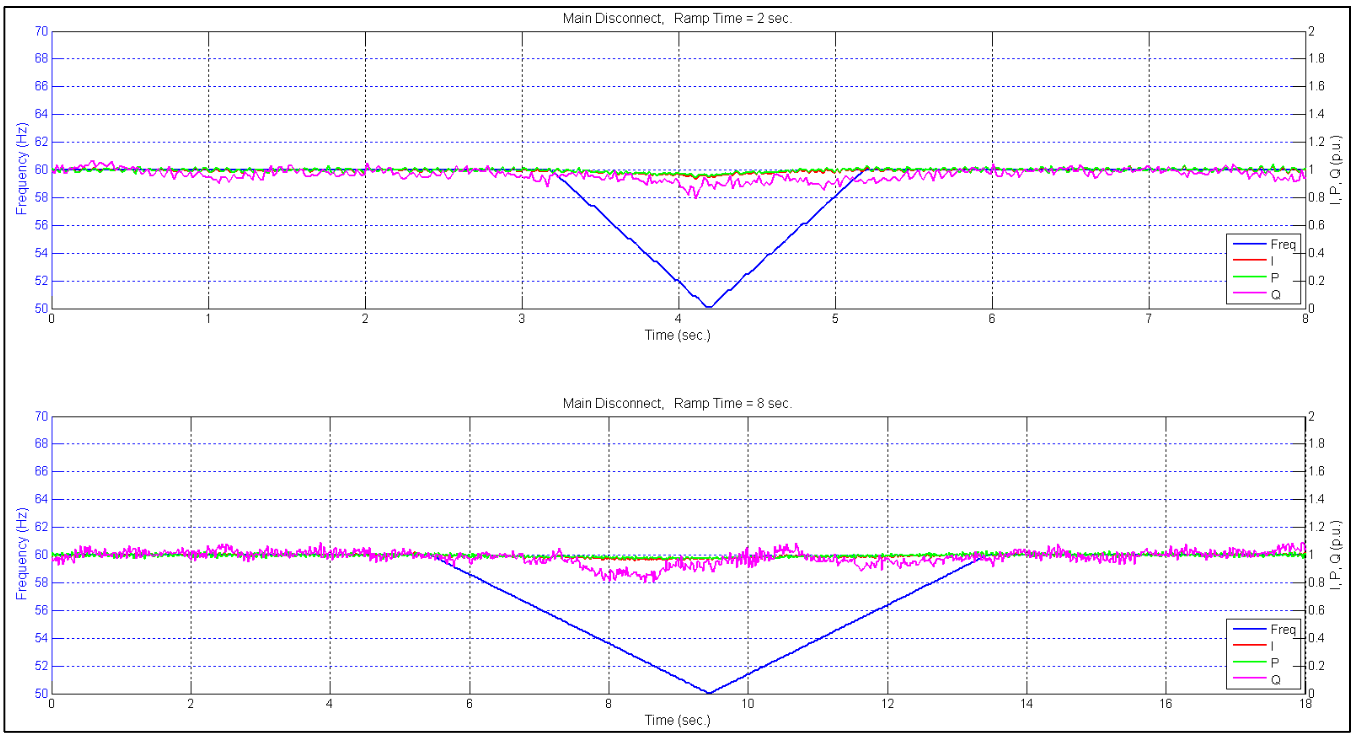

Figure 5.10.1 VFD A/C #3 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

Frequency was ramped up to 70 Hz and back down to 60 Hz at different ramp rates to demonstrate the load performance while operating at higher frequency values as shown in the figure below.

Current and real power remain relatively constant throughout the entire over-frequency ramp, but there is a slight increase in consumption by approximately 4% of nominal. Reactive power consumption for the unit is already low due to a large power factor and the response to frequency is not consistent. Reactive power is reduced by 16% below steady state during the 2 second ramp test and slightly increases to 8% above steady state during the 8 second ramp test.

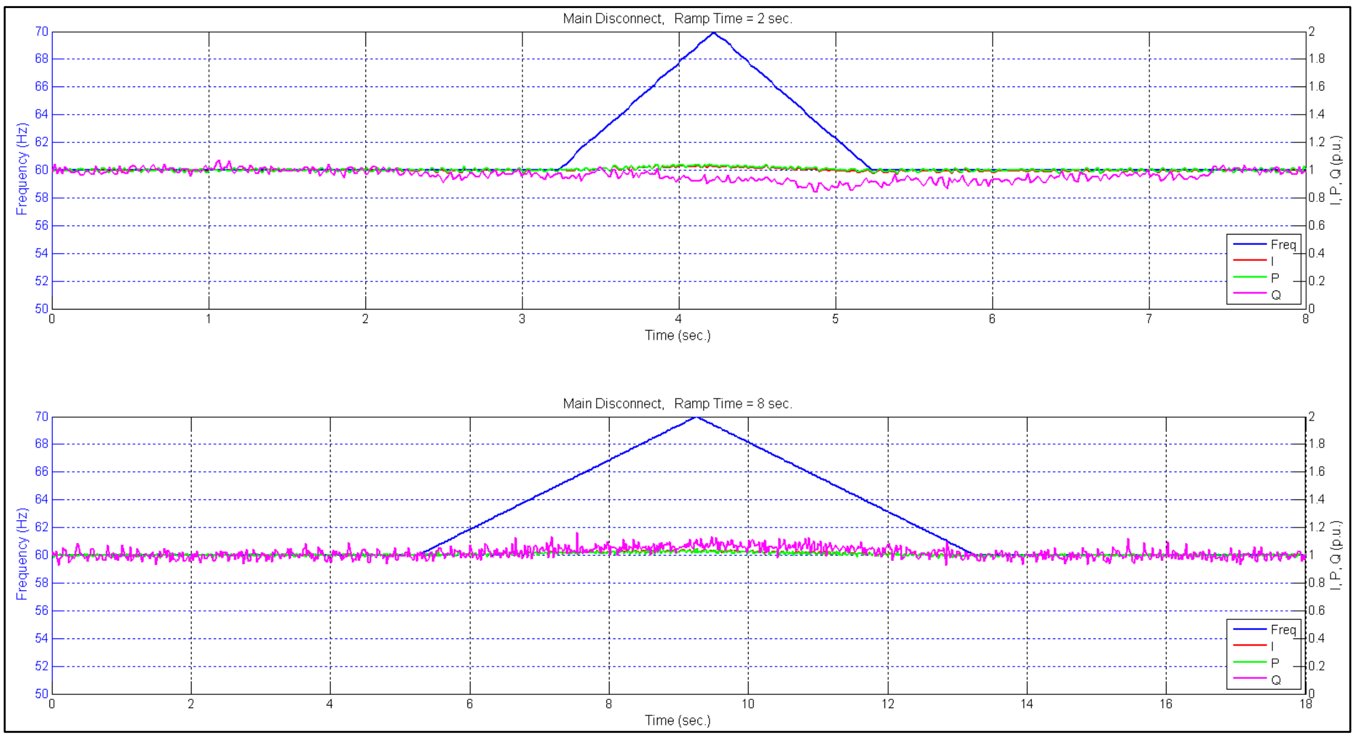

Figure 5.10.2 VFD A/C #3 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

5.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times without scope filters to calculate the actual harmonic contribution of VFD A/C unit #3 to the grid. The maximum total harmonic distortion of current was found to be just above 29.43% of the fundamental. The following table gives the total harmonic distortion calculations and the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)		
	$V_{(L1-L2)}$	$I_{(L1)}$	$I_{(L2)}$
1	0.36	27.68	27.71
2	0.37	29.40	29.43
3	0.38	28.25	28.28

Table 5.11.1 VFD A/C #3 Total Harmonic Distortion

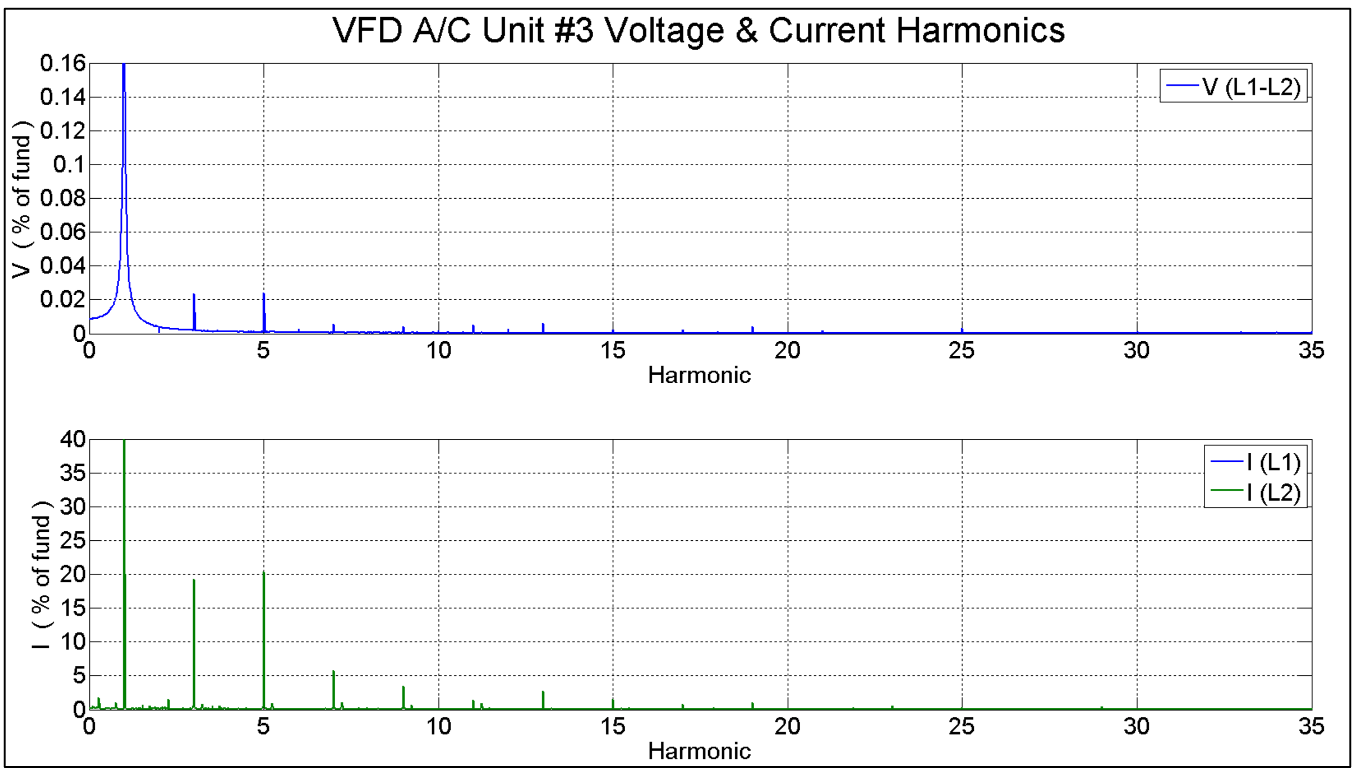

Figure 5.11.1 VFD A/C #3 Harmonics Contribution

5.12 Conservation Voltage Reduction

Voltage was decreased by 1% nominal voltage in 5 second intervals down to 90% before recovering back to steady state as shown in the figure below.

CVR would not be effective since it has little impact on the real power consumption of the VFD A/C unit. Current increases by approximately 0.9% of nominal current for every 1% decrease in nominal voltage over the course of the CVR test. This results in nearly constant real power, within ±3% of normal consumption. Reactive power decreases with voltage, but consumption is very low and difficult to plot in per unit values with the other electrical measurements.

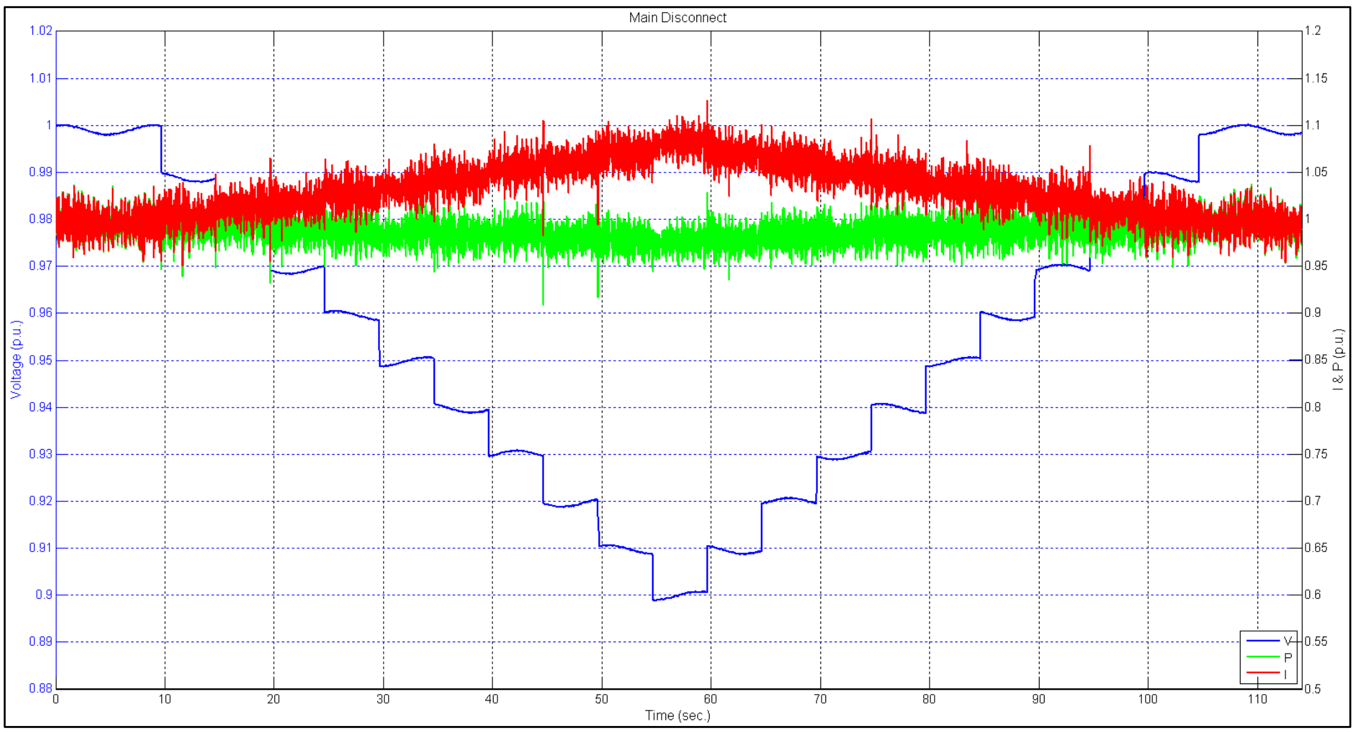

Figure 5.12.1 VFD A/C #3 CVR Response Down to 90% Voltage

Alternatively, the main terminal voltage at the VFD A/C unit was increased by 1% nominal voltage in 5 second intervals up to 105% before stepping back to steady state as shown in the figure below.

Current decreases by approximately 0.8% of its nominal value for every 1% increase in nominal voltage. Therefore real power remains near steady state consumption, with ±2% of nominal. Reactive power does increase with voltage, but again is a very low value relative to the other measurements.

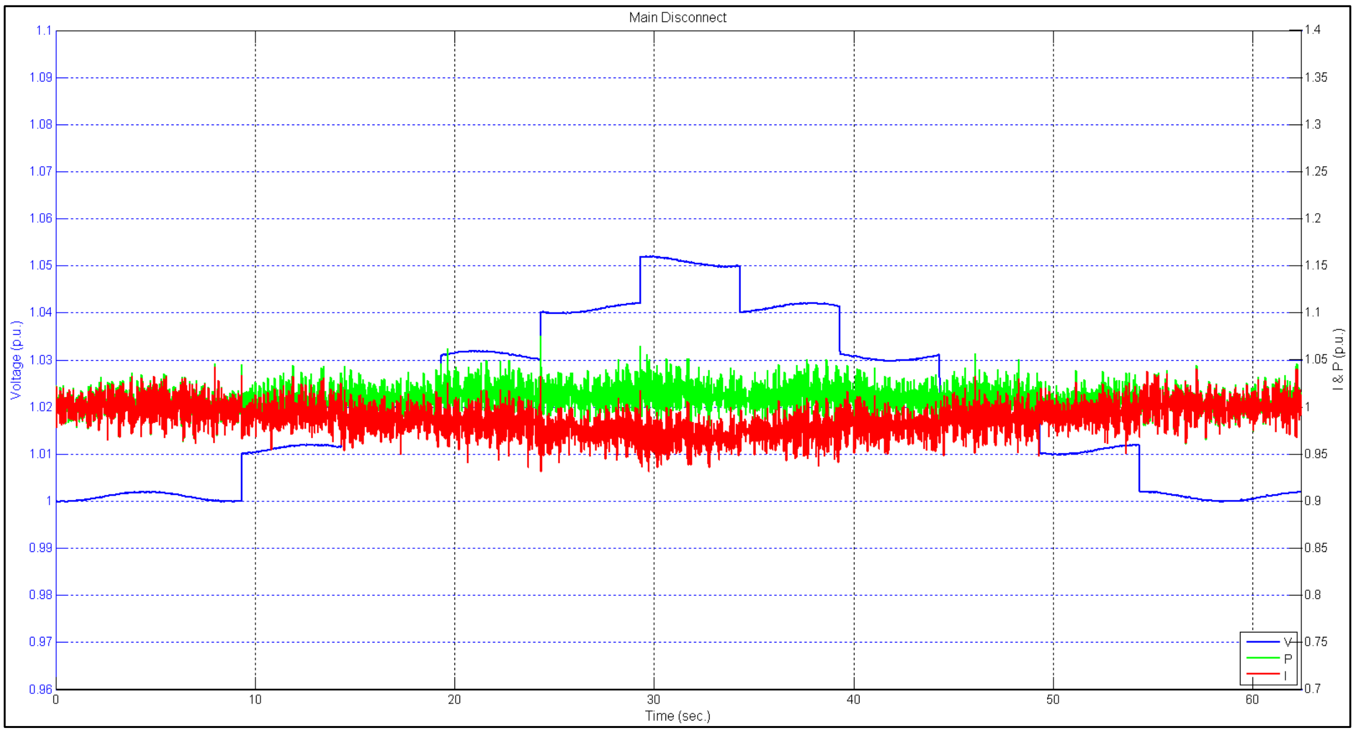

Figure 5.12.2 VFD A/C #3 CVR Response Up to 105% Voltage

6.0 VFD AIR CONDITIONER #4 TEST RESULTS

The figure below shows a snapshot of VFD A/C unit #4 sinusoidal voltages and currents captured at the main terminals and compressor motor using a filter on the digital scope. Notice the slight distortion in the main currents waveforms. The compressor motor is seen operating at approximately 210 Volts peak, 5.5 Amps peak, and 133 Hz at this particular loading condition. The specifications for the VFD A/C #4 components are provided in the table below.

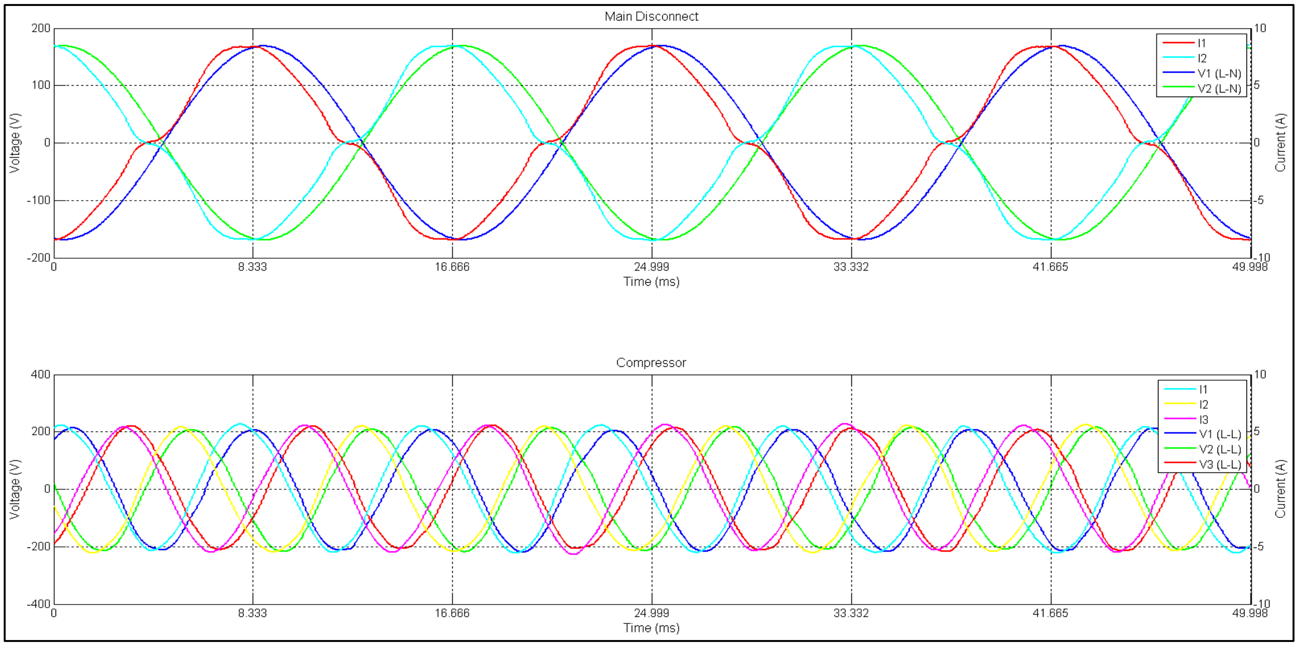

Figure 6.0.1 VFD A/C #4 Voltage and Current Waveforms

Manufacturer	Goodman
Voltage (V)	230
Refrig.	R-410A
SEER	15
Compressor, Model #	GMCC DA150S1C-20FZ
Compressor, RLA (Amps)	11.5
Compressor, LRA (Amps)	-
Outdoor Fan Motor, FLA (Amps)	0.6
Indoor Fan Motor, FLA (Amps)	0.4
Design Pressure High (PSI)	550
Design Pressure Low (PSI)	340

Table 6.0.1 VFD A/C #4 Specifications

6.1 Compressor Shutdown

VFD A/C #4 was shut down during normal operation using the programmable thermostat remote for the indoor blower unit. The figure below displays the measurements taken at the main terminal connections of the entire A/C unit.

The indoor unit shuts down after adjusting the thermostat followed by the compressor shutting down 1 second later. The delay time for compressor current to ramp down is short, within 9 cycles. However, the outdoor unit fan continued operating for another 29.3 seconds before shutting down. While in standby mode, the device's power consumption is less than 0.3 Amps.

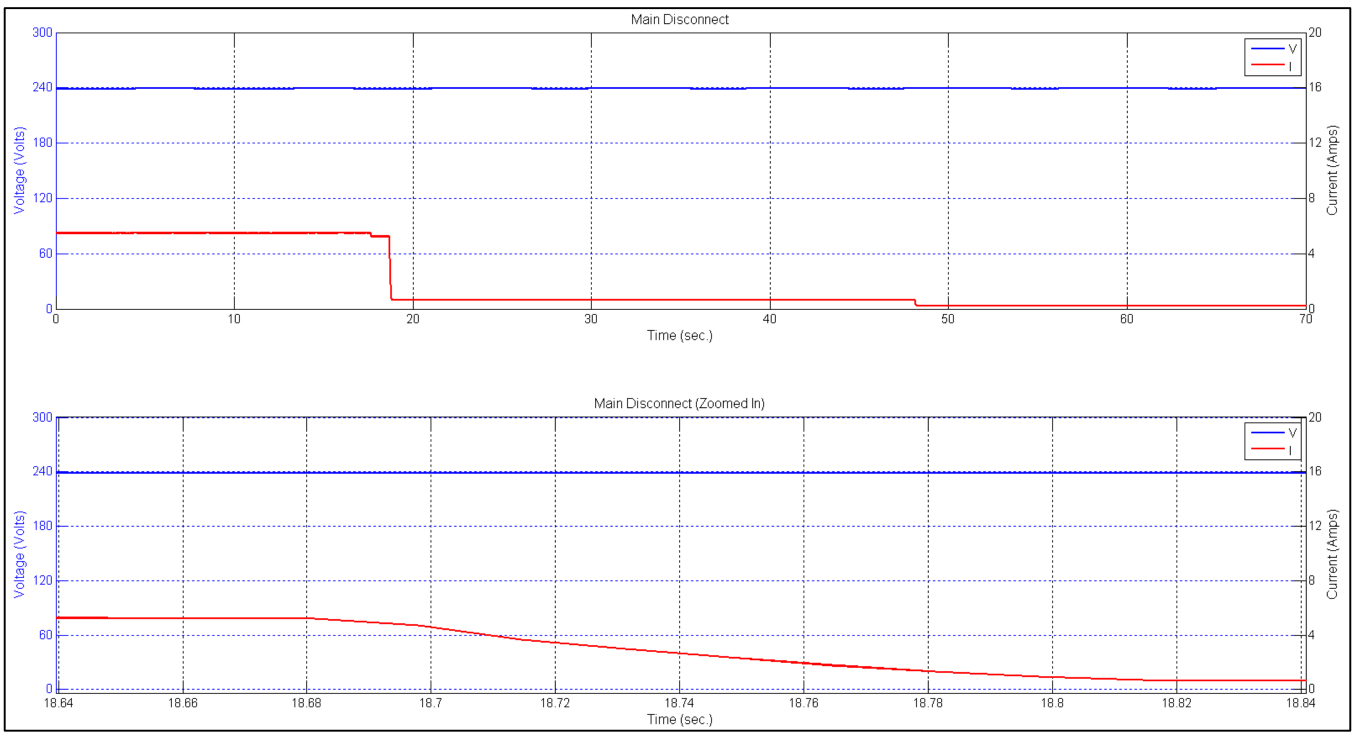

Figure 6.1.1 VFD A/C #4 Compressor Shutdown

6.2 Inrush Current

After starting up the VFD A/C unit via the programmable thermostat remote, the device does not display any sign of significant inrush current. The unit slowly ramps up over the course of nearly 45 seconds until the unit is drawing a minimum of 4.5 Amps. The VFD compressor will increase in intervals over the course of several minutes to meet temperature demand until the unit is more heavily loaded. The room temperature was approximately 77 degrees Fahrenheit and the unit would typically operate between 5.6 and 6.1 Amps steady state.

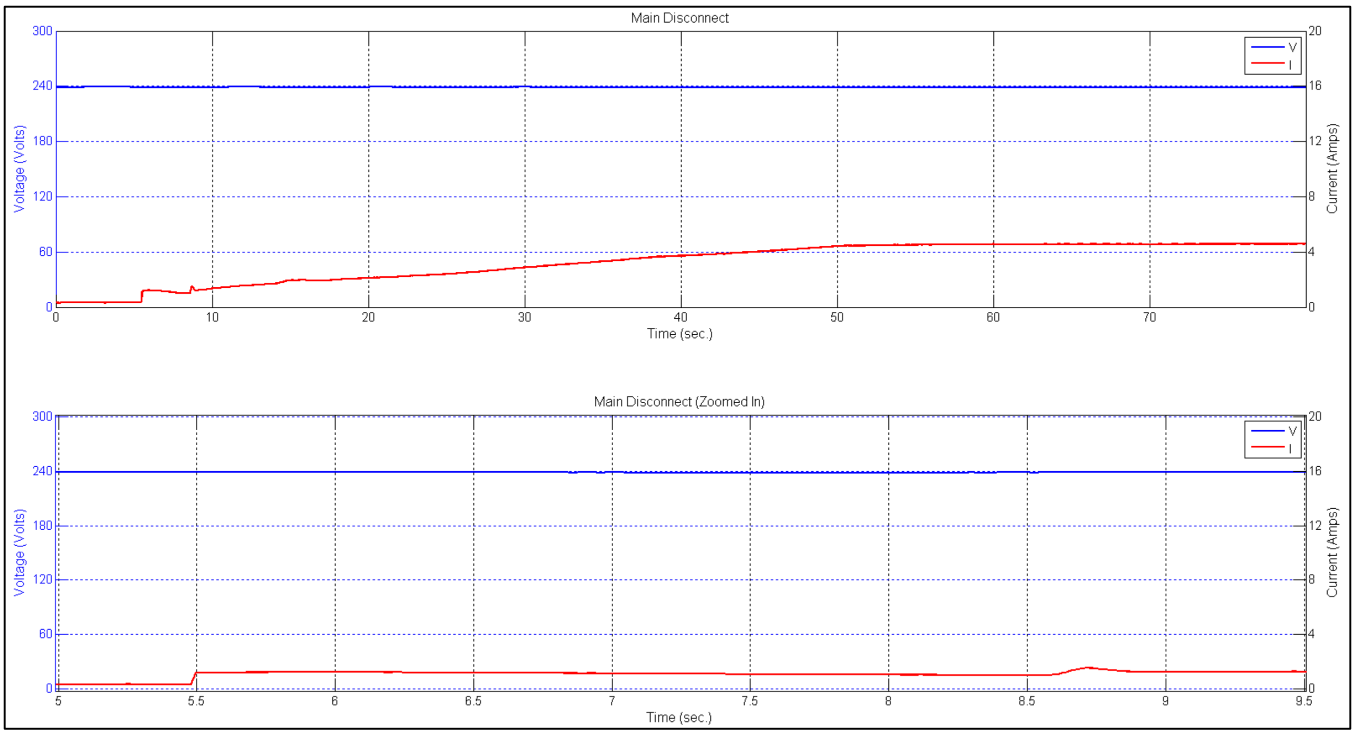

Figure 6.2.1 VFD A/C #4 Inrush Current

6.3 Balanced & Unbalanced Under-voltages

VFD A/C #4 was subjected to a series of balanced under-voltage sags in decrements of 10% to identify the conditions required to cause device dropout and tripping behavior. The unit consistently disconnected the compressor at 70% nominal voltage for longer sags with a duration of 130 cycles. Shorter voltage sags with a duration of 12 cycles resulted in the compressor being tripped at either 50% or 40% nominal voltage. This VFD A/C unit, as shown in Table 6.3.1, would always disconnect either towards the very end of the voltage sag or within 2 cycles after voltage recovered. This may be due to the spike in current observed at the end of each voltage sag or possibly logic on the controller PCB to preventing load disconnection until voltage is near nominal.

Although data points were captured several seconds after the compressors were disconnected, no restarting behavior was observed and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor was only observed restarting several minutes after tripping occurred. No stalling behavior was observed at any time during the transients or after the compressor restarted.

Any voltage sags with a duration less than 6 cycles did not cause the compressor to disconnect, allowing ride through for all voltage magnitudes (down to 0% voltage). “N/A” or “not applicable” represents these ride through situations where there is no trip voltage or trip time available in the following tables.

The following figure visually displays one of the balanced tests where the under-voltage sags have a duration time of 130 cycles. The figure reveals that the compressor began slowing down and was eventually disconnected at 70% voltage towards the end of the 130 cycle voltage sag. The following table provides the voltage magnitude (V_{trip}) where the compressor shut down and time (t_{trip}) taken after the under-voltage was initiated for the A/C unit’s controls to dropout resulting in the compressor tripping off.

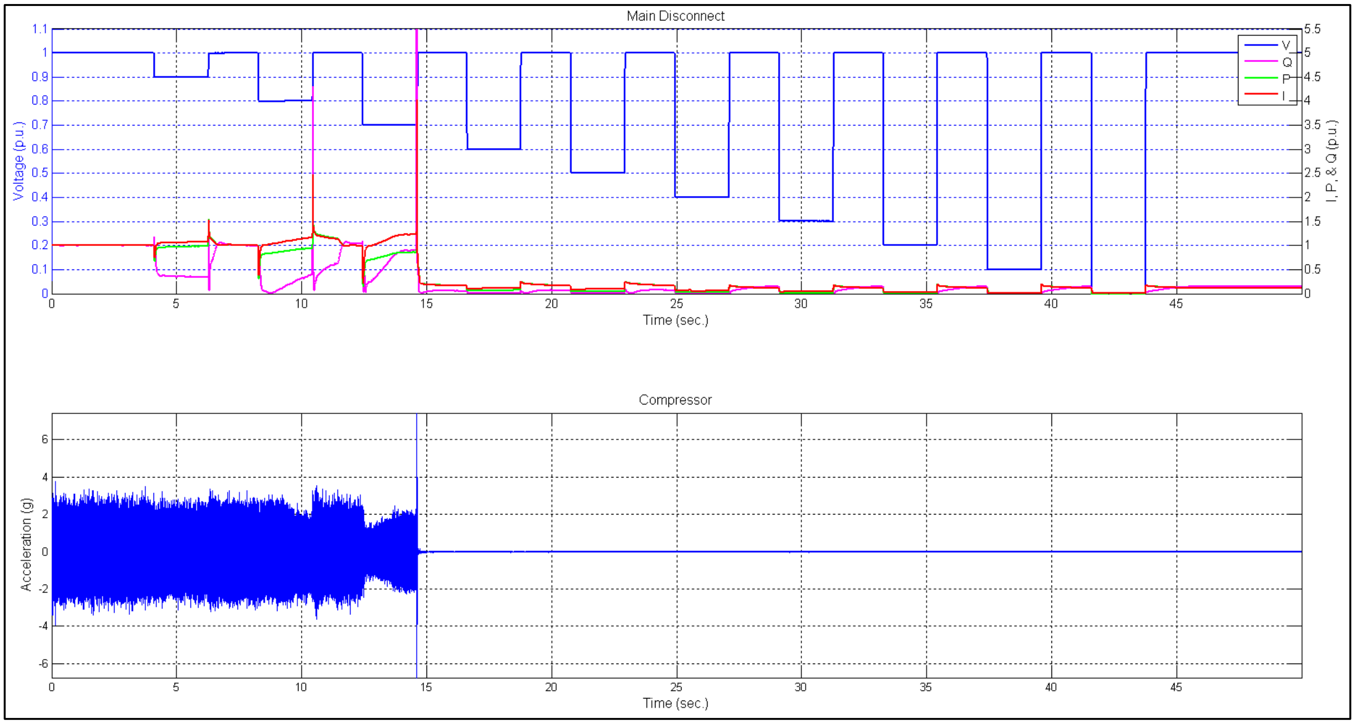

Figure 6.3.1 VFD A/C #4 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		**Compressor**	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	70%	130
		70%	130.2
		70%	130.1
100%, 90%, 80%,... 0%	12	40%	11.9
		50%	12.1
		40%	12.1
100%, 90%, 80%,... 0%	9	0%	10.8
		10%	10.8
		0%	9.6
100%, 90%, 80%,... 0%	6	N/A	N/A
		N/A	N/A
		N/A	N/A
100%, 90%, 80%,... 0%	3	N/A	N/A
		N/A	N/A
		N/A	N/A
100%, 90%, 80%,... 0%	1	N/A	N/A
		N/A	N/A
		N/A	N/A

Table 6.3.1 VFD A/C #4 Balanced Under-voltages in 10% Decrements Results

Additional balanced under-voltage tests in decrements of 1% nominal voltage were performed to verify where the controls drop out and result in the compressor being disconnected. The tests suggested that the compressor would consistently be disconnected at 69% nominal and 49% nominal voltage after voltage recovers from the 130 cycle and 12 cycle voltage sags. This may be the result of the inrush current as voltage steps up or even the controller PCB. The following table provides the details of the compressor disconnection behavior during some these 1% voltage decrement tests.

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
70%, 69%, 68%,…	130	69%	130.1
70%, 69%, 68%,…	130	69%	130.2
60%, 59%, 58%,…	12	49%	12.9
60%, 59%, 58%,…	12	49%	12.9

Table 6.3.2 VFD A/C #4 Balanced Under-voltages in 1% Decrements Results

The unbalanced under-voltages on VFD A/C #4 unit remained consistent with the balanced under-voltage tests with respect to the line-to-line voltage at the main terminals. The unit has dropout and tripping behavior at 40% nominal of the line-neutral voltage with the line-to-line voltage at 70% of nominal. Therefore the voltage at the PCB that operates the controls for the compressor must be supplied by the line-to-line voltage. Since the lowest line-to-line voltage from an unbalanced test is 50% of nominal, unbalanced voltage sags with a duration less than 12 cycles did not cause any dropout/tripping behavior.

The following figure shows an example of these unbalanced cases (Line 1 under-voltages for 130 cycles) where the compressor shut down at 40% nominal line-to-neutral voltage as the voltage sag is recovering. The following table provides the compressor disconnection behavior during unbalanced voltage transients as observed at the main terminals of the VFD A/C unit, including the voltage magnitudes where disconnection occurs and how long it takes to disconnect after the voltage sag begins.

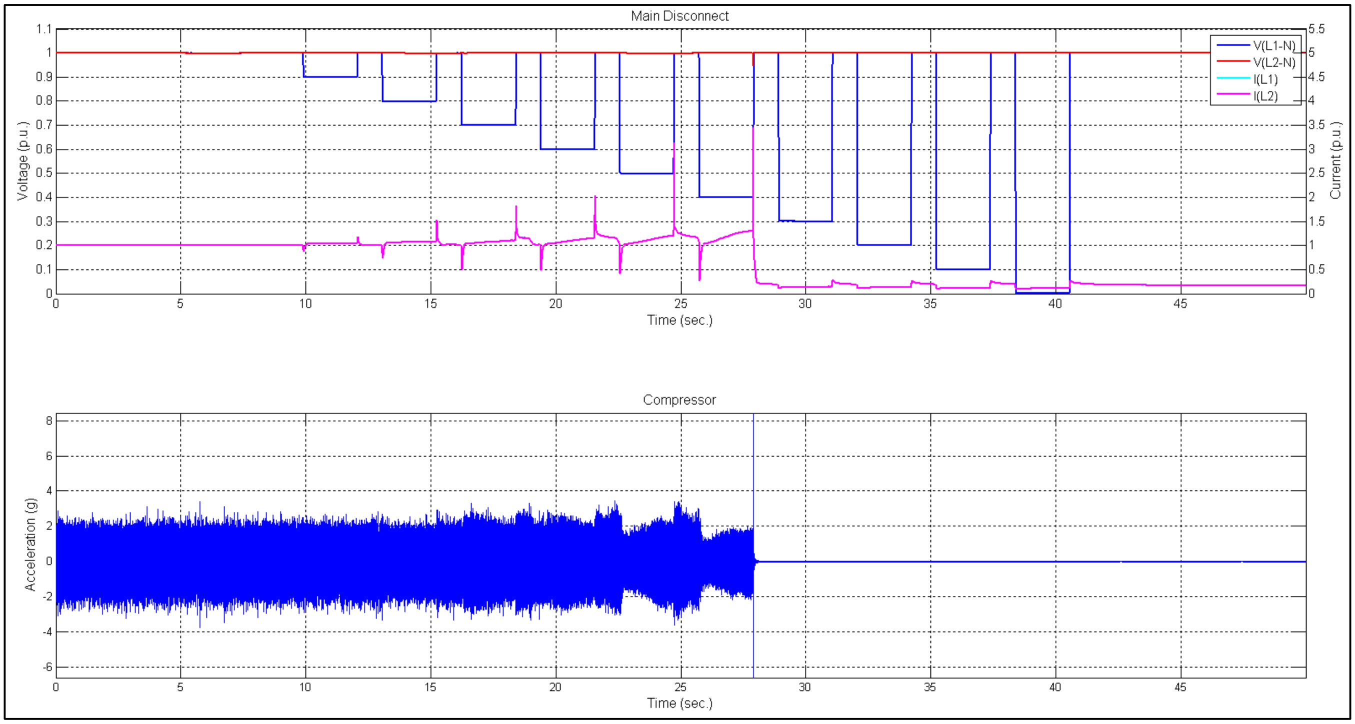

Figure 6.3.2 VFD A/C #4 Unbalanced Under-voltage Response (Line 1, 130 cycles)

Under-Voltage Transient			Compressor		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1	100%, 90%, 80%,... 0%	130	40%	70%	130.8
		12	N/A	N/A	N/A
		6	N/A	N/A	N/A
		3	N/A	N/A	N/A
		1	N/A	N/A	N/A
L2	100%, 90%, 80%,... 0%	130	40%	70%	130.8
		12	N/A	N/A	N/A
		6	N/A	N/A	N/A
		3	N/A	N/A	N/A
		1	N/A	N/A	N/A

Table 6.3.3 VFD A/C #4 Unbalanced Under-voltage Results

6.4 Balanced & Unbalanced Over-voltages

The VFD A/C unit was subjected to balanced and unbalanced over-voltages performed in 2% increments for up to 120% nominal voltage within the parameters of the ITIC (CBEMA) curve, a voltage tolerance curve, to avoid device damage. No over-voltage protection was observed during any of these tests, only voltage ride-through. The following figure shows a sample over-voltage test and the following table specifies the types of tests performed.

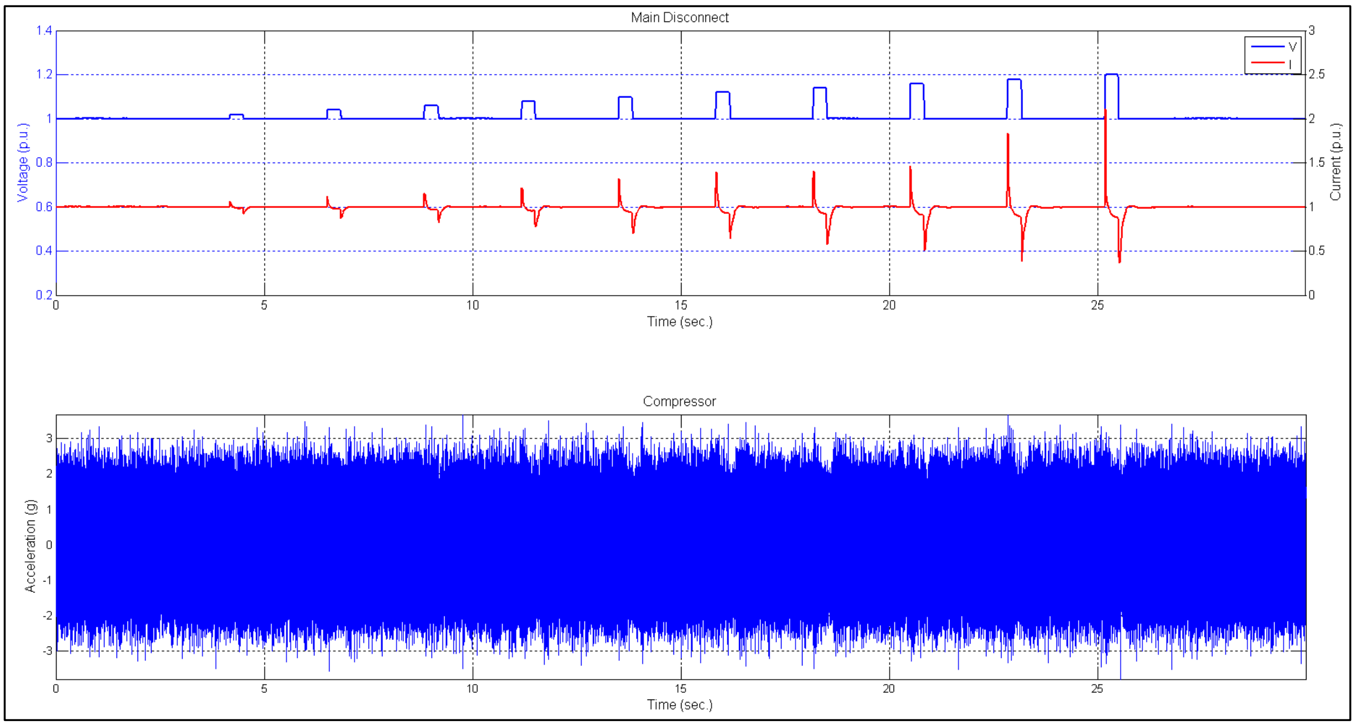

Figure 6.4.1 VFD AC #4 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1 & L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L1	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A

Table 6.4.1 VFD A/C #4 Balanced & Unbalanced Over-voltage Results

6.5 Voltage Oscillations

The following figure shows the performance of VFD A/C unit #4 during voltage oscillations between 100% and 90% nominal voltage for a variety of swing frequencies or oscillation rates.

Current oscillates in the opposite direction of voltage, up to 10% above nominal, for oscillation rates between 0.10 Hz and 0.25 Hz. In response to current, the real power deviates within ±4% of nominal. As the oscillation rate increases, the current deviations become larger (e.g. 12% above nominal at 2 Hz) and the shape of the current profile becomes less linear. During these faster oscillation rates, the real power profile begins deviating nonlinearly like current within ±11% of nominal.

Reactive power oscillates in the same direction as voltage. Similar to current and real power, deviations during oscillation become slightly larger at higher swing frequencies or faster oscillation rates. Reactive linearly ramps down 55% to 58% below steady state.

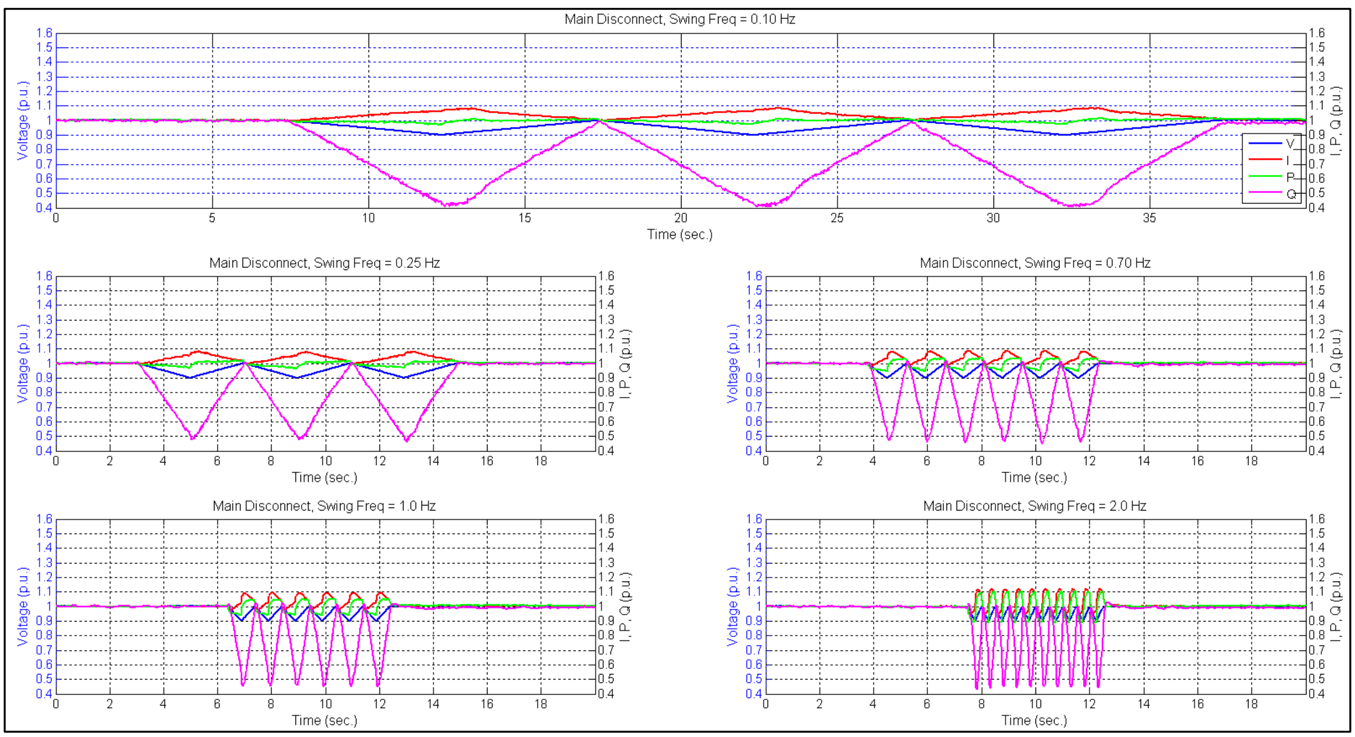

Figure 6.5.1 VFD AC #4 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

6.6 Under-frequency Events

After subjecting the VFD A/C unit to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection while operating between 60 Hz and 58 Hz. The device simply rides through these under-frequency conditions. The constant current suggests that the VFD is maintaining frequency at the motor. The following figure and table identify the magnitude and duration of the frequency transient tests that were performed on VFD A/C #4.

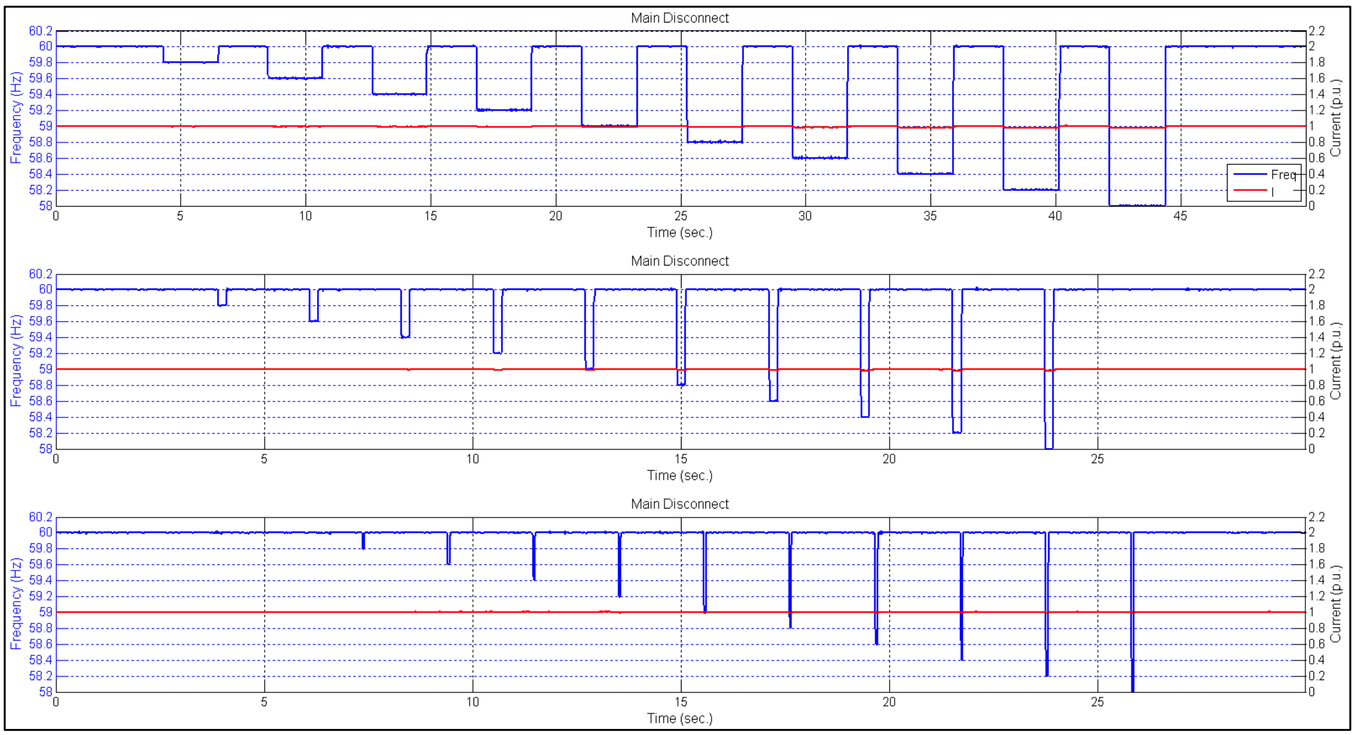

Figure 6.6.1 VFD A/C #4 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		**Compressor**	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 6.6.1 VFD A/C #4 Under-frequency Test Results

6.7 Over-frequency Events

Similar to the under-frequency tests, the VFD A/C unit was subjected to over-frequency transients to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. Similar to under-frequency conditions, the VFD maintains frequency at the actual compressor motor. The following figure and table identify the magnitude and duration of the specific over-frequency tests that were performed on VFD A/C #4.

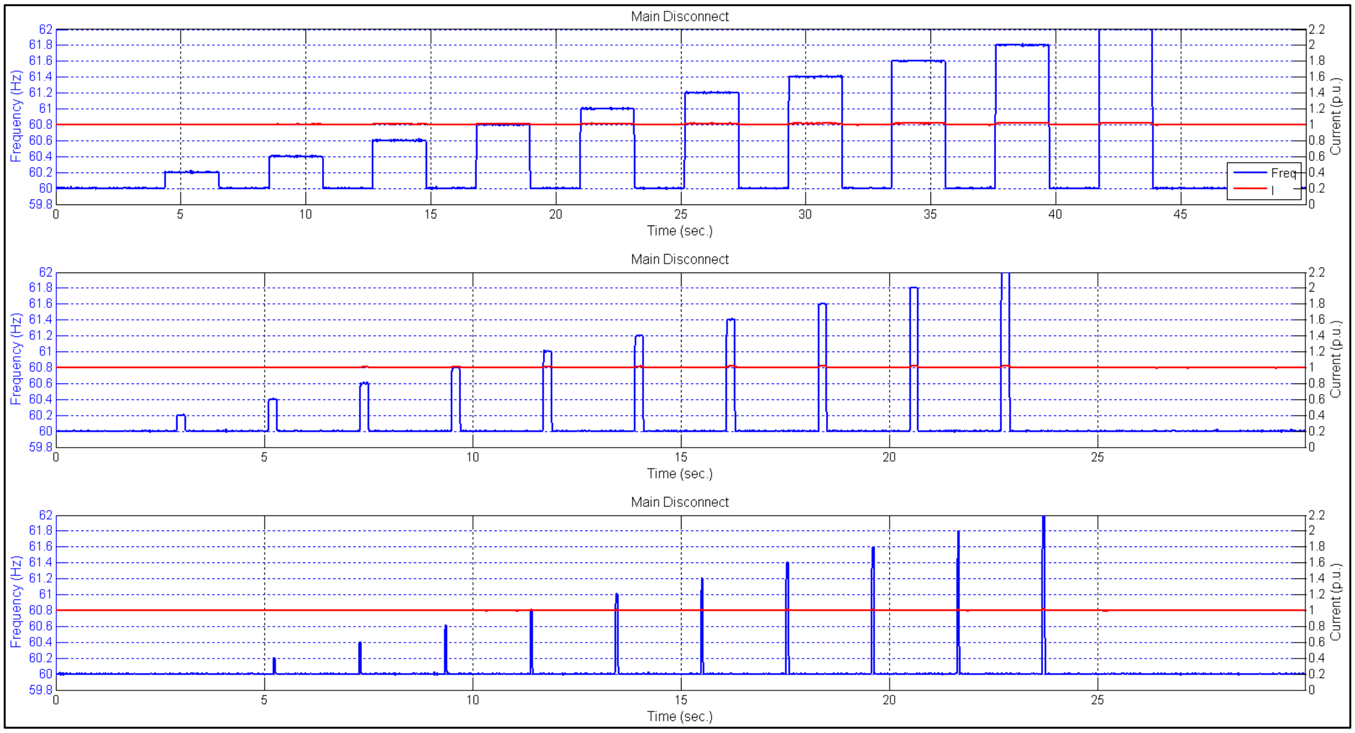

Figure 6.7.1 VFD A/C #4 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 6.7.1 VFD A/C #4 Over-frequency Test Results

6.8 Frequency Oscillations

The following figure shows the performance of VFD A/C #4 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates (0.10, 0.25, 0.70, 1.0, and 2.0 Hz).

Although the current and real power measured at the main terminals of the VFD A/C slightly oscillate in the same direction as voltage, both values stay relatively constant. Both remain within $\pm$2% of their respective steady state values. Therefore, the VFD does an excellent job keeping the motor consumption constant.

Reactive power oscillates in the same direction of voltage and deviations from nominal are similar for all oscillation rates. Reactive power consumption remains within $\pm$13% of nominal.

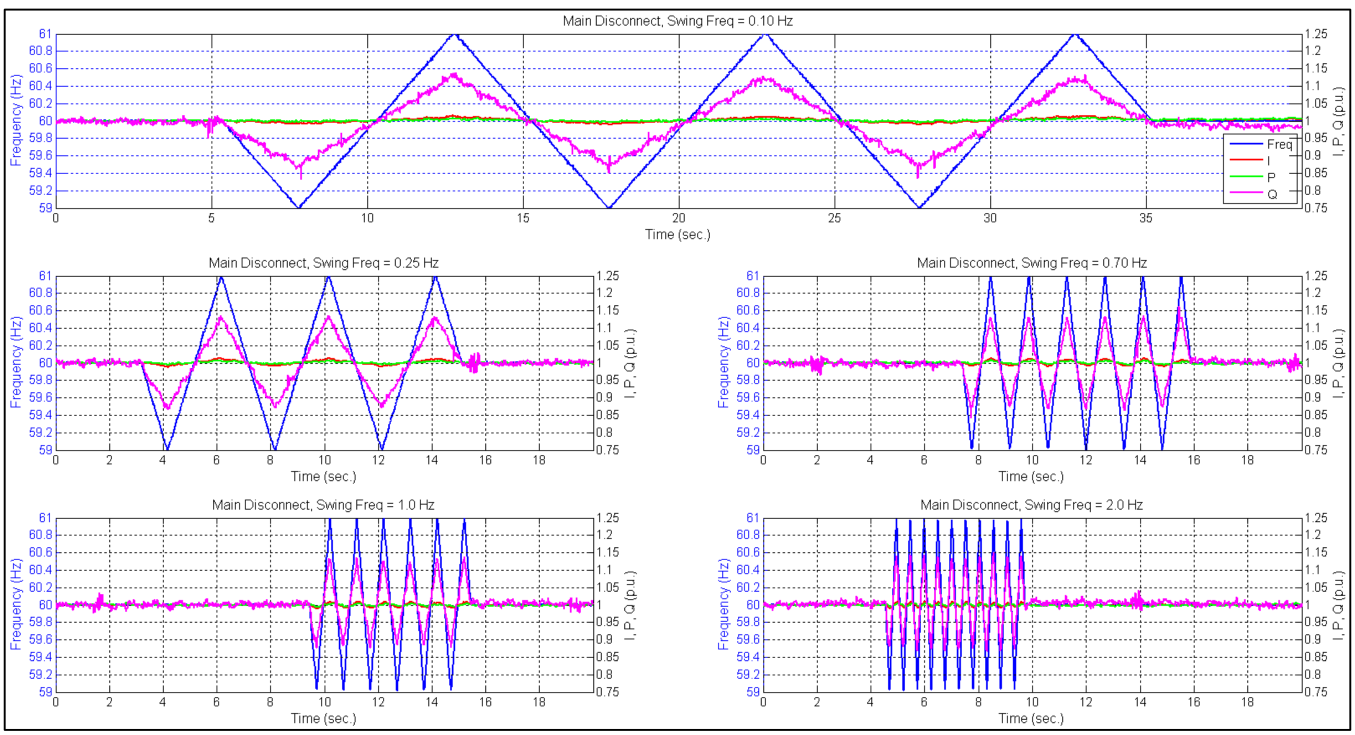

Figure 6.8.1 VFD A/C #4 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

6.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the VFD A/C unit tripped while ramping down to 50% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation (down to 60% nominal voltage).

There appears to be a delay in the response of the A/C load. Current does not behave linearly in response to the voltage ramp decreasing initially by 8% below nominal for the 2 second ramp and increasing to approximately 30% above nominal during both tests. Real power consumption decreases in both cases, deviating by 42% below steady state for the 2 second ramp test and 30% below steady state for the 8 second ramp test. Reactive power also decreases nonlinearly during the voltage ramp, reaching approximately 0% of nominal in both ramp tests.

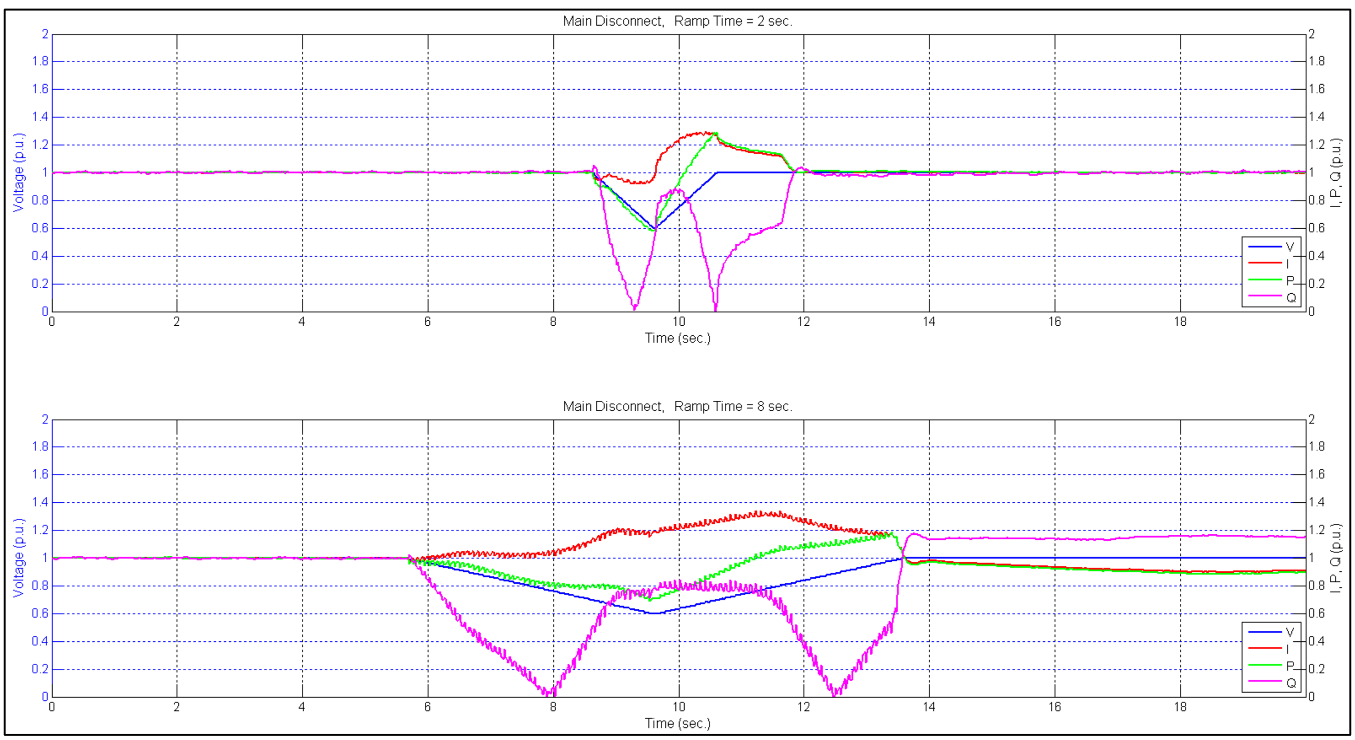

Figure 6.9.1 VFD A/C #4 Voltage Ramp Down to 60% (2 & 8 sec.)

Voltage was ramped up to 110% and back down steady state voltage at different ramp rates to demonstrate the load performance while operating at over-voltage values.

Current is observed ramping down to nearly 7% below nominal in response to the voltage ramp. Real power consumption increases slightly, up to 3% above steady state for both ramp tests and also falls to 3% below steady state for the 2 second ramp test. Reactive power is ramps up and back down with voltage, peaking at approximately 52% of nominal for both ramp tests.

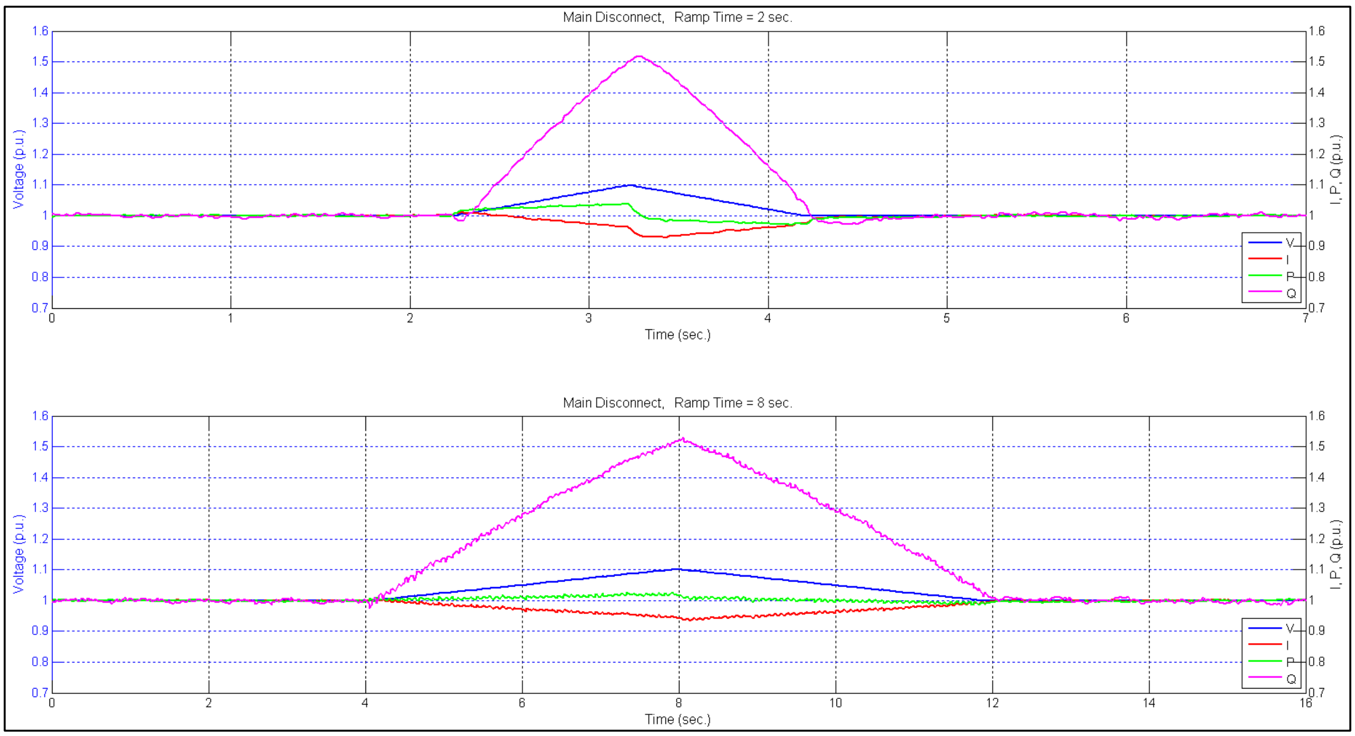

Figure 6.9.2 VFD A/C #4 Voltage Ramp Up to 110% (in 2 & 8 sec.)

6.10 Frequency Ramps

Frequency was ramped down to 50 Hz and back up to 60 Hz at different ramp rates to demonstrate the load performance while operating at lower frequency values as shown in the figure below.

Current and real power slowly decrease during the frequency ramp test, but remain within 4% of their respective nominal values. Reactive power begins decreasing as frequency ramps down and begins plateauing at approximately 50% of nominal once frequency reaches 55 Hz. As frequency continues decreasing, reactive power consumption then increases until peaking at 17% below nominal. Afterwards reactive power follows the same pattern of behavior as frequency ramps up to nominal.

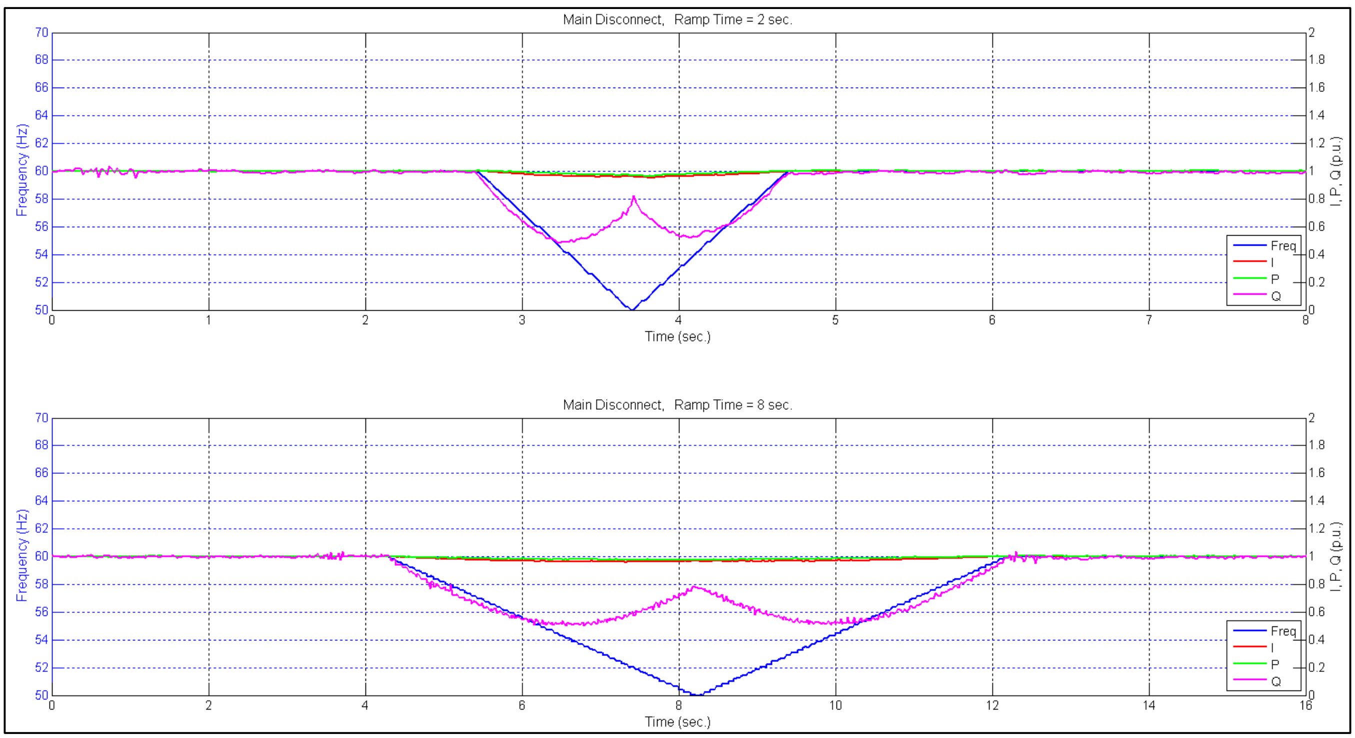

Figure 6.10.1 VFD A/C #4 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

Frequency was ramped up to 70 Hz and back down to 60 Hz at different ramp rates to demonstrate the load performance while operating at higher frequency values as shown in the figure below.

Current slowly ramps up with frequency until peaking at approximately 15% above nominal current. Real power also displays this same behavior but at a slower rate until peaking at 6% above steady state. Reactive power displays the greatest increase in consumption as it ramps up until it is at 240% of nominal reactive power (or 140% above nominal).

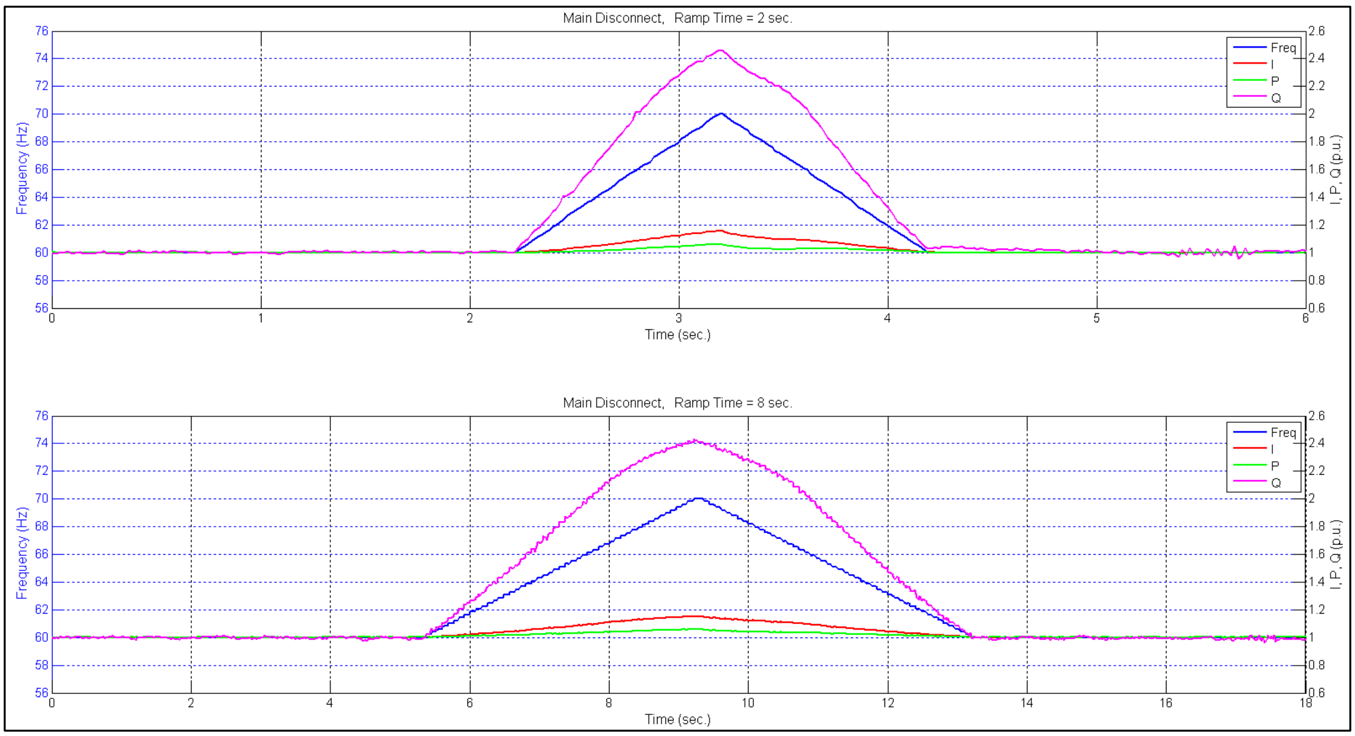

Figure 6.10.2 VFD A/C #4 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

6.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times without scope filters to calculate the actual harmonic contribution of VFD A/C unit #4 to the grid. The maximum total harmonic distortion of current was calculated as 11.28% of the fundamental. This is the smallest total harmonic distortion of all the VFD A/C units. The following table gives the total harmonic distortion calculations and the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)		
	$V_{(L1-L2)}$	$I_{(L1)}$	$I_{(L2)}$
1	0.39	11.26	11.28
2	0.40	11.09	11.11
3	0.40	11.21	11.23

Table 6.11.1 VFD A/C #4 Total Harmonic Distortion

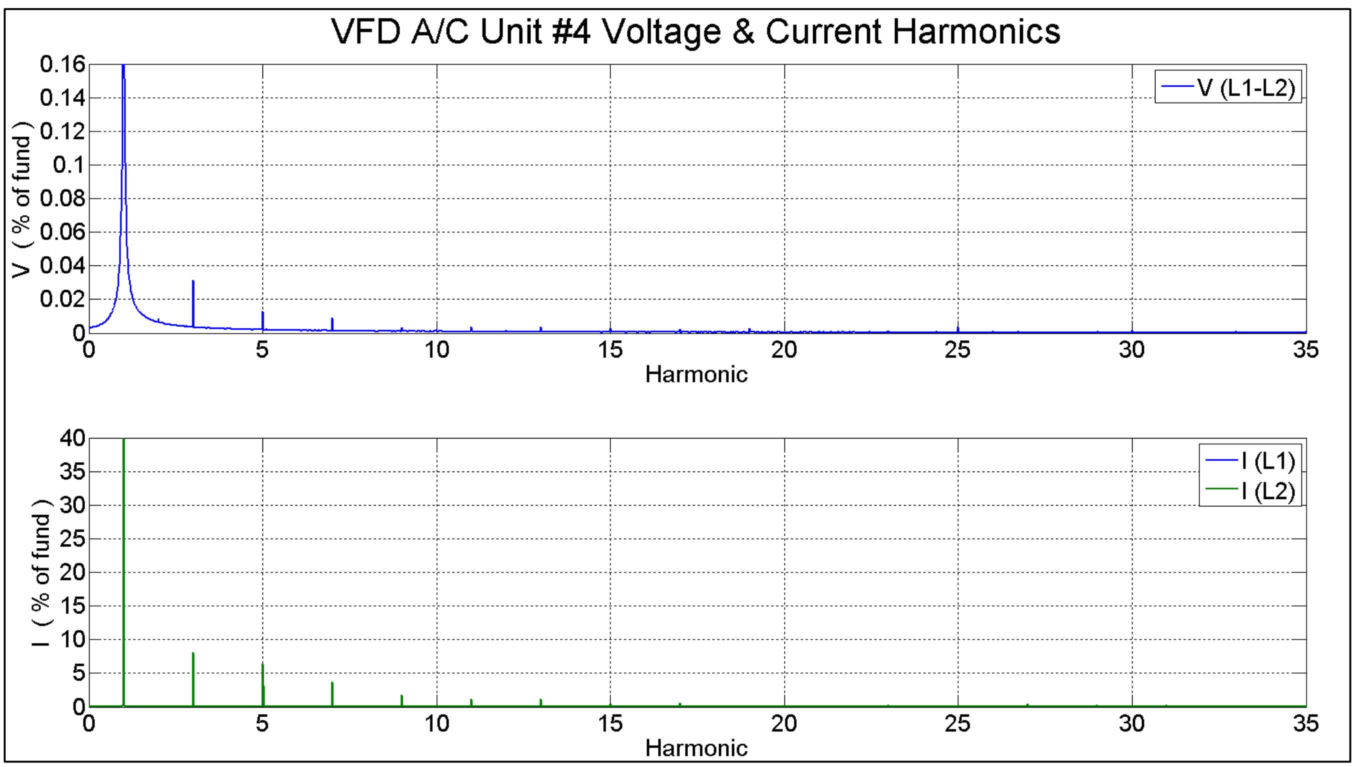

Figure 6.11.1 VFD A/C #4 Harmonics Contribution

6.12 Conservation Voltage Reduction

Voltage was decreased by 1% nominal voltage in 5 second intervals down to 90% before recovering back to steady state as shown in the figure below.

CVR has little impact on this specific load. Current increases by approximately 0.8% of nominal current for every 1% decrease in nominal voltage. Real power remains relatively constant, within ±2% of nominal, over the course of the CVR test. Reactive power is observed decreasing by approximately 6% of nominal for every 1% decrease in voltage.

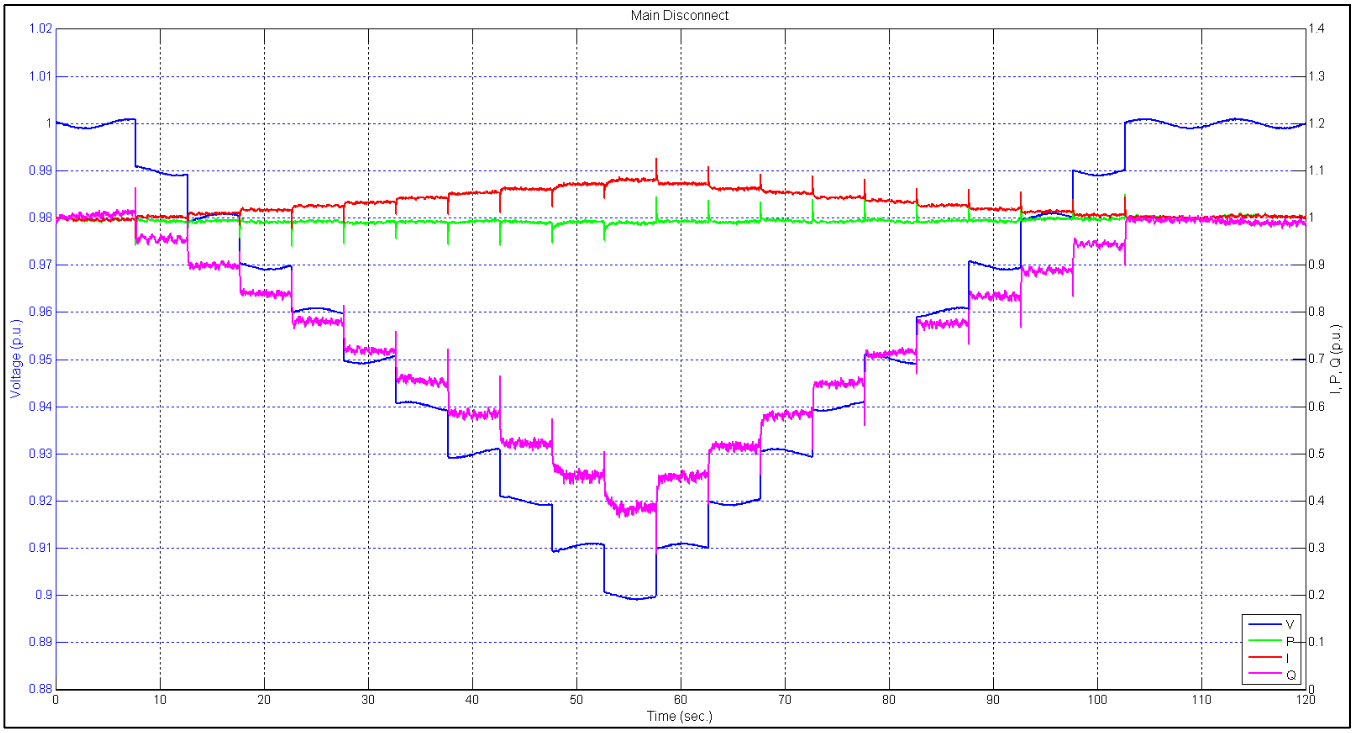

Figure 6.12.1 VFD A/C #4 CVR Response Down to 90% Voltage

Alternatively, the main terminal voltage at the VFD A/C unit was increased by 1% nominal voltage in 5 second intervals up to 105% before stepping back to steady state as shown in the figure below.

Current decreases by approximately 0.6% of its nominal value for every 1% increase in nominal voltage over the course of the CVR test. Real power consumption remains at its steady state value within 2% of nominal. Reactive power is observed increasing by approximately 5.4% of its nominal value for every 1% increase in nominal voltage.

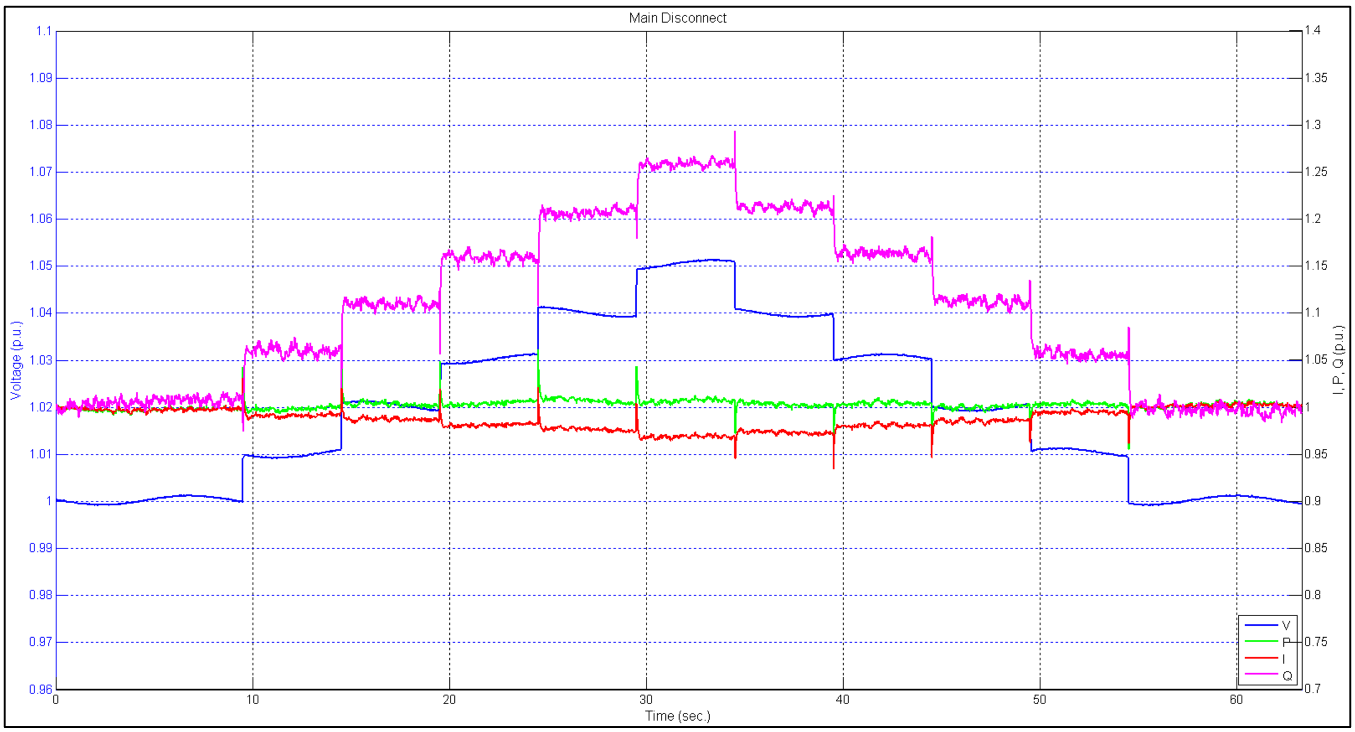

Figure 6.12.2 VFD A/C #4 CVR Response Up to 105% Voltage

7.0 VFD AIR CONDITIONER #5 TEST RESULTS

The figure below shows a snapshot of VFD A/C unit #5 sinusoidal voltages and currents captured at the main terminals and compressor motor using a filter on the digital scope. Notice the distortion in the main current waveforms. The compressor is operating at approximately 155 Volts peak, 10 Amps peak, and 95 Hz at the observed loading condition. The specifications for the VFD A/C #5 components are provided in the table below.

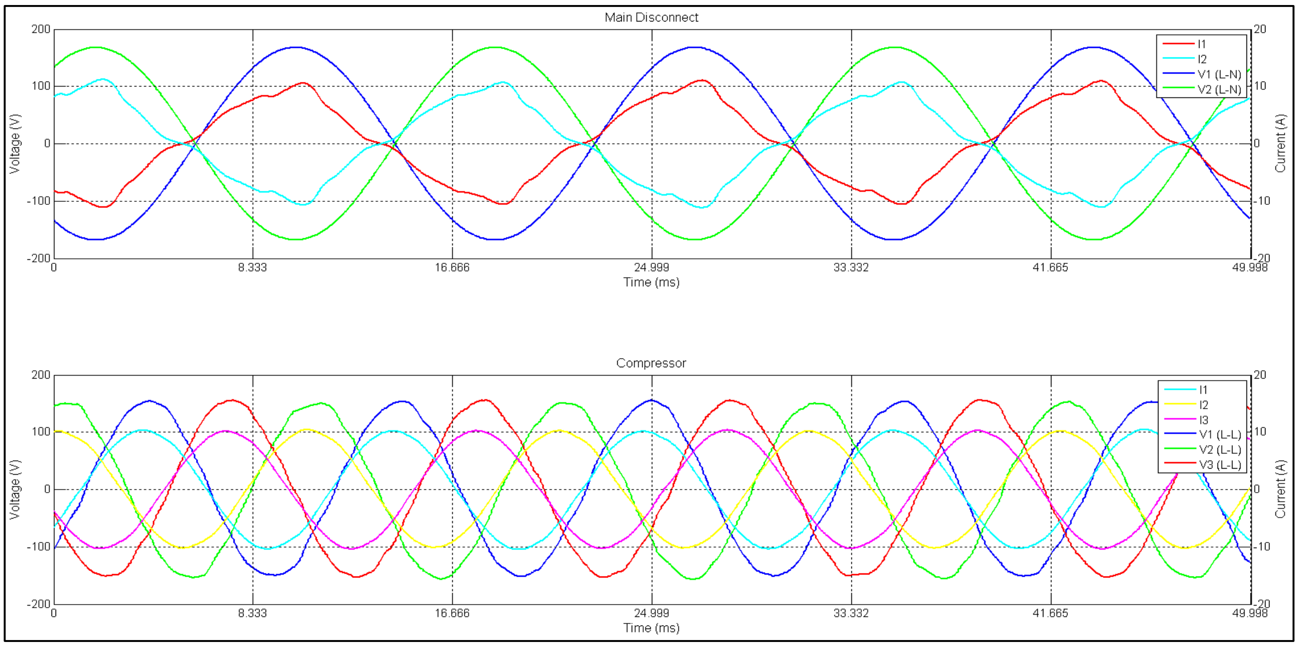

Figure 7.0.1 VFD A/C #5 Voltage and Current Waveforms

Manufacturer	Klimaire
Voltage (V)	230
Refrig.	R-410A
SEER	19
Compressor, Model #	GMCC DA250S2C-30MT
Compressor, RLA (Amps)	11.0
Compressor, LRA (Amps)	-
Outdoor Fan Motor, FLA (Amps)	0.55
Indoor Fan Motor, FLA (Amps)	0.36
Design Pressure High (PSI)	550
Design Pressure Low (PSI)	340

Table 7.0.1 VFD A/C #5 Specifications

7.1 Compressor Shutdown

VFD A/C #5 was shut down during normal operation using the programmable thermostat remote for the indoor blower unit. The figure below displays the measurements taken at the main terminal connections of the entire A/C unit.

After adjusting the thermostat, the indoor unit shuts down immediately and compressor shuts down shortly after, within 1 second. The delay time for compressor current to ramp down is approximately 2 cycles. The outdoor unit fan continued operating for another 28.9 seconds before shutting down. While in standby mode, the device's power consumption is less than 0.4 Amps.

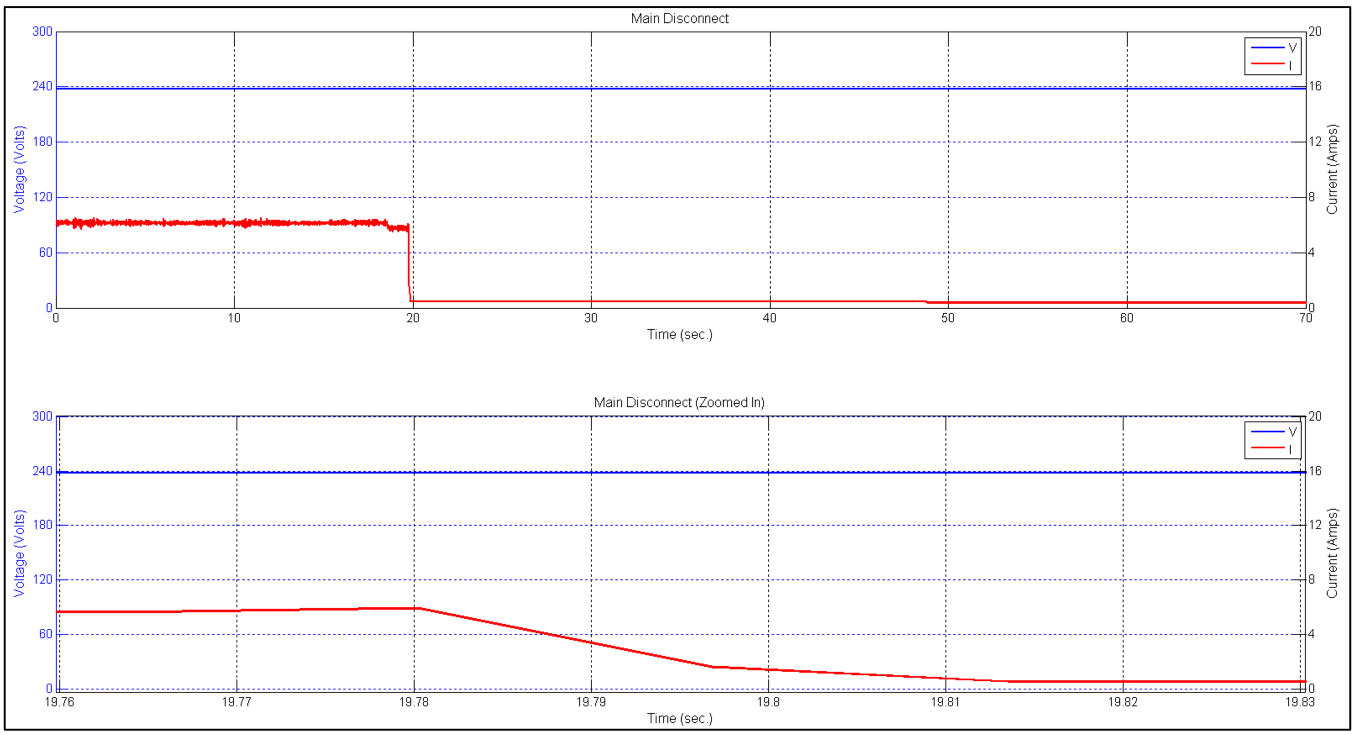

Figure 7.1.1 VFD A/C #5 Compressor Shutdown

7.2 Inrush Current

After starting up the VFD A/C unit via the programmable thermostat remote, the device does not display any sign of significant inrush current. The unit slowly ramps up over the course of nearly 30 seconds until the unit is drawing a minimum of 4.5 Amps. Only a small spike in current, 2 Amps, is observed as the ramp up begins. The VFD controlled compressor will increase in intervals over the course of several minutes to meet temperature demand until the unit is more heavily loaded. The room temperature was approximately 79 degrees Fahrenheit and the unit would typically operate near 6.2 to 6.9 Amps steady state.

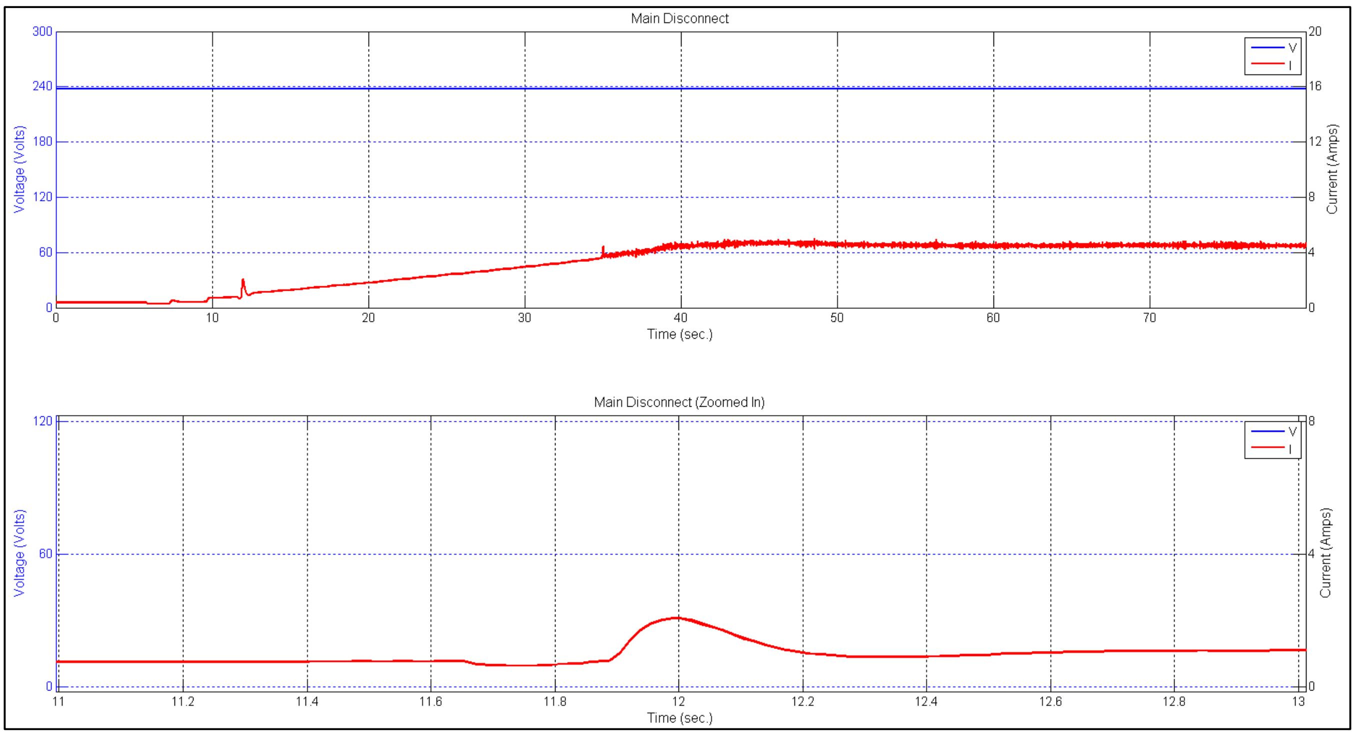

Figure 7.2.1 VFD A/C #5 Inrush Current

7.3 Balanced & Unbalanced Under-voltages

After performing various under-voltages on VFD A/C #5 in decrements of 10%, the compressor is observed disconnecting at different voltage magnitudes depending on the duration of the under-voltage transient. Longer voltage sags with a duration of 130 cycles caused the compressor to shut down consistently at 40% nominal voltage within 114 and 127.8 cycles. Voltage sags with a duration time of 12 and 9 cycles typically caused the compressor to disconnect at 10% nominal voltage near the end of the sag or even up to 1.2 cycles after voltage recovered. Tripping at the end of the voltage sag may be due to the spike in current at that time or even some form of logic from the unit controller.

Data captured several seconds after the disconnection of the compressors did not reveal restarting behavior and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor would only restart approximately 4 minutes after tripping occurred.

The VFD A/C unit rode through all voltage sags (down to 0% voltage) with a duration less than or equal to 6 cycles. "N/A" or "not applicable" represents these ride through situations where there is no trip voltage or trip time available in the following tables.

The following figure visually displays one of these balanced tests where the under-voltage sags have a duration time of 130 cycles. Less under-voltage tests are shown in the following figure because the time between voltage sags was increased for this unit to ensure the load returned to steady state before performing the next voltage sag test in the sequence. The compressor is observed being disconnected towards the end of the 40% voltage sag. The following table provides additional details regarding the compressor operation during a variety of balanced under-voltage transient tests including the voltage where the unit was tripped (V_{trip}) as well as the time it took for the unit controls to trip it offline after the voltage sag was initiated (t_{trip}).

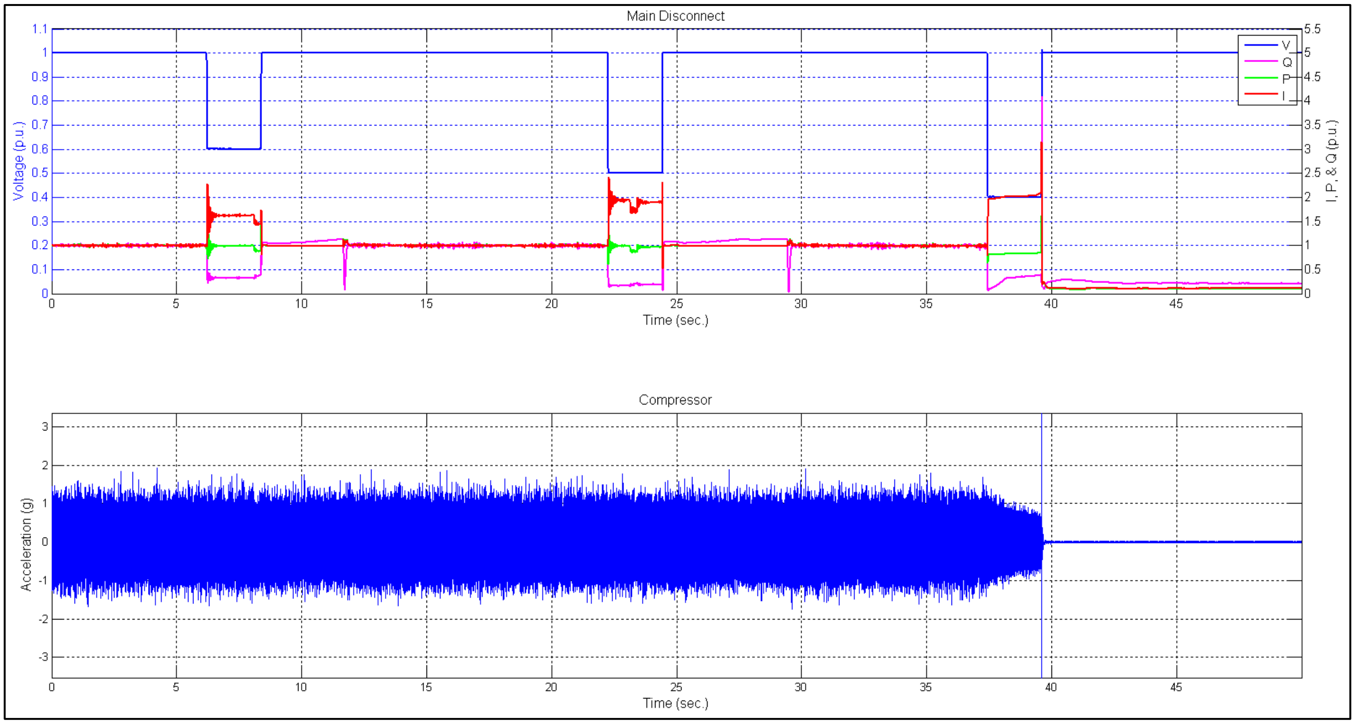

Figure 7.3.1 VFD A/C #5 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)
100%, 90%, 80%,... 0%	130	40%	115.8
		40%	127.8
		40%	114
100%, 90%, 80%,... 0%	12	10%	9.6
		20%	12.6
		10%	10.2
100%, 90%, 80%,... 0%	9	10%	10.2
		10%	9.6
		10%	9.6
100%, 90%, 80%,... 0%	6	N/A	N/A
		N/A	N/A
		N/A	N/A
100%, 90%, 80%,... 0%	3	N/A	N/A
		N/A	N/A
		N/A	N/A
100%, 90%, 80%,... 0%	1	N/A	N/A
		N/A	N/A
		N/A	N/A

Table 7.3.1 VFD A/C #5 Balanced Under-voltages in 10% Decrements Results

The specific voltage where the compressors are disconnected and/or the controls dropped were identified by performing additional balanced under-voltage tests in decrements of 1% nominal voltage. The voltage sags with longer duration times showed that the compressor could begin tripping off for voltage sags between 41% and 39% nominal voltage. Under-voltage transients in the range of 12 cycles revealed tripping at 19% nominal voltage. Each of these tests resulted in the compressor disconnecting after voltage recovered from the sag (up to 1.2 cycles after recovery). This could be the result of the spike in inrush current as voltage steps up to nominal or even the outdoor condensing unit's controller PCB preventing loss of load until voltage is near steady state. The following table provides the details of the compressor disconnection behavior during these 1% voltage decrement tests.

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
50%, 49%, 48%,…	130	41%	130.8
50%, 49%, 48%,…	60	39%	61.2
50%, 49%, 48%,…	12	19%	12.6

Table 7.3.2 VFD A/C #5 Balanced Under-voltages in 1% Decrements Results

The unbalanced under-voltages on VFD A/C #5 did not reveal any tripping or disconnection of the compressor. The unit rode through these transients and continued operating normally. This is expected since the lowest voltage magnitude possible is 50% line-to-line nominal voltage and balanced under-voltages did not cause tripping until voltage reached approximately 40% nominal voltage. Therefore the voltage at the PCB that operates the controls for the compressor is likely supplied by the line-to-line voltage.

The following figure shows an example of these unbalanced cases (Line 1 under-voltages for 130 cycles) where the compressor rides through a 0% line-to-neutral nominal voltage. The following table provides details on the unbalanced voltage transients performed at the main terminals of the VFD A/C unit.

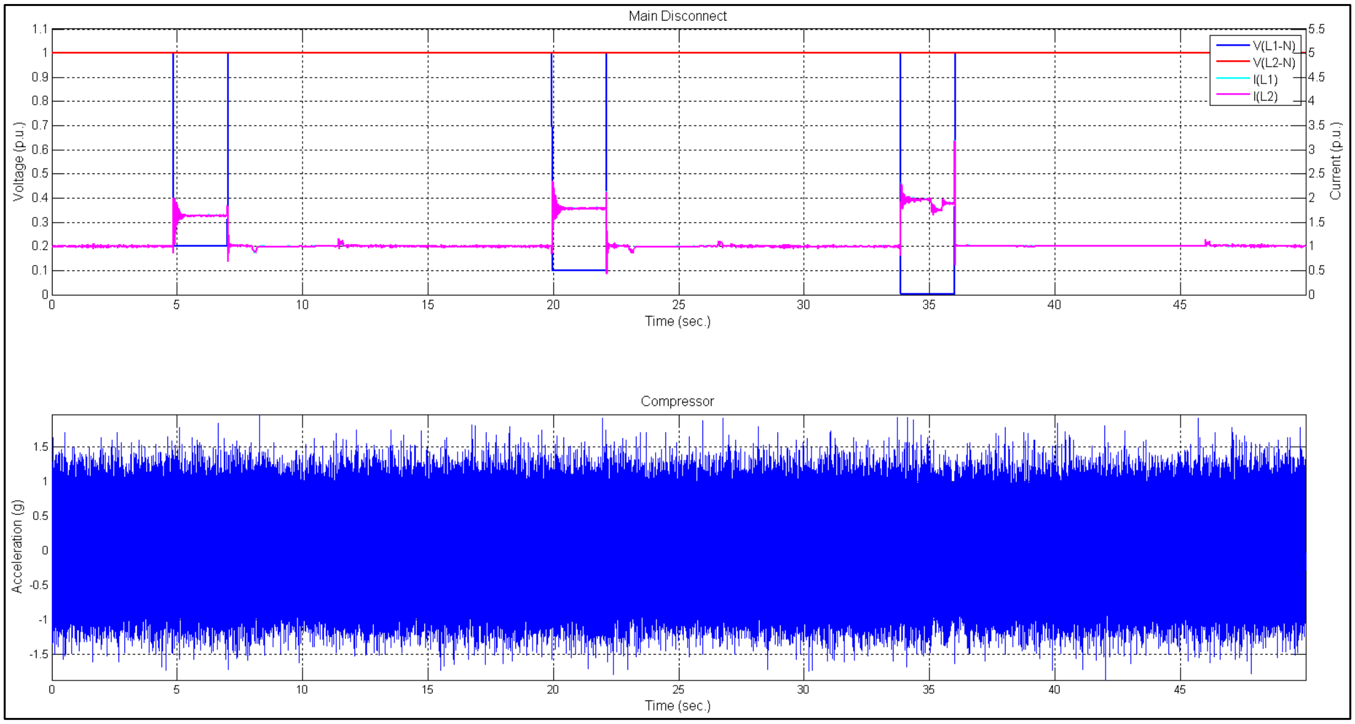

Figure 7.3.2 VFD A/C #5 Unbalanced Under-voltage Response (Line 1, 130 cycles)

Under-Voltage Transient			Compressor		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1	100%, 90%, 80%,... 0%	130	N/A	N/A	N/A
		12	N/A	N/A	N/A
		6	N/A	N/A	N/A
		3	N/A	N/A	N/A
		1	N/A	N/A	N/A
L2	100%, 90%, 80%,... 0%	130	N/A	N/A	N/A
		12	N/A	N/A	N/A
		6	N/A	N/A	N/A
		3	N/A	N/A	N/A
		1	N/A	N/A	N/A

Table 7.3.3 VFD A/C #5 Unbalanced Under-voltage Results

7.4 Balanced & Unbalanced Over-voltages

VFD A/C #5 was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve to avoid damaging any voltage sensitive equipment. These tests include multiple voltage swells performed in 2% increments for up to 120% nominal voltage to identify any tripping behavior. No over-voltage protection was observed during any of these tests, only voltage ride-through. The following figure shows a sample over-voltage test and the following table specifies the types of tests performed.

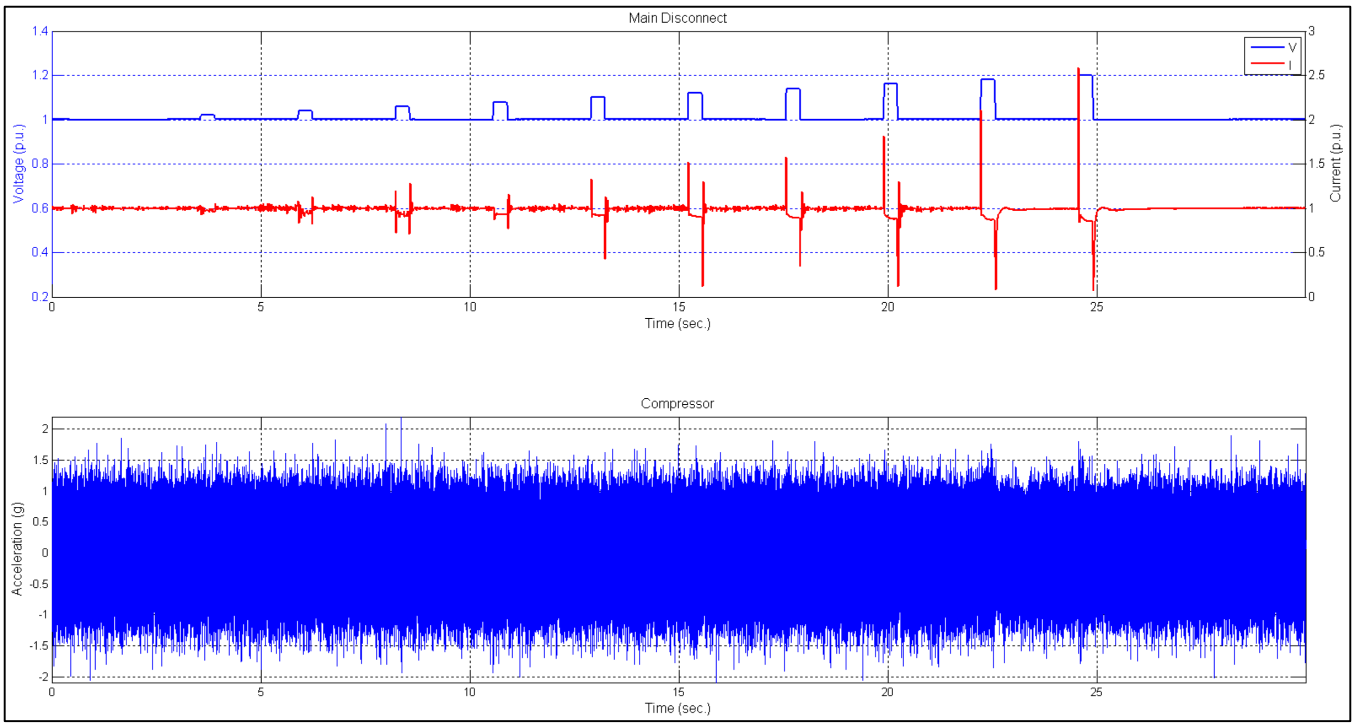

Figure 7.4.1 VFD AC #5 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1 & L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L1	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A

Table 7.4.1 VFD A/C #5 Balanced & Unbalanced Over-voltage Results

7.5 Voltage Oscillations

The following figure shows the performance of VFD A/C #5 during voltage oscillations between 100% and 90% nominal voltage for a variety of swing frequencies or oscillation rates.

Current oscillates in the opposite direction of voltage, between 11% and 13% above nominal, to minimize any oscillations or deviations in real power for all swing frequencies. The consumption of real power remains relatively constant within 3% of nominal during a periods of the voltage oscillations. However, there appear to be sudden swings in real power as voltage and current return to nominal following each oscillation caused by changes in the shape of the current sinusoidal waveform.

Reactive power consumption is very low since the power factor is greater than 0.98 for the device. Therefore any minor change in reactive load, even during steady state, results in drastic changes to the per unit values. As a result, reactive power was not included in the figure below.

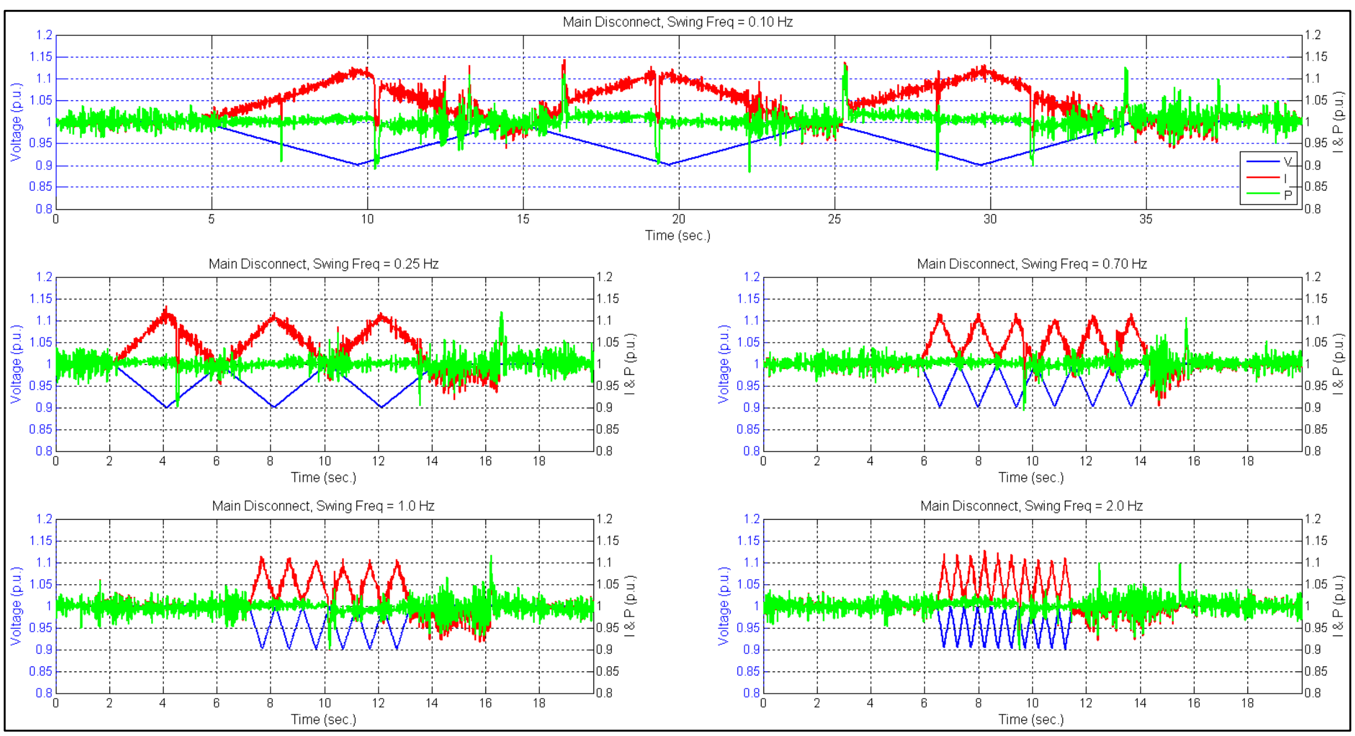

Figure 7.5.1 VFD AC #5 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

7.6 Under-frequency Events

After subjecting VFD A/C #5 to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection while operating between 60 Hz and 58 Hz. The device simply rides through these under-frequency conditions. Constant current suggests that the VFD is maintaining frequency of the motor. The following figure and table identify the magnitude and duration of the frequency transient tests that were performed.

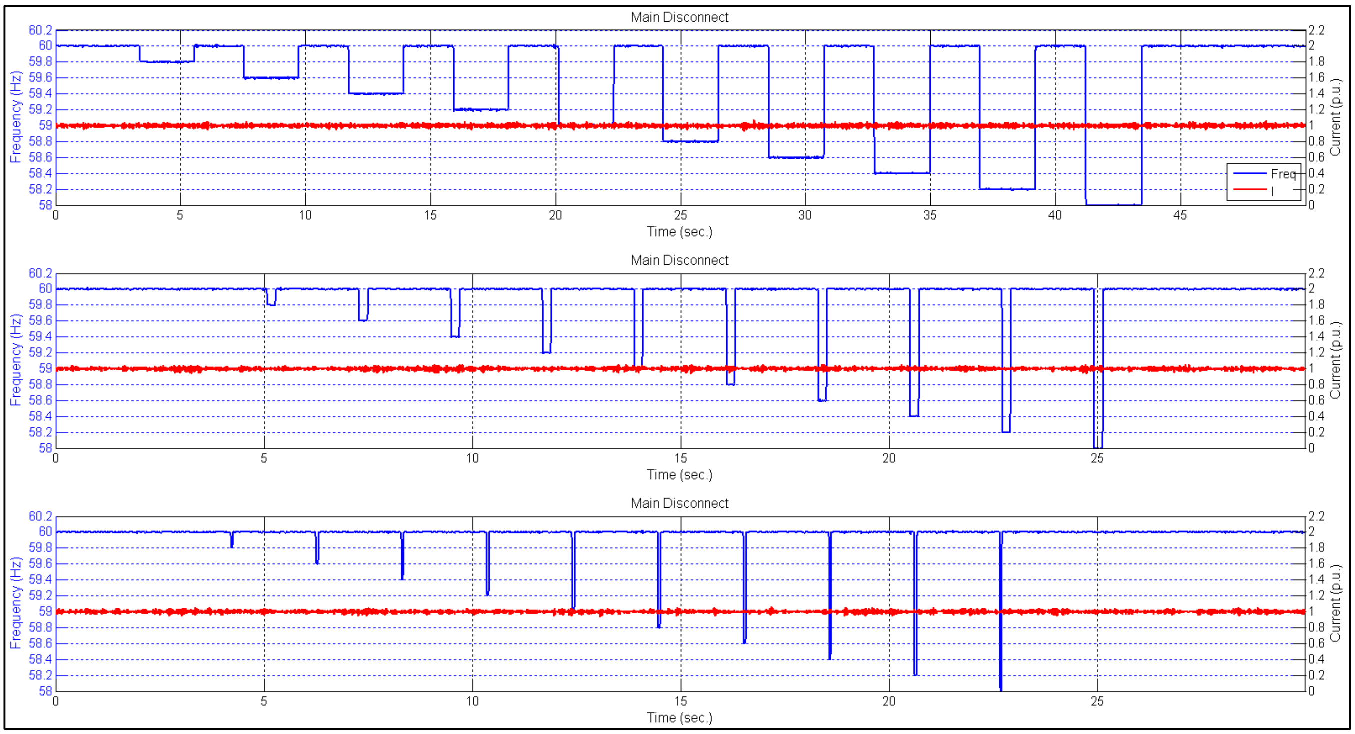

Figure 7.6.1 VFD A/C #5 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 7.6.1 VFD A/C #5 Under-frequency Test Results

7.7 Over-frequency Events

Similar to the under-frequency tests, VFD A/C #5 was subjected to over-frequency transients to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. Again, frequency of the motor is constant due to the VFD operations. The following figure and table identify the magnitude and duration of the specific over-frequency tests that were performed.

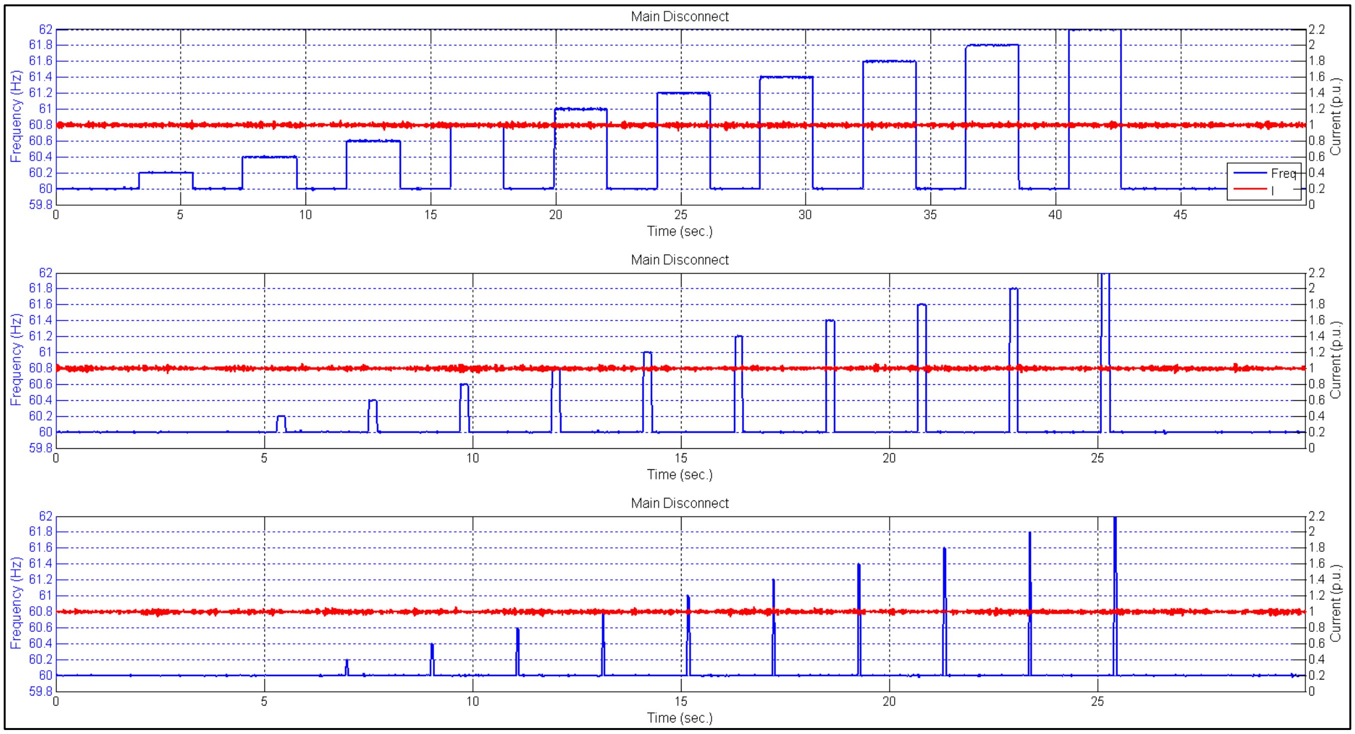

Figure 7.7.1 VFD A/C #5 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 7.7.1 VFD A/C #5 Over-frequency Test Results

7.8 Frequency Oscillations

The following figure shows the performance of VFD A/C #5 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates (0.10, 0.25, 0.70, 1.0, and 2.0 Hz).

Current does not oscillate or deviate in response to frequency oscillations at the main terminals of the A/C unit. The active power consumption remains constant as well, within ±2% of its steady state value along with current for all swing frequencies or oscillation rates.

Reactive power was not included in the figure below because of its low consumption (power factor is greater than 0.97). Even minor deviations that naturally occur during steady state cause significant changes to the per unit values plotted, making other measurements difficult to interpret.

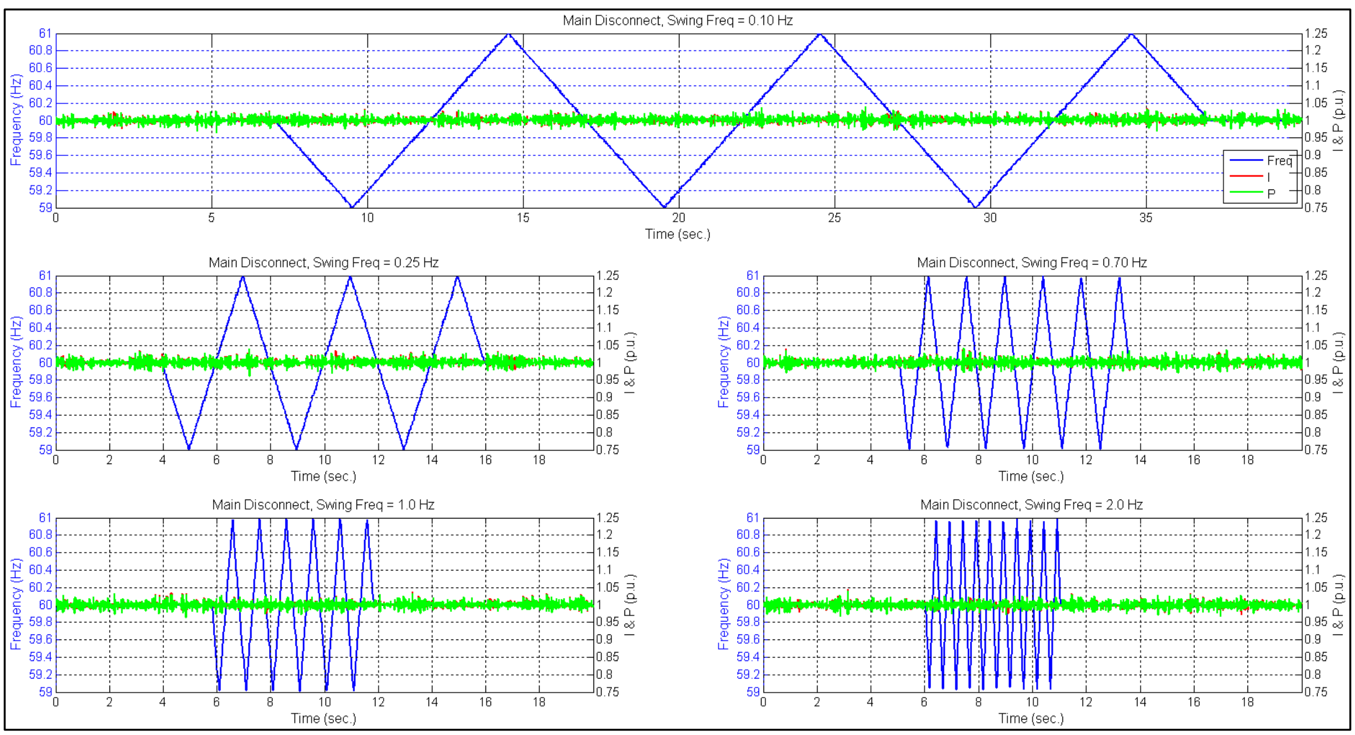

Figure 7.8.1 VFD A/C #5 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

7.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit tripped while ramping down to 40% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation (down to 50% nominal voltage).

Current ramps up to approximately 98% above nominal while voltage ramps down to 50% below nominal. Real power consumption is held constant for most of the voltage ramp test, within ±2% of nominal. However during both the 2 and 8 second ramp tests, current does experience a sudden decrease while ramping down to nominal which results in a reduction of real power consumption.

Reactive power consumption is low due to the large power factor, but it ramps down to nearly 17% of its nominal value at the bottom of the voltage ramp. Its behavior changes dramatically during voltage recovery, which was consistent in a number of voltage ramp tests.

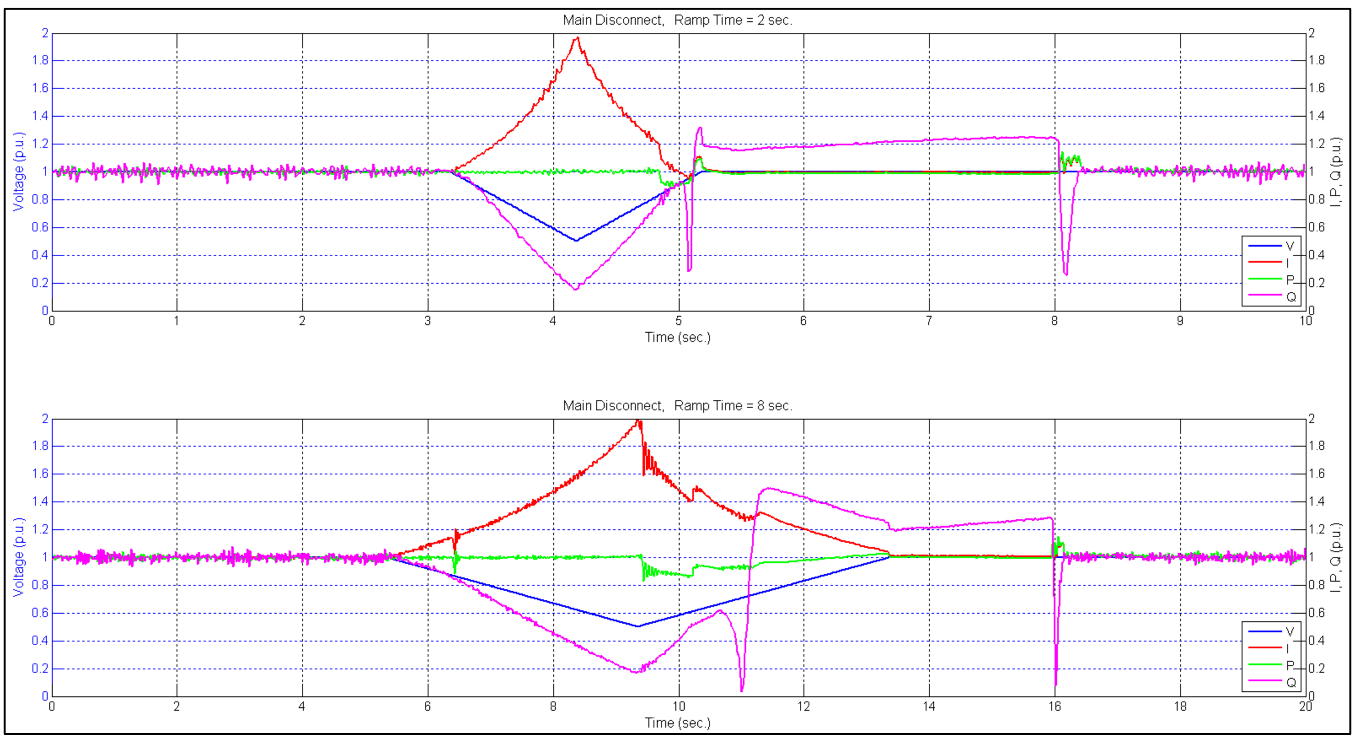

Figure 7.9.1 VFD A/C #5 Voltage Ramp Down to 50% (2 & 8 sec.)

Voltage was ramped up to 110% and back down steady state voltage at different ramp rates to demonstrate the load performance while operating at over-voltage values.

Current is observed ramping down to nearly 10% below nominal in response to voltage. Real power consumption remain relatively close to nominal for most of the voltage ramp, within +3% of steady state. Both current and real power take a sudden dip in consumption at the peak of the voltage ramp for faster 2 second test. Little reactive power is consumed during normal operation and therefore displays the greatest deviation from nominal.

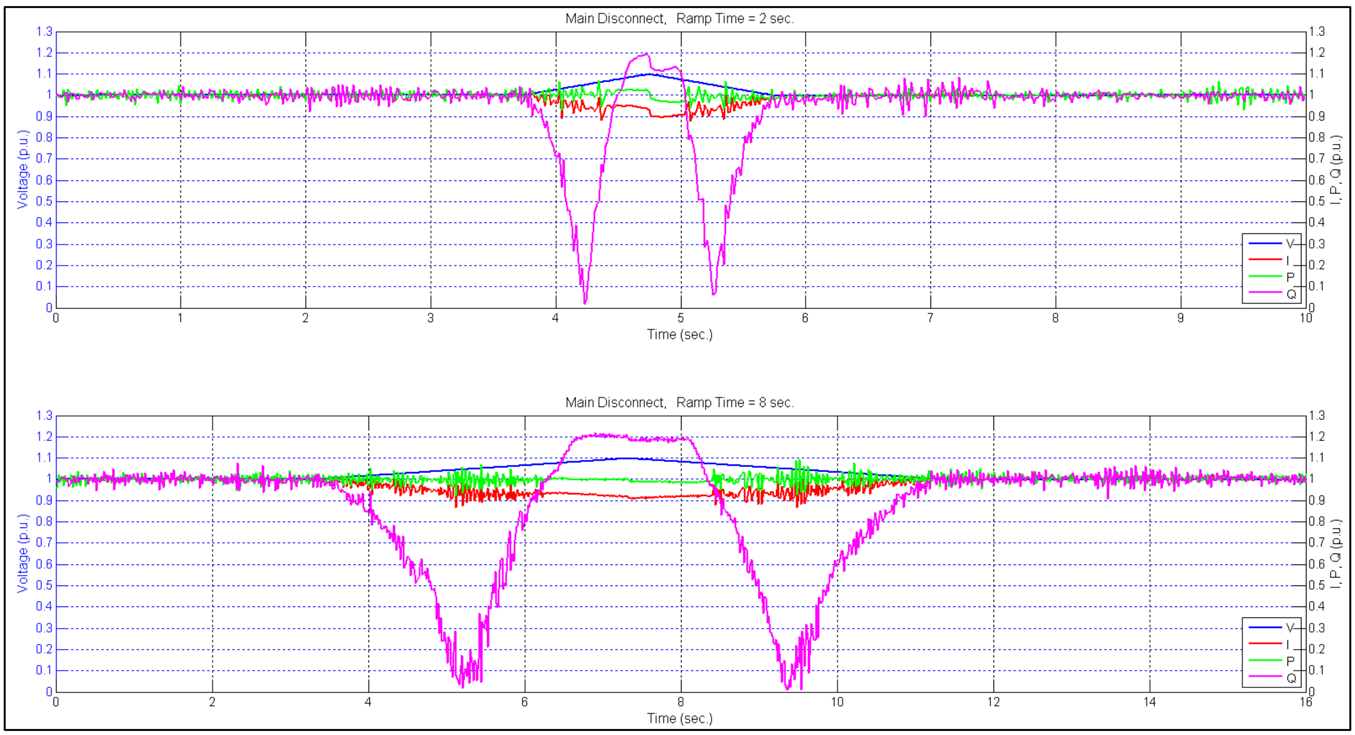

Figure 7.9.2 VFD A/C #5 Voltage Ramp Up to 110% (in 2 & 8 sec.)

7.10 Frequency Ramps

Frequency was ramped down to 50 Hz and back up to 60 Hz at different ramp rates to demonstrate the load performance while operating at lower frequency values as shown in the figure below.

The VFD does a good job maintaining the motor consumption at varying grid frequencies. Current and real power remain relatively constant, within ±3% of respective nominal values. Reactive power is low and also remains close to its value at steady state.

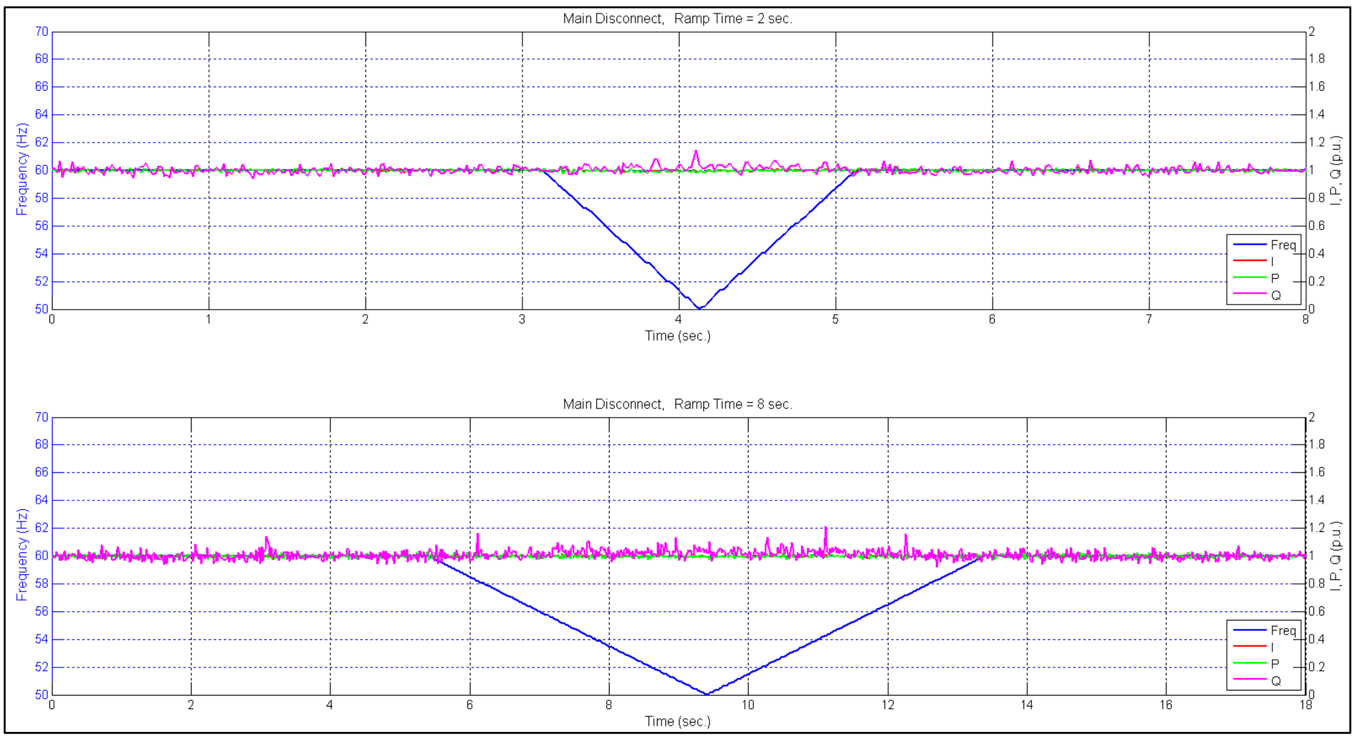

Figure 7.10.1 VFD A/C #5 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

Frequency was ramped up to 70 Hz and back down to 60 Hz at different ramp rates to demonstrate the load performance while operating at higher frequency values as shown in the figure below.

Similar to the under-frequency ramp test, current and real power remain relatively constant throughout the entire over-frequency ramp, within $\pm$3% of nominal. Reactive power consumption for the unit is already low due to a large power factor and does not reveal any type of response due to the increase in frequency.

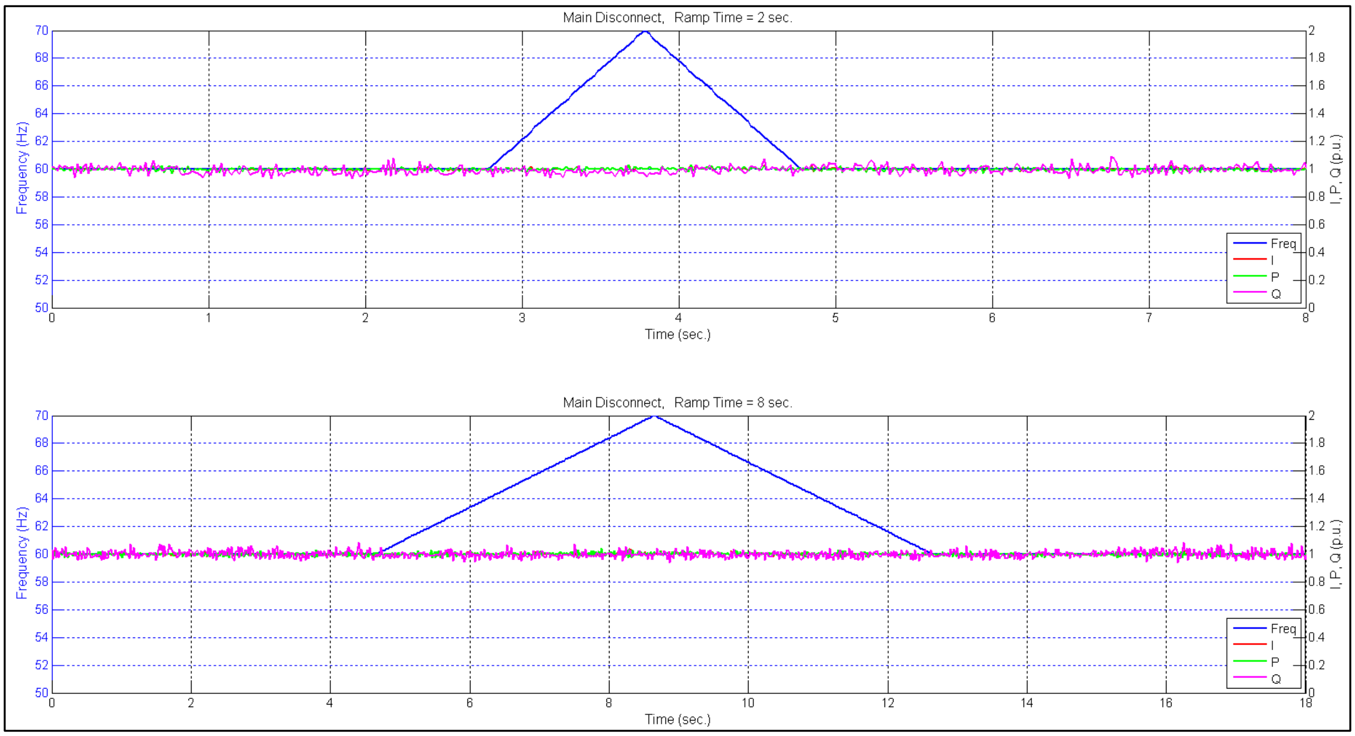

Figure 7.10.2 VFD A/C #5 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

7.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times without scope filters to calculate the actual harmonic contribution of VFD A/C unit #5 to the grid. The maximum total harmonic distortion of current discovered was 16.87% of the fundamental. The following table gives the total harmonic distortion calculations and the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)		
	$V_{(L1-L2)}$	$I_{(L1)}$	$I_{(L2)}$
1	0.22	16.82	16.87
2	0.23	16.34	16.40
3	0.22	16.25	16.30

Table 7.11.1 VFD A/C #5 Total Harmonic Distortion

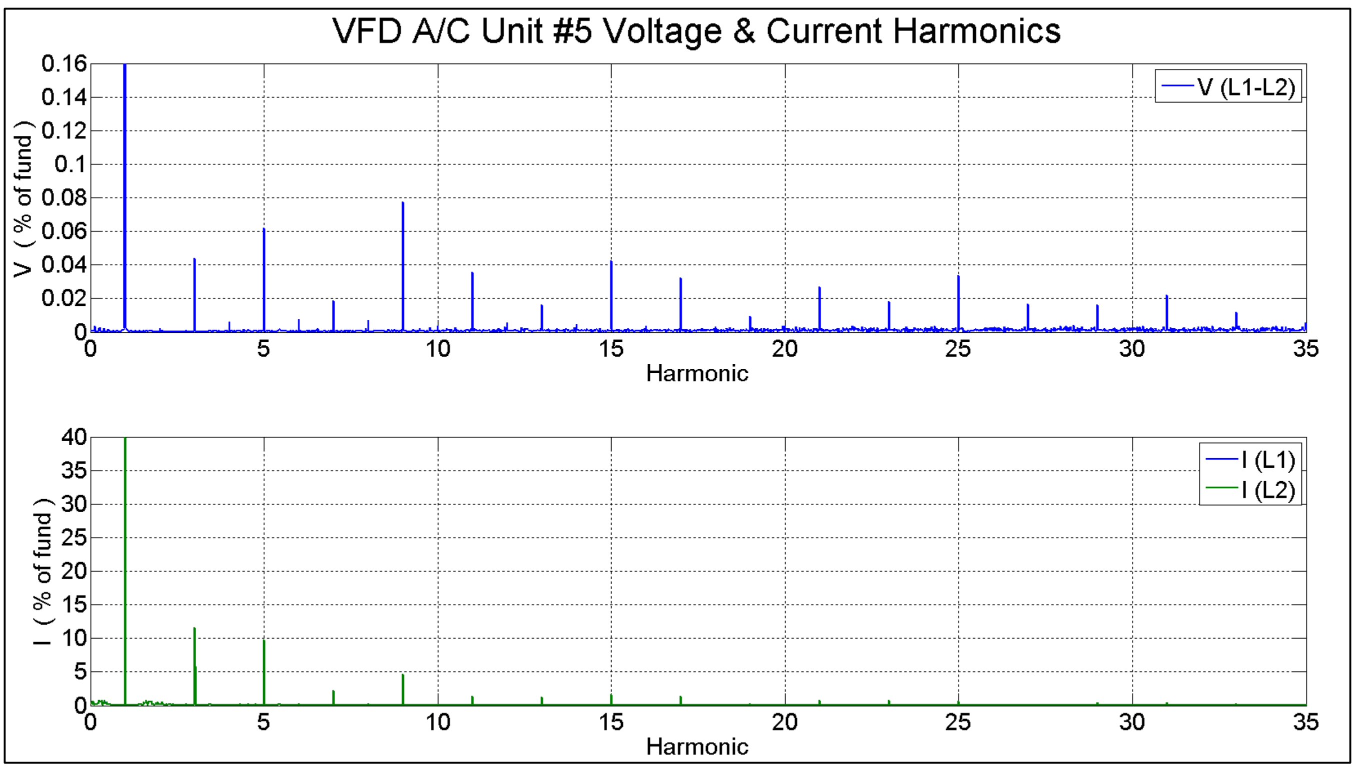

Figure 7.11.1 VFD A/C #5 Harmonics Contribution

7.12 Conservation Voltage Reduction

Voltage was decreased by 1% nominal voltage in 5 second intervals down to 90% before recovering back to steady state as shown in the figure below.

CVR would not be effective on this type of load device. Current increases by approximately 1.1% of nominal current for every 1% decrease in nominal voltage over the course of the CVR test. Therefore the real power consumption is fairly constant. Reactive power slowly decreases over time. All electrical measurements appear deviate in response to the shape of the current waveform as voltage begins recovering to nominal.

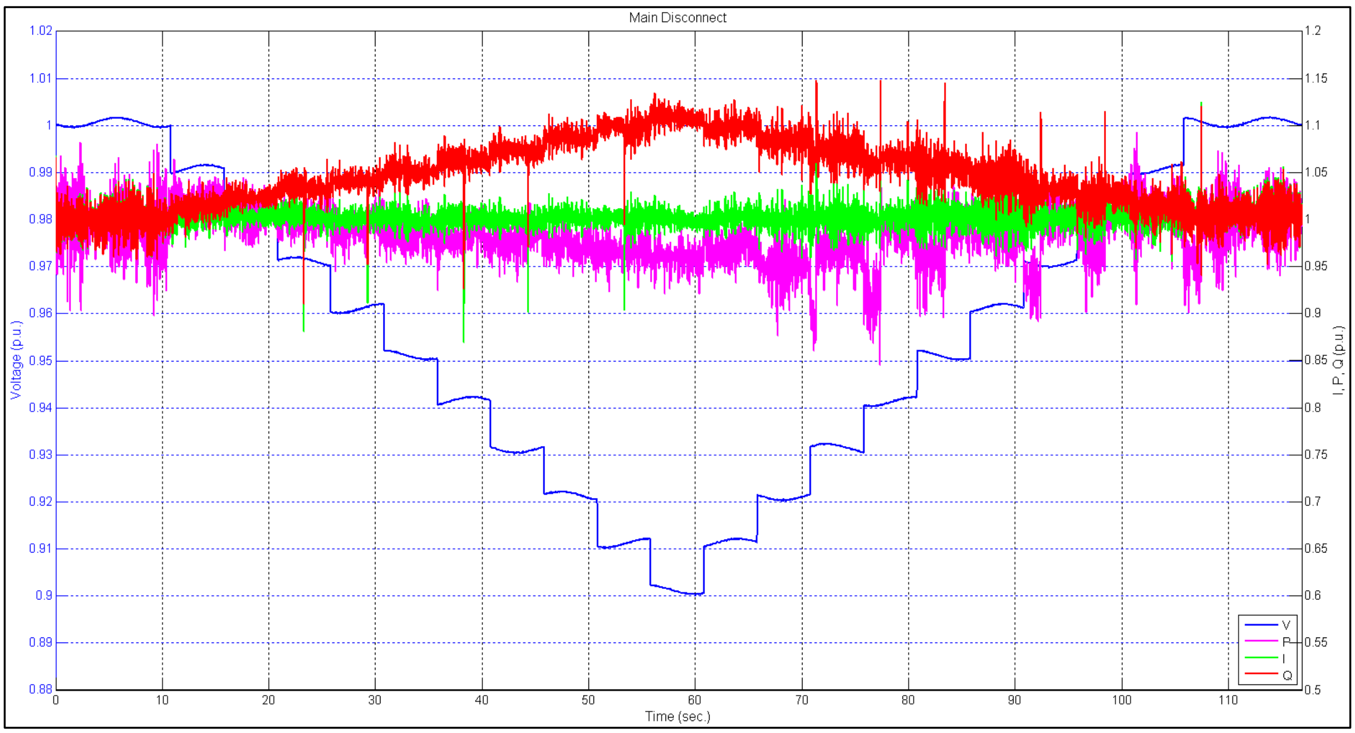

Figure 7.12.1 VFD A/C #5 CVR Response Down to 90% Voltage

Alternatively, the main terminal voltage at the VFD A/C unit was increased by 1% nominal voltage in 5 second intervals up to 105% before stepping back to steady state as shown in the figure below.

The average current decreases down to 7% below nominal as voltage increases. Therefore real power remains near steady state consumption, with ±2% of nominal. Reactive power consumption is low but progressively decreases in response to the voltage increase.

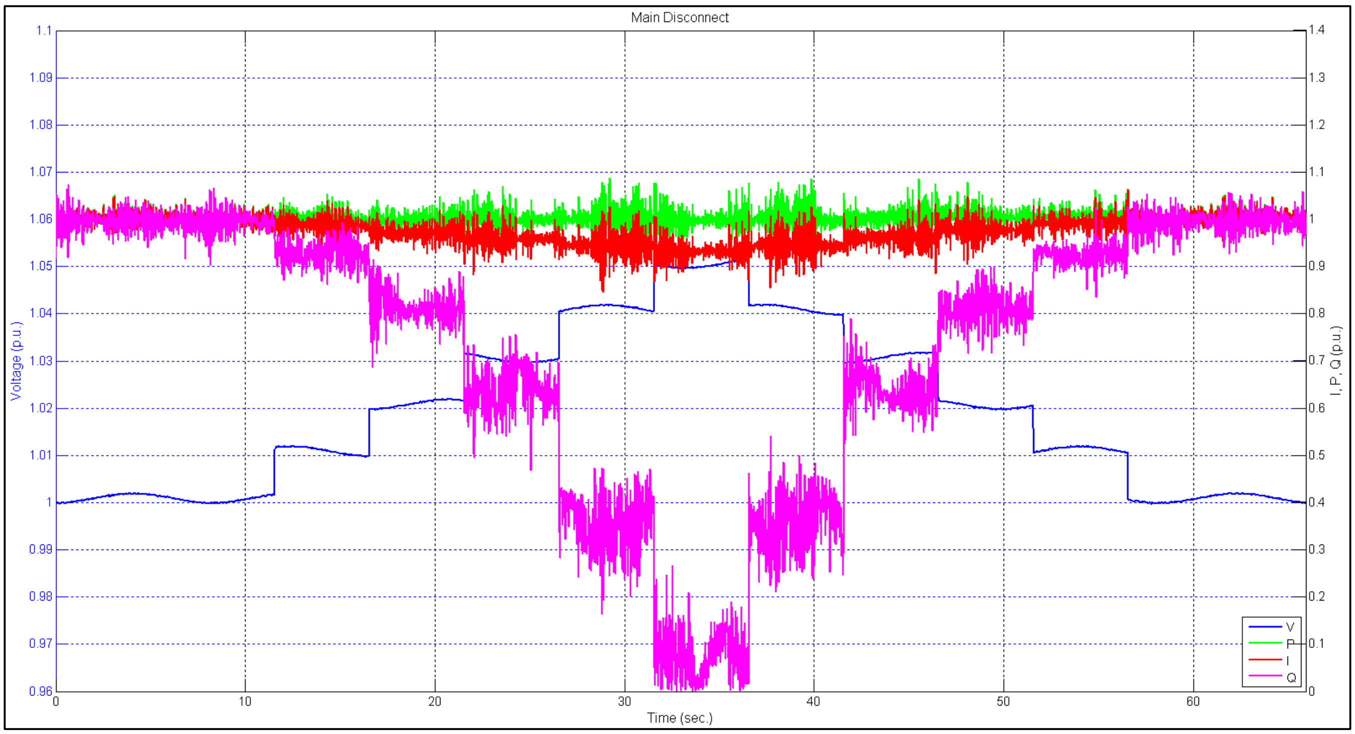

Figure 7.12.2 VFD A/C #5 CVR Response Up to 105% Voltage

8.0 VFD AIR CONDITIONER #6 TEST RESULTS

The figure below shows a snapshot of VFD A/C unit #6 sinusoidal voltages and currents captured at the main terminals and compressor motor using a filter on the digital scope. The main currents are significantly different from a traditional sinusoidal shaped waveform. The compressor is operating at approximately 170 Volts peak, 20 Amps peak, and 111 Hz at the observed loading condition. The specifications for the VFD A/C #6 components are provided in the table below.

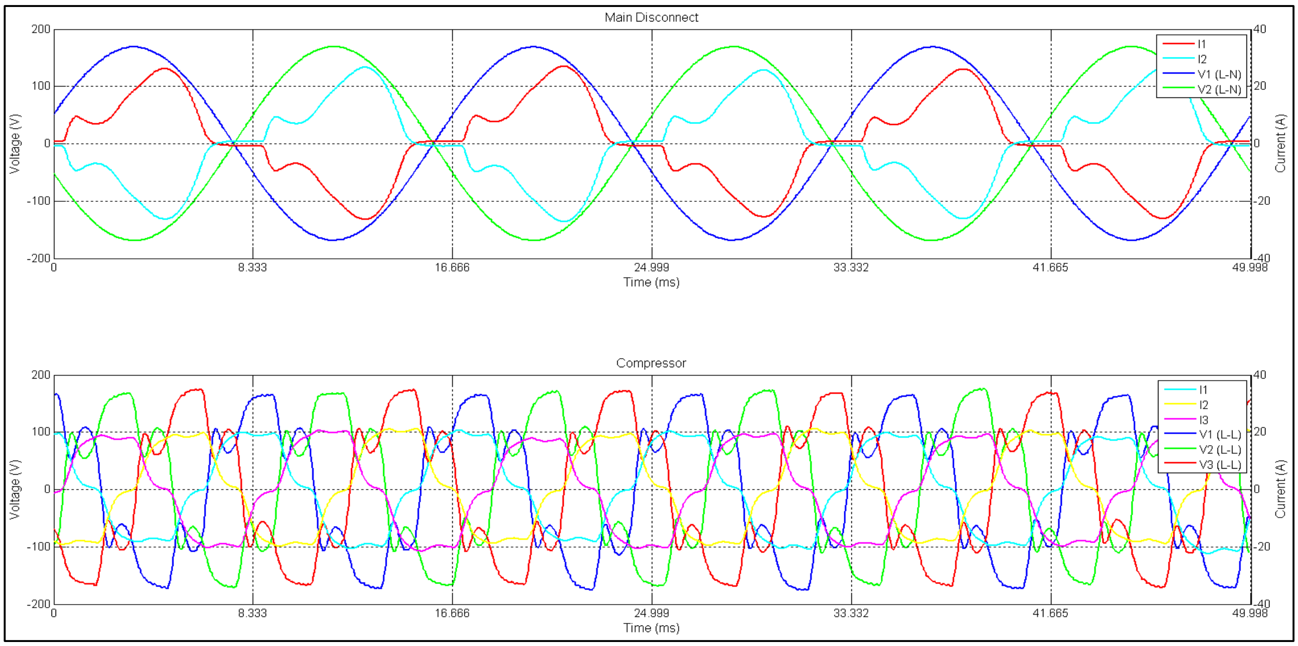

Figure 8.0.1 VFD A/C #6 Voltage and Current Waveforms

Manufacturer	Panasonic
Voltage (V)	230
Refrig.	R-410A
SEER	16
Compressor, Model #	SANYO C-9RVN273HOH
Compressor, RLA (Amps)	18.9
Compressor, LRA (Amps)	-
Outdoor Fan Motor, FLA (Amps)	0.7
Indoor Fan Motor, FLA (Amps)	0.7
Design Pressure High (PSI)	489
Design Pressure Low (PSI)	235

Table 8.0.1 VFD A/C #6 Specifications

8.1 Compressor Shutdown

VFD A/C #6 was shut down during normal operation using the programmable thermostat remote for the indoor blower unit. The figure below displays the measurements taken at the main terminal connections of the entire A/C unit.

The fans and compressor shut down immediately after changing settings on the programmable thermostat. The delay time for current to ramp down is incredibly short, within 5 cycles. Once the unit is in standby mode, the device's power consumption is less than 0.5 Amps.

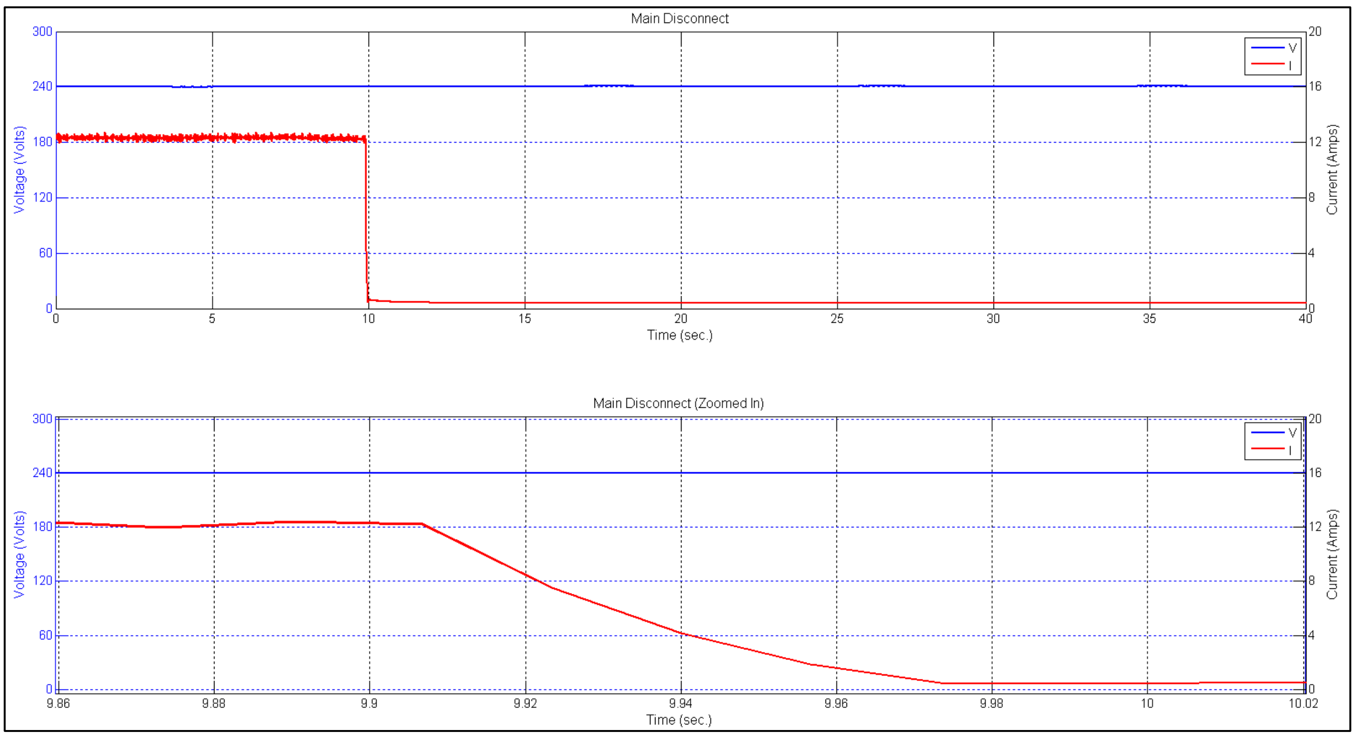

Figure 8.1.1 VFD A/C #6 Compressor Shutdown

8.2 Inrush Current

After starting up the VFD A/C unit via the programmable thermostat remote, the device does not display any sign of significant inrush current. The unit compressor load ramps up in nearly to steady state in approximately 20 seconds and then slightly increases over the next 10 seconds. The VFD compressor will increase in intervals over the course of several minutes to meet temperature demand until the unit is more heavily loaded. The room temperature was approximately 78 degrees Fahrenheit and the unit would typically operate between 12.8 and 13.8 Amps steady state.

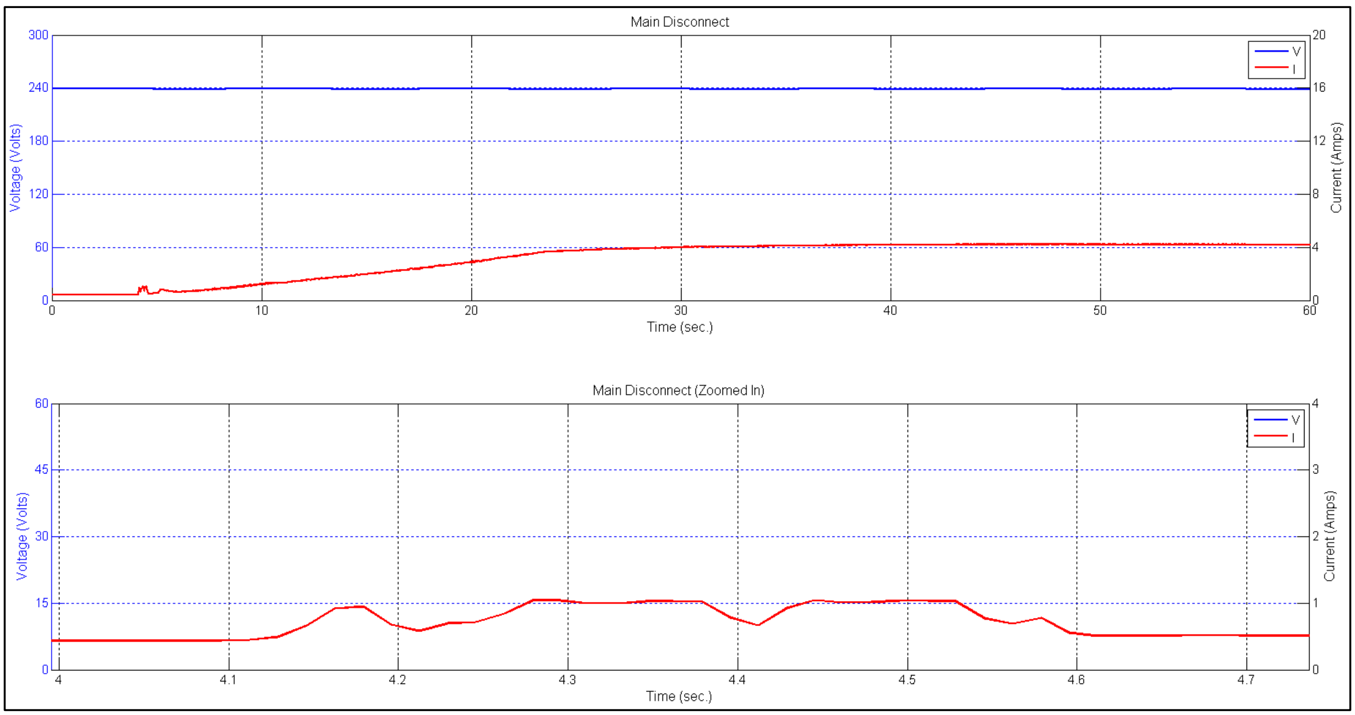

Figure 8.2.1 VFD A/C #6 Inrush Current

8.3 Balanced & Unbalanced Under-voltages

VFD A/C #6 was subjected to a series of balanced under-voltage sags in decrements of 10% to identify the conditions required to cause device dropout and tripping behavior. The unit consistently disconnected the compressor at 80% nominal voltage for longer sags with a duration of 130 cycles. Shorter voltage sags with a duration of 12 cycles to 6 cycles typically resulted in the compressor being tripped at 50% nominal voltage. An important observation in Table 8.3.1 is that the VFD A/C unit would always disconnect the compressor within 3 cycles after voltage recovered from a sag. A theory is that this may be caused by the spike or inrush current observed when voltage returns to nominal at the end of the sag. Another, less likely, possibility is that the controller PCB on the outdoor condensing unit operating to prevent loss of load until voltage recovers.

Although data points were captured several seconds after the compressors were disconnected, no restarting behavior was observed and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor was only observed restarting several minutes after tripping occurred. No stalling was observed during transients or upon restarting.

Any voltage sags with a duration less than 3 cycles usually did not cause the compressor to disconnect, allowing it to ride through all voltage magnitudes (down to 0% voltage). “N/A” or “not applicable” represents these ride through situations where there is no trip voltage or trip time available in the following tables.

The following figure visually displays one of the balanced tests where the under-voltage sags have a duration time of 130 cycles. The figure reveals that the compressor was disconnected at 80% voltage almost immediately after voltage recovers from the 130 cycle voltage sag. The following table provides the voltage magnitude (V_{trip}) where the compressor shut down and time (t_{trip}) taken after the under-voltage started for the A/C unit’s controls to trip it off.

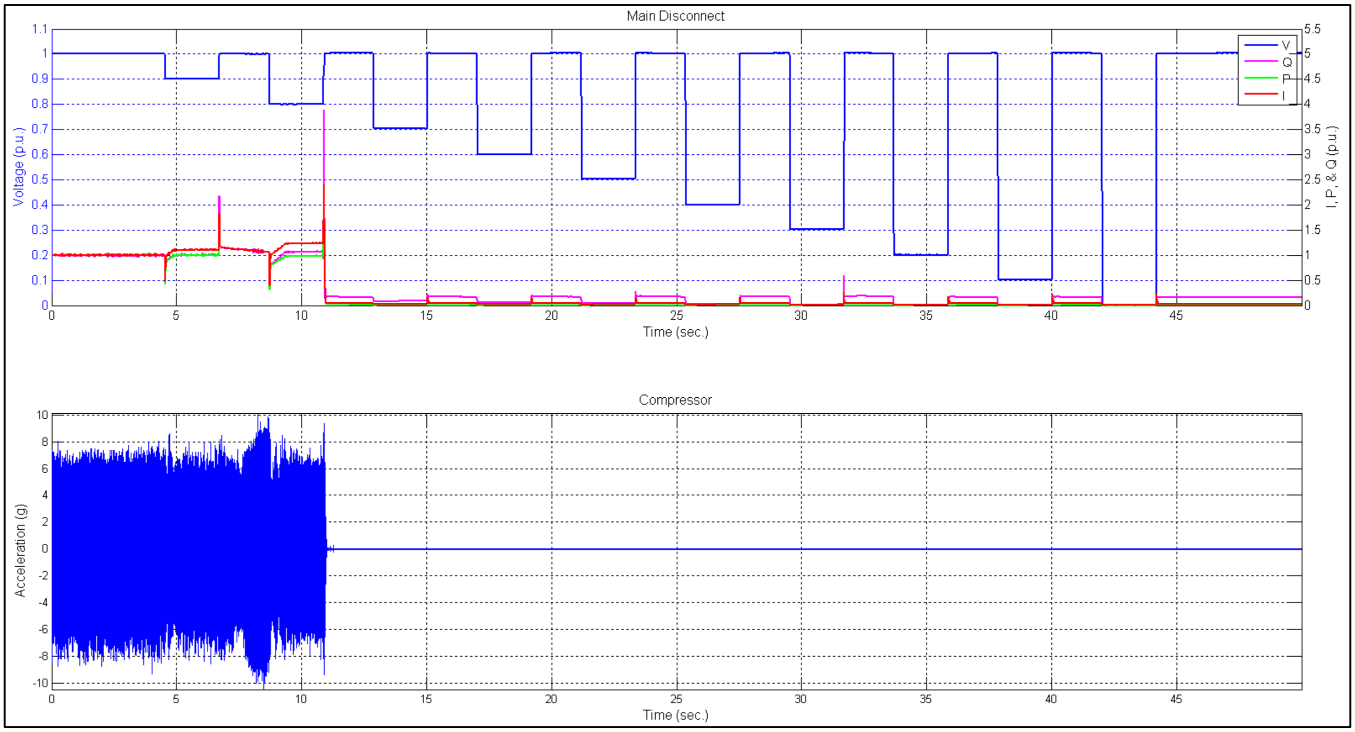

Figure 8.3.1 VFD A/C #6 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	80%	131.9
		80%	132.9
		80%	131.8
100%, 90%, 80%,... 0%	12	50%	13.2
		50%	12.6
		50%	13.8
100%, 90%, 80%,... 0%	9	60%	11.4
		50%	10.8
		50%	10.2
100%, 90%, 80%,... 0%	6	50%	7.2
		50%	7.8
		50%	8.4
100%, 90%, 80%,... 0%	3	0%	3.6
		N/A	N/A
		N/A	N/A
100%, 90%, 80%,... 0%	1	N/A	N/A
		N/A	N/A
		N/A	N/A

Table 8.3.1 VFD A/C #6 Balanced Under-voltages in 10% Decrements Results

Additional balanced under-voltage tests in decrements of 1% nominal voltage were performed to verify where the controls drop out causing the compressor to be disconnected. The tests showed that the compressor would consistently be disconnected between 81% and 84% nominal voltage for 130 cycle voltage sags and at 56% nominal voltage for 12 cycle voltage sags. Again, the compressor is consistently disconnected within 1.8 cycles after voltage recovers from the sag likely due to the sudden increase in current at the end of the voltage sag. The following table provides the details of the compressor disconnection behavior during some these 1% voltage decrement tests.

Under-Voltage Transient		Compressor	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)
90%, 89%, 88%,…	130	81%	130.1
90%, 89%, 88%,…	130	85%	130.2
90%, 89%, 88%,…	130	84%	131.8
60%, 59%, 58%,…	12	56%	12.2

Table 8.3.2 VFD A/C #6 Balanced Under-voltages in 1% Decrements Results

The unbalanced under-voltages on VFD A/C #6 were consistent with some of the balanced under-voltage tests with respect to the line-to-line voltage at the main terminals, but not all voltage sag tests. The unit has similar dropout/tripping behavior as the balanced tests for 130 cycle and 6 cycle voltage sags (80% - 85% and 55% line-to-line nominal voltage). However, the dropout/tripping voltages for 12 and 3 cycles are higher than observed during balanced under-voltage tests. Tripping doesn’t occur until voltage already recovers from an under-voltage condition, up to 3 cycles after voltage recovered. Ride through behavior for all voltage magnitudes was consistent for 1 cycle sags.

The following figure shows an example of these unbalanced cases (Line 2 under-voltages for 130 cycles) where the compressor shut down after recovering from the 70% nominal line-to-neutral voltage sag. The following table provides the compressor disconnection behavior during unbalanced voltage transients as observed at the main terminals of the VFD A/C unit, including the voltage magnitudes where disconnection occurs and how long it takes to disconnect after the voltage sag begins. As previously noted, the trip times for this A/C unit were longer than the actual voltage sag.

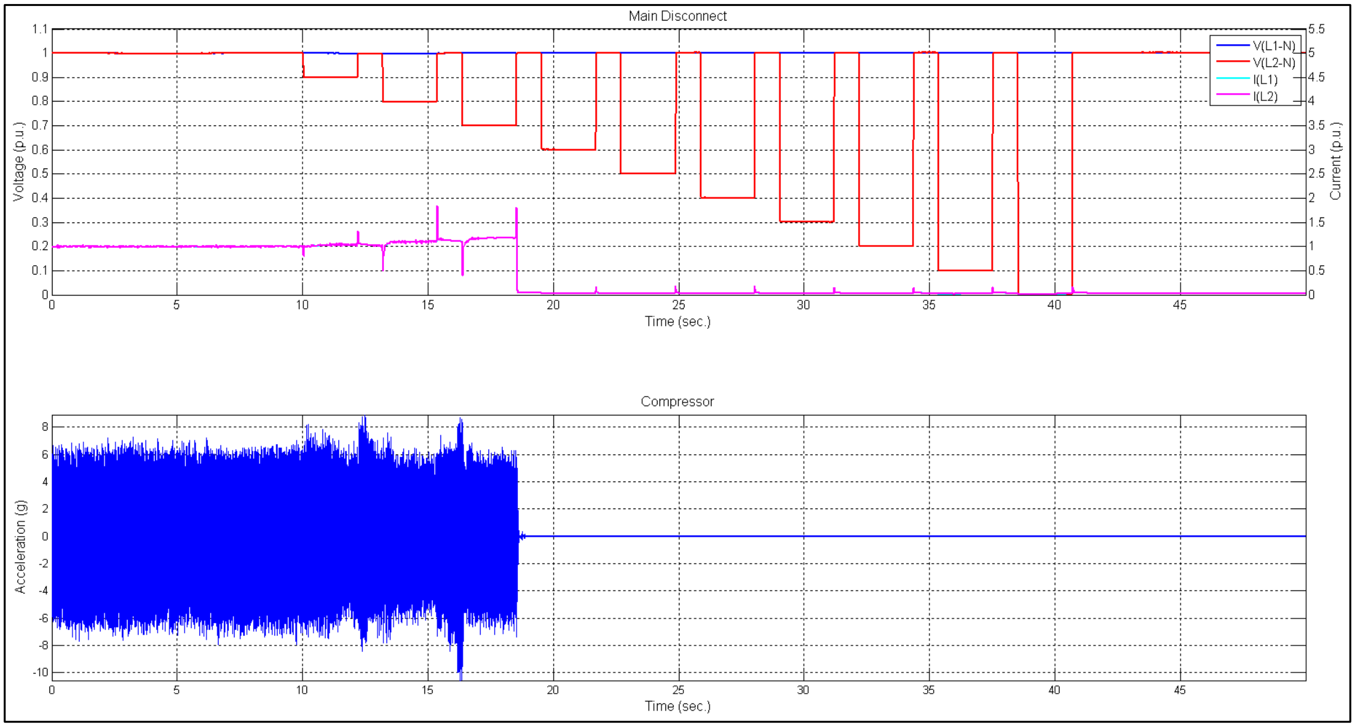

Figure 8.3.2 VFD A/C #6 Unbalanced Under-voltage Response (Line 2, 130 cycles)

Under-Voltage Transient			Compressor		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1	100%, 90%, 80%,... 0%	130	60%	80%	130.8
		12	50%	75%	12.6
		6	10%	55%	7.2
		3	50%	75%	5.4
		1	N/A	N/A	N/A
L2	100%, 90%, 80%,... 0%	130	70%	85%	132
		12	70%	85%	13
		6	10%	55%	9
		3	50%	75%	4.8
		1	N/A	N/A	N/A

Table 8.3.3 VFD A/C #6 Unbalanced Under-voltage Results

8.4 Balanced & Unbalanced Over-voltages

The VFD A/C unit was subjected to balanced and unbalanced over-voltages performed in 2% increments for up to 120% nominal voltage within the parameters of the ITIC (CBEMA) curve, a voltage tolerance curve, to avoid device damage. No over-voltage protection was observed during any of these tests, only voltage ride-through. The following figure shows a sample over-voltage test and the following table specifies the types of tests performed.

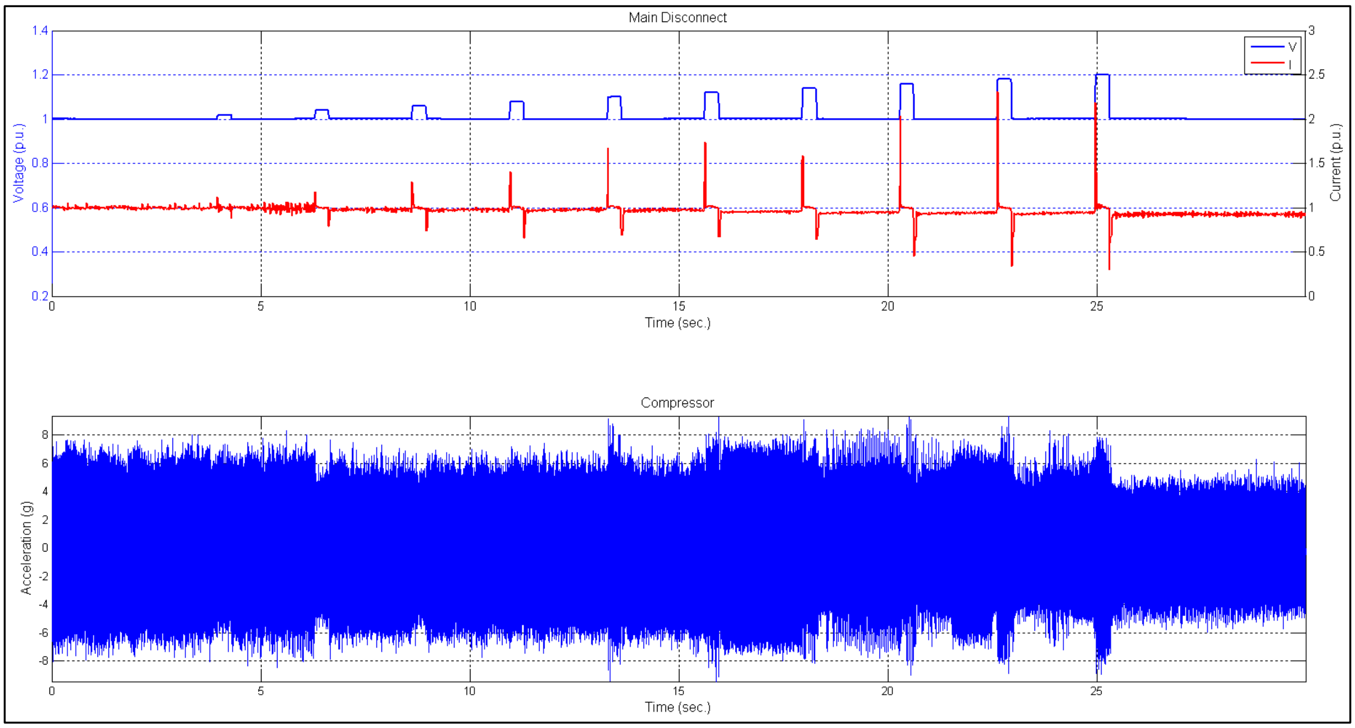

Figure 8.4.1 VFD AC #6 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		
Lines	Volt Range	Duration (cyc)	$V_{trip\ L\text{-}N}$ (%)	$V_{trip\ L1\text{-}L2}$ (%)	t_{trip} (cyc)
L1 & L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L1	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A

Table 8.4.1 VFD A/C #6 Balanced & Unbalanced Over-voltage Results

8.5 Voltage Oscillations

The following figure shows the performance of VFD A/C unit #6 during voltage oscillations between 100% and 90% nominal voltage for a variety of swing frequencies or oscillation rates.

Current oscillates in the opposite direction of voltage, up to 9% or 10% above nominal, for oscillation rates between 0.10 Hz and 0.25 Hz. In response to current, the real power deviates within +4% of nominal. As the oscillation rate increases, the current deviations become larger (e.g. up to 15% above nominal at 2 Hz) and the shape of the current profile becomes less linear. During these faster oscillation rates, the real power profile begins deviating with current within +15% of nominal.

Reactive power oscillates in the same direction as voltage. Deviations remain similar during oscillations at higher swing frequencies or faster oscillation rates. Reactive linearly ramps down 15% below steady state.

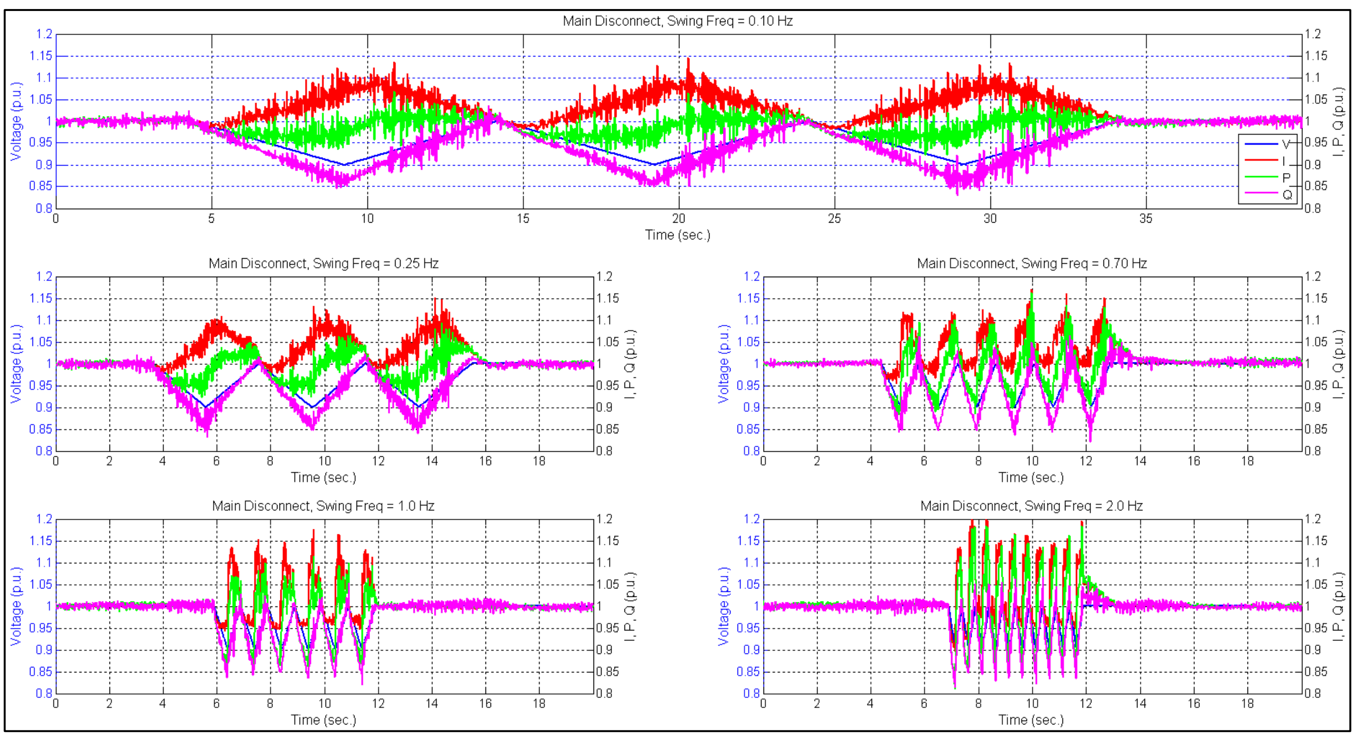

Figure 8.5.1 VFD AC #6 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

8.6 Under-frequency Events

After subjecting the VFD A/C unit to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection while operating between 60 Hz and 58 Hz. The device simply rides through these under-frequency conditions. The constant current suggests that the VFD is effectively maintaining motor load. The following figure and table identify the magnitude and duration of the frequency transient tests that were performed on VFD A/C #6.

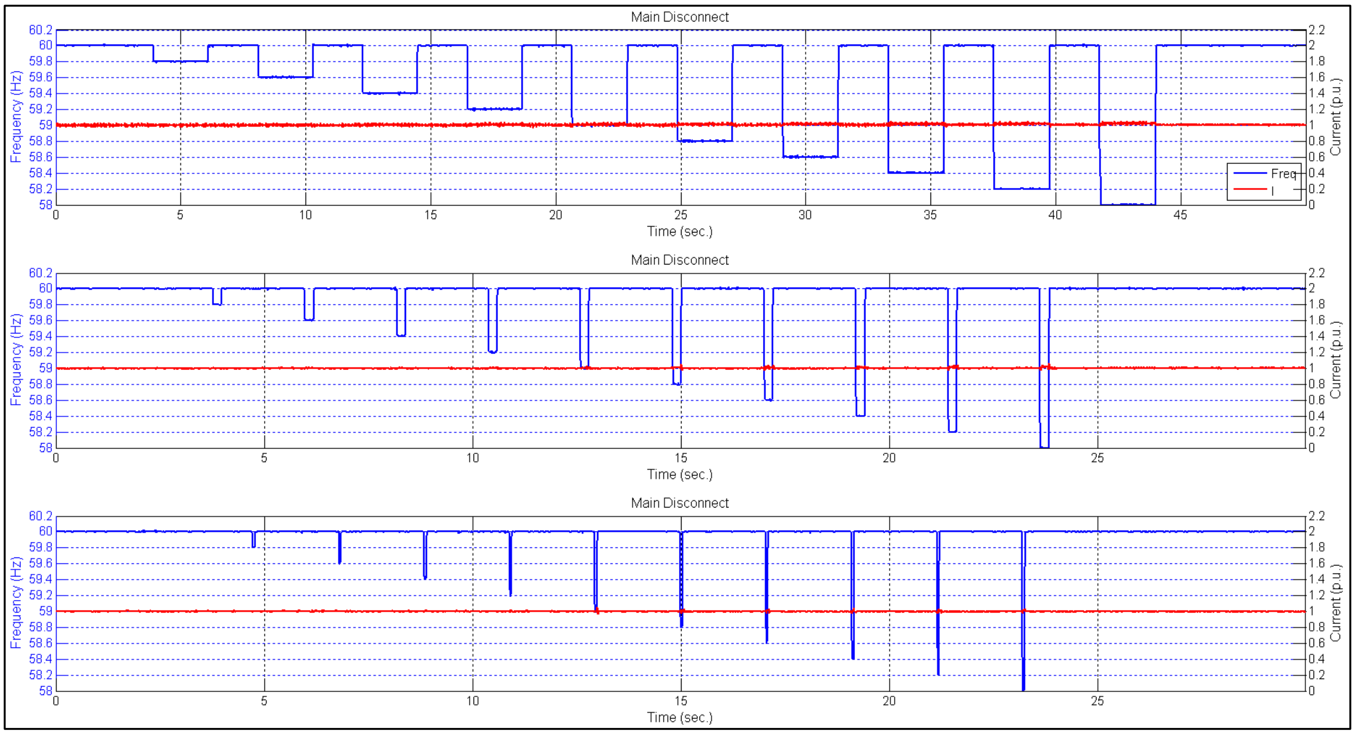

Figure 8.6.1 VFD A/C #6 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 8.6.1 VFD A/C #6 Under-frequency Test Results

8.7 Over-frequency Events

Similar to the under-frequency tests, the VFD A/C unit was subjected to over-frequency transients to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The constant current suggests that the VFD is effectively maintaining motor load. The following figure and table identify the magnitude and duration of the specific over-frequency tests that were performed on VFD A/C #6.

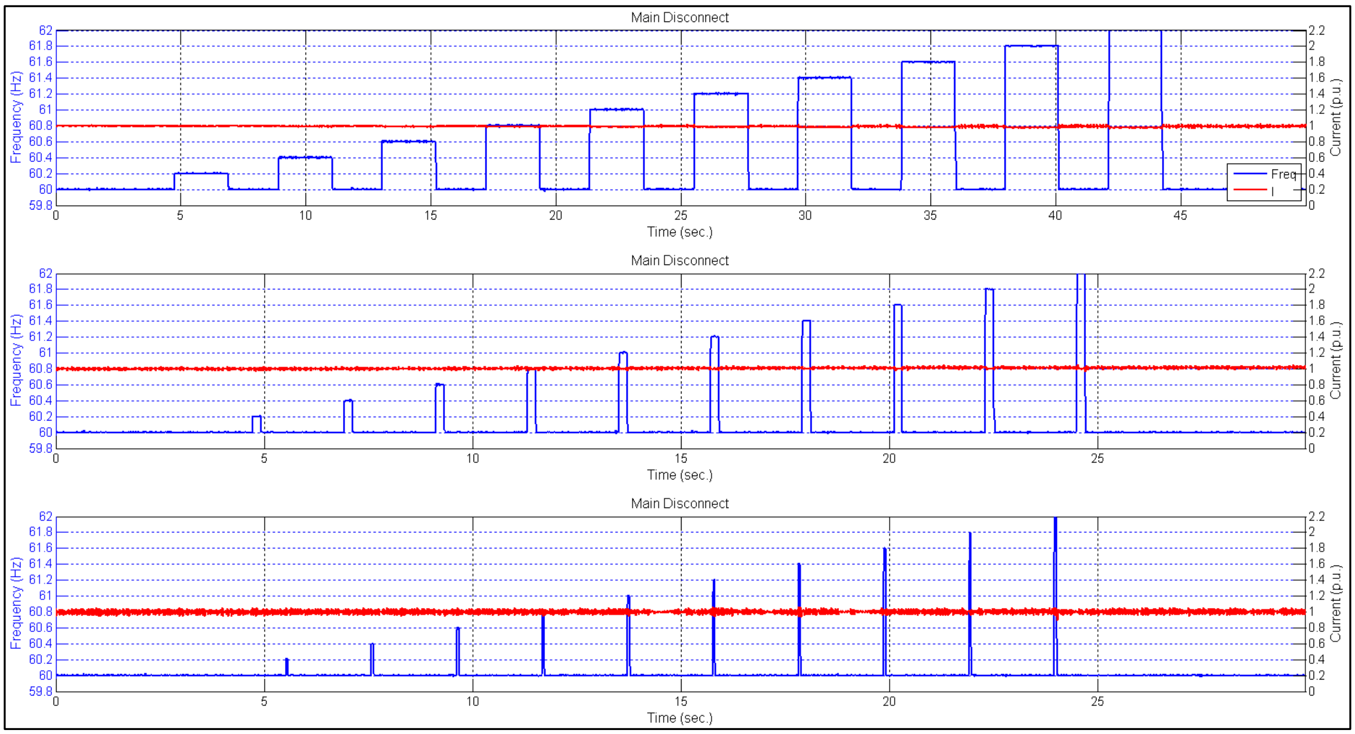

Figure 8.7.1 VFD A/C #6 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 8.7.1 VFD A/C #6 Over-frequency Test Results

8.8 Frequency Oscillations

The following figure shows the performance of VFD A/C #6 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates (0.10, 0.25, 0.70, 1.0, and 2.0 Hz).

Although the current and real power measured at the main terminals of the VFD A/C slightly oscillate in the opposite direction as voltage at faster oscillation rates, both values stay relatively constant for 0.10 Hz and 0.25 Hz. Overall, both remain within +5% of their respective steady state values.

Reactive power oscillates in the opposite direction of voltage as well and deviations from nominal are similar for all oscillation rates. Reactive power consumption remains within +5% of nominal.

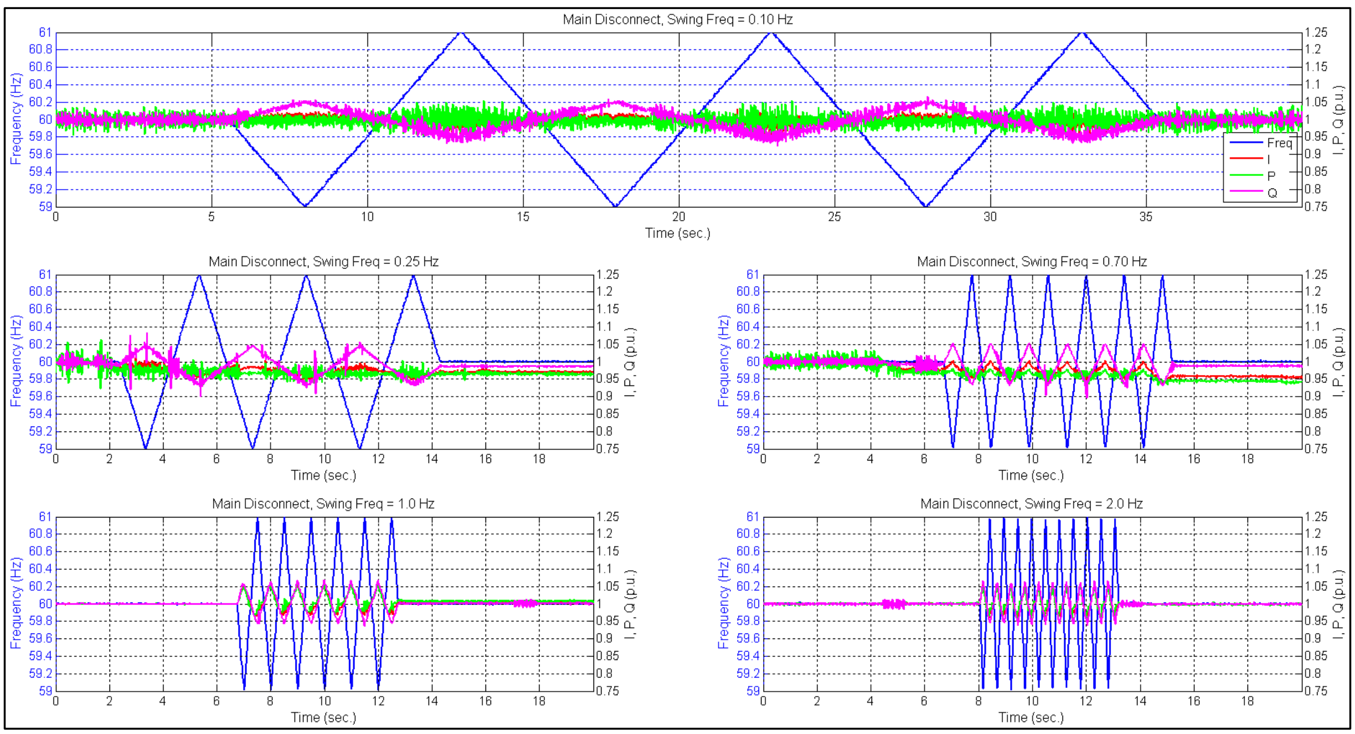

Figure 8.8.1 VFD A/C #6 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

8.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the VFD A/C unit tripped while ramping down to 60% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation (down to 70% nominal voltage).

Similar to VFD A/C #4, the unit has a delay in the control response for current and real power. Current initially decreases initially by 11% below nominal at the beginning of the 2 second ramp and increases to approximately 15% above nominal as voltage recovers. For the 8 second ramp test however, current ramps up to 45% above nominal before reducing during voltage recovery. Current, real, and reactive power are all above their nominal values as voltage returns to steady state and take approximately 1.5 to 4 seconds before they reach steady state.

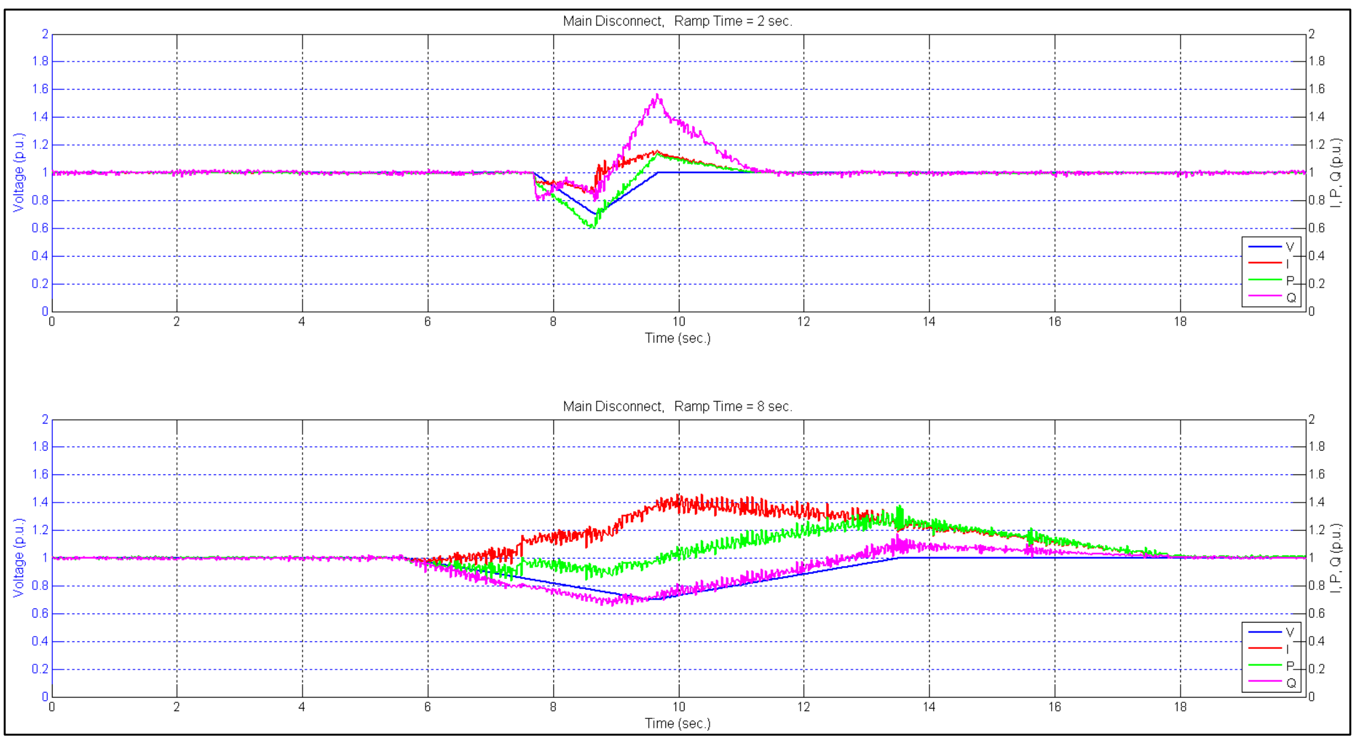

Figure 8.9.1 VFD A/C #6 Voltage Ramp Down to 70% (2 & 8 sec.)

Voltage was ramped up to 110% and back down steady state voltage at different ramp rates to demonstrate the load performance while operating at over-voltage values.

Current is decreases as low as 10% below nominal in response to the voltage ramp. Real power consumption stays within ±4% of steady state for the 8 second ramp tests, but increases up to 10% above nominal for the 2 second ramp test due to the delayed response of current. Reactive power is ramps up and back down with voltage, peaking at approximately 11% of nominal.

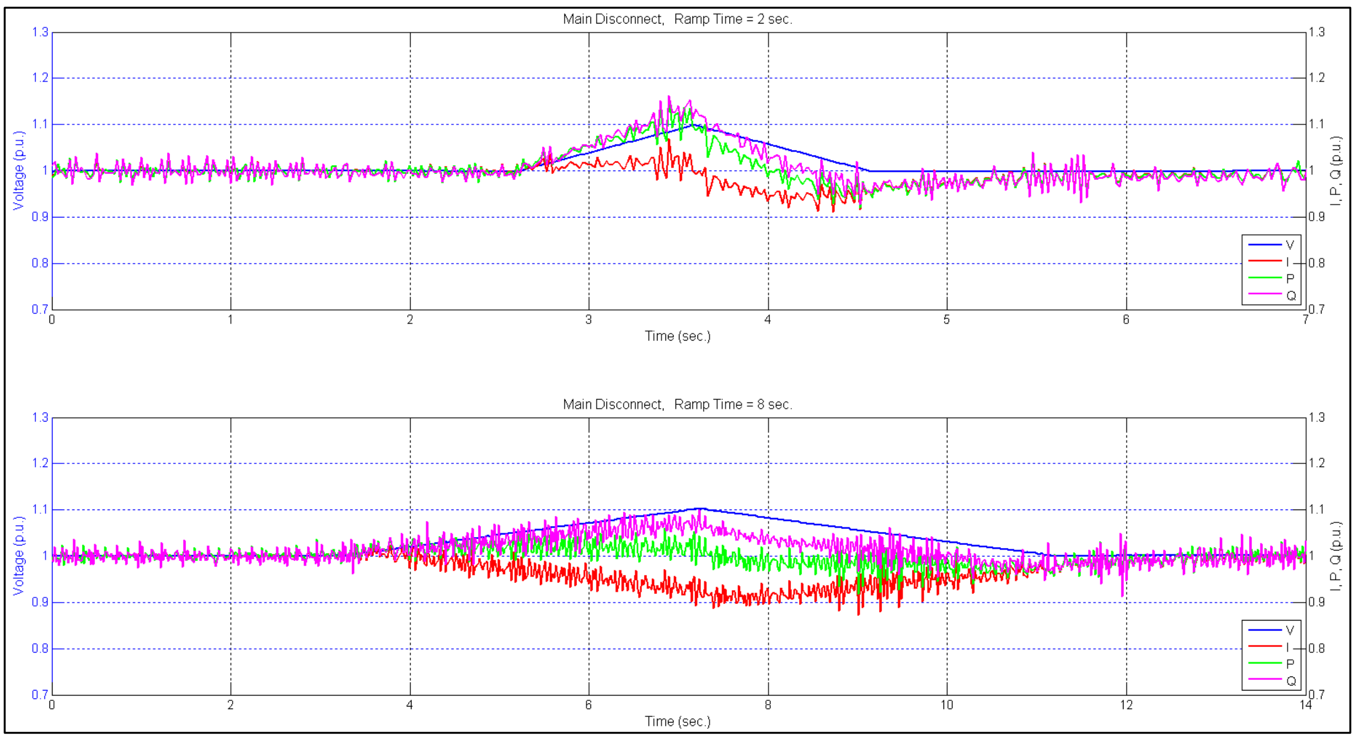

Figure 8.9.2 VFD A/C #6 Voltage Ramp Up to 110% (in 2 & 8 sec.)

8.10 Frequency Ramps

Frequency was ramped down to 50 Hz and back up to 60 Hz at different ramp rates to demonstrate the load performance while operating at lower frequency values as shown in the figure below.

It appears the VFD is attempting to maintain motor load when there are large deviations in grid frequency. Following an increase of 10%, current slowly decreases during the frequency ramp test as low as 6% below nominal. Real power does not fall below its nominal consumption. Reactive power decreases down to 20% below steady state during the under-frequency ramp.

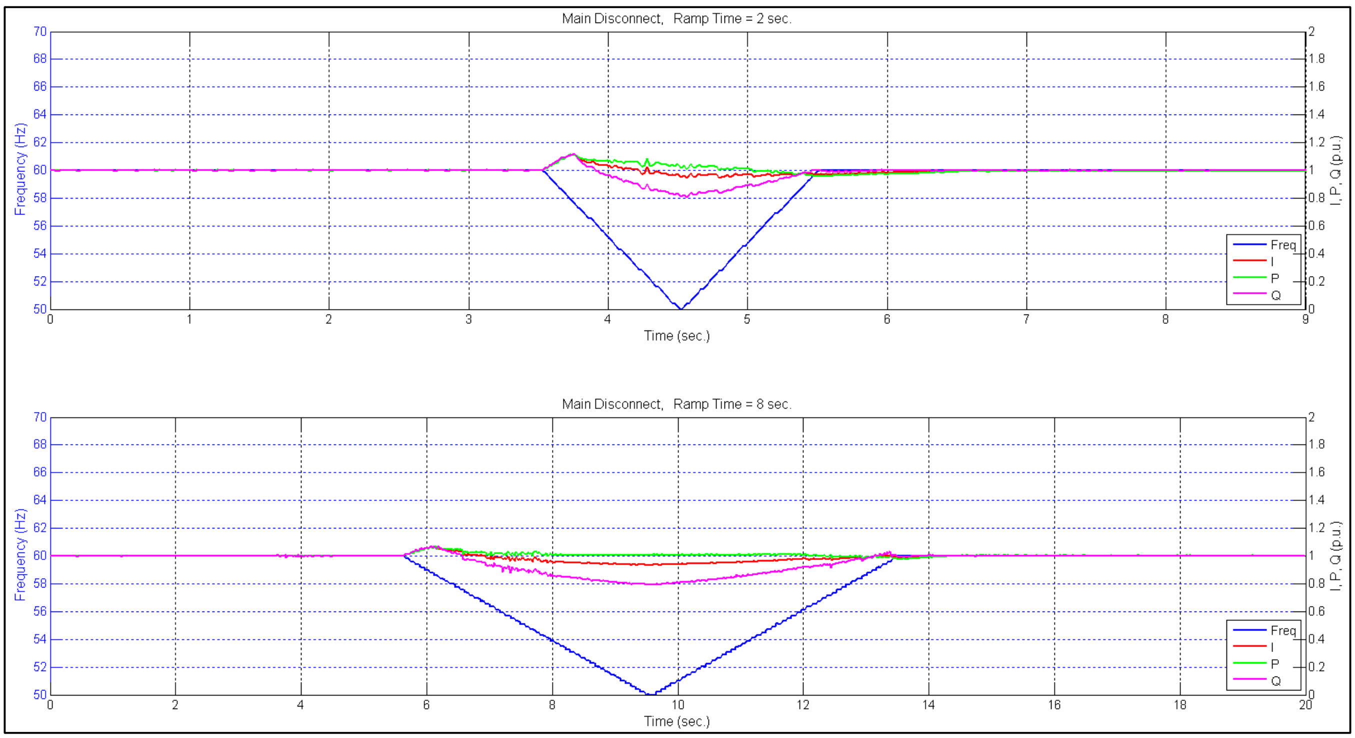

Figure 8.10.1 VFD A/C #6 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

Frequency was ramped up to 70 Hz and back down to 60 Hz at different ramp rates to demonstrate the load performance while operating at higher frequency values as shown in the figure below.

Current slowly ramps down until plateauing at approximately 15% below nominal current. Real power remains relatively close to steady state consumption throughout the frequency ramp. Reactive power displays the greatest decrease in consumption as it ramps up until it at 43% below its nominal value.

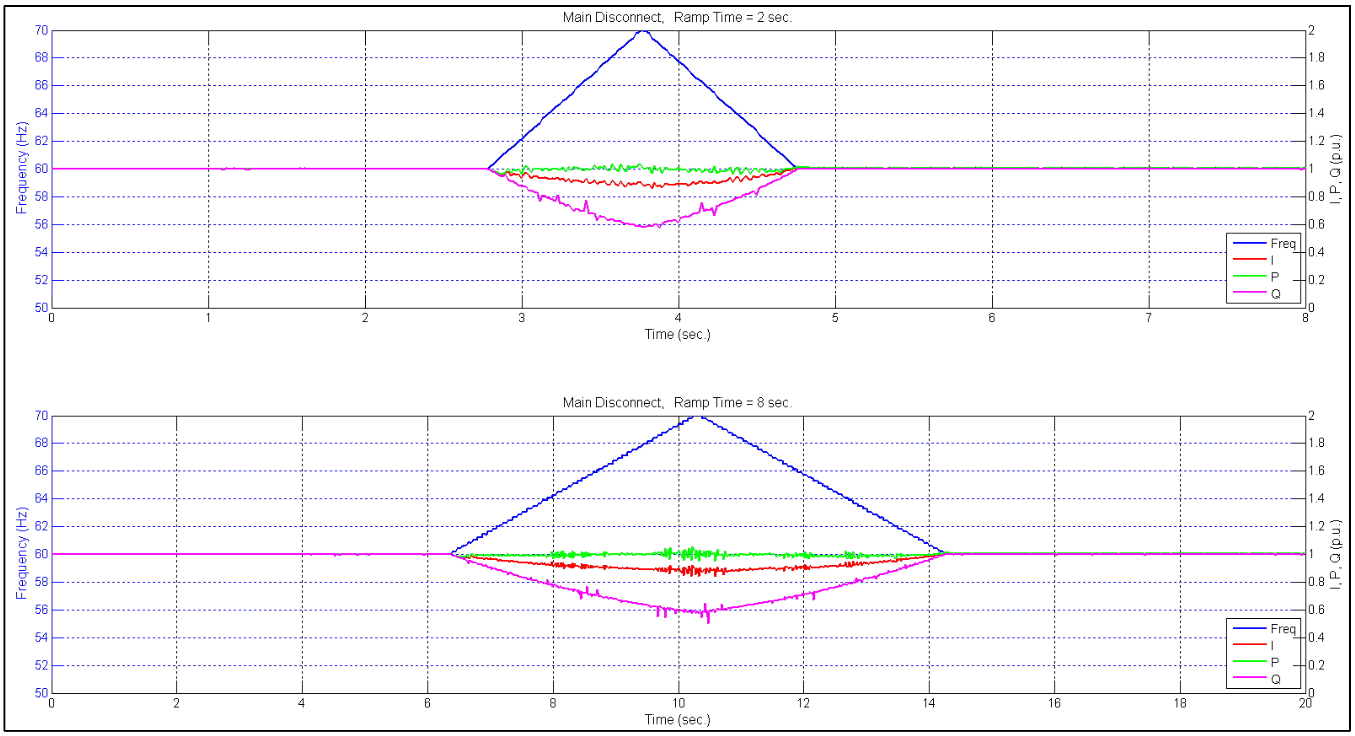

Figure 8.10.2 VFD A/C #6 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

8.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times without scope filters to calculate the actual harmonic contribution of VFD A/C unit #6 to the grid. The maximum total harmonic distortion for current was found to be nearly 47.5% of the fundamental. This unit has that largest current harmonic distortion of all the VFD A/C units which is clear when observing the current waveforms in Figure 8.0.1. The following table gives the total harmonic distortion calculations and the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)		
	$V_{(L1-L2)}$	$I_{(L1)}$	$I_{(L2)}$
1	0.41	46.55	46.28
2	0.40	46.48	46.11
3	0.39	47.43	47.49

Table 8.11.1 VFD A/C #6 Total Harmonic Distortion

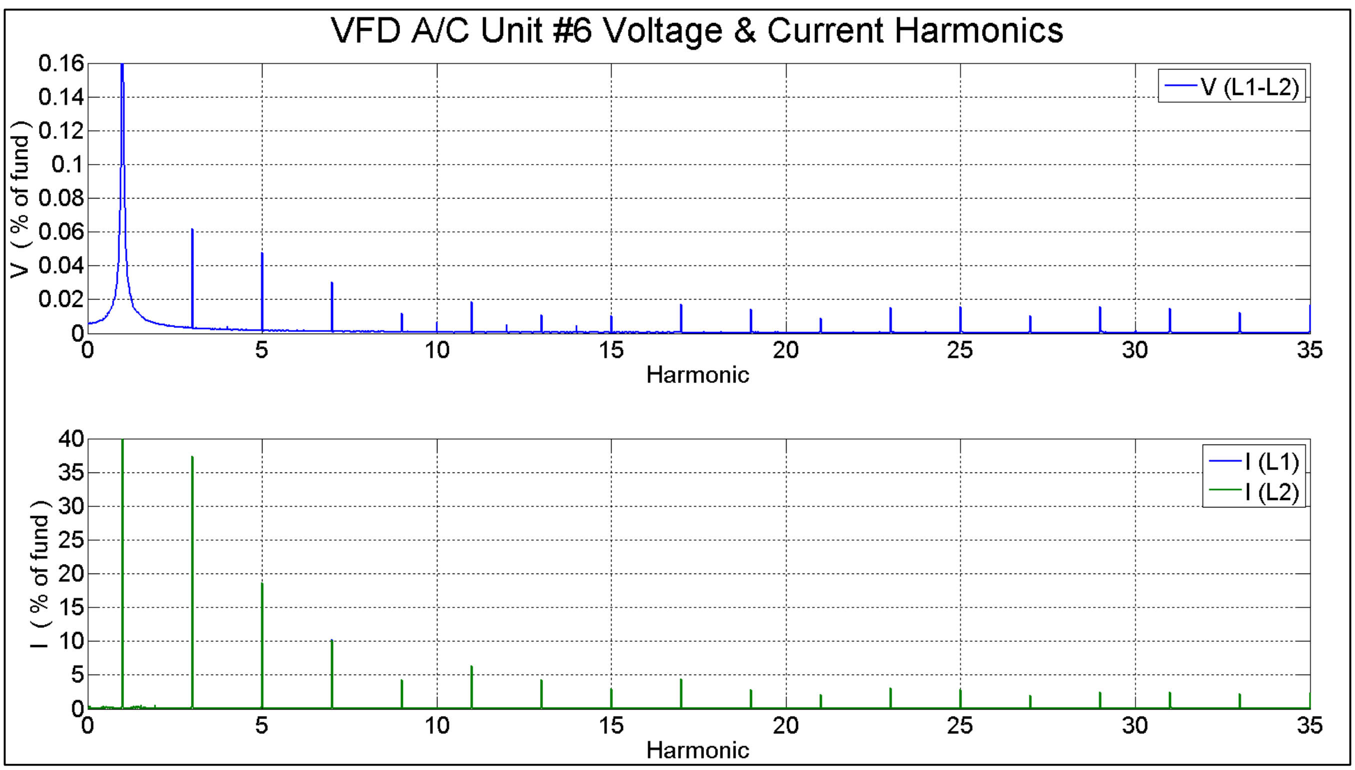

Figure 8.11.1 VFD A/C #6 Harmonics Contribution

8.12 Conservation Voltage Reduction

Voltage was decreased by 1% nominal voltage in 5 second intervals down to 90% before recovering back to steady state as shown in the figure below.

Current increases by approximately 0.9% of nominal current for every 1% decrease in nominal voltage. Real power remains relatively constant, within ±4% of nominal, over the course of the CVR test. Reactive power is observed decreasing by approximately 1.2% of nominal for every 1% decrease in voltage.

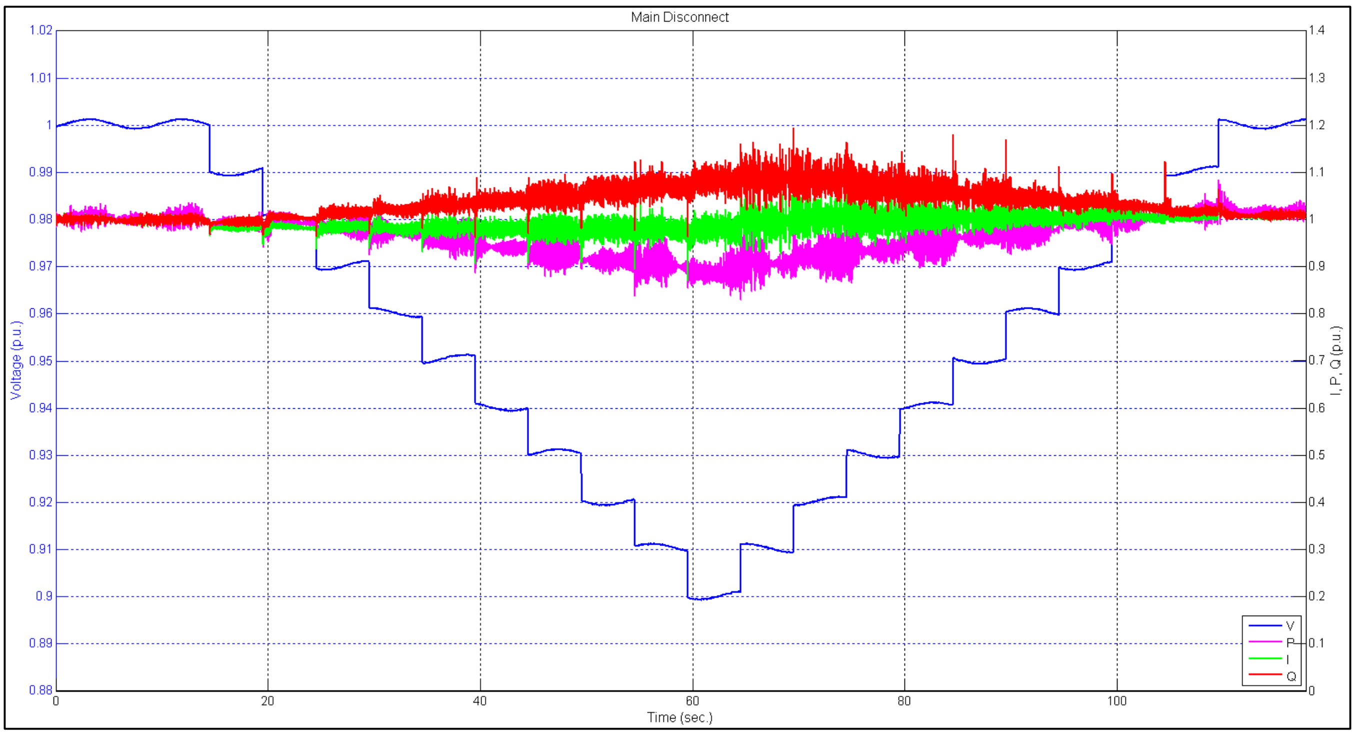

Figure 8.12.1 VFD A/C #6 CVR Response Down to 90% Voltage

Alternatively, the main terminal voltage at the VFD A/C unit was increased by 1% nominal voltage in 5 second intervals up to 105% before stepping back to steady state as shown in the figure below.

Current does not decrease as expected over the course of the CVR test. Current steps to as low as 3% below nominal when voltage is 3% above nominal during recovery. Real power consumption increases as much as 4.5% above its nominal value. Reactive power increases as much as 8.5% above its nominal value.

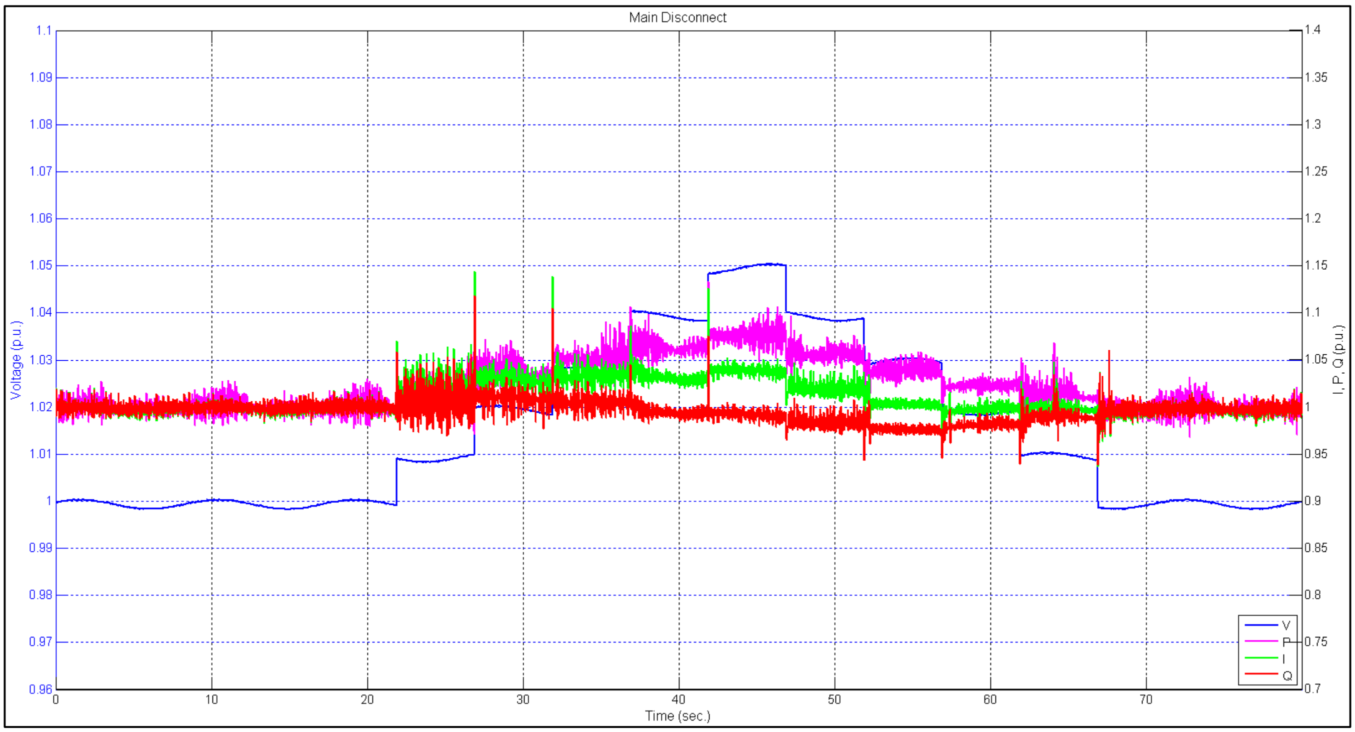

Figure 8.12.2 VFD A/C #6 CVR Response Up to 105% Voltage

9.0 VFD AIR CONDITIONER #7 TEST RESULTS

The figure below shows a snapshot of VFD A/C unit #7 sinusoidal voltages and currents captured at the main terminals and compressor motor using a filter on the digital scope. Notice the slight distortion in the main current waveforms compared to the voltage waveforms. The compressor is shown operating at approximately 265 Volts peak, 10 Amps peak, and 240 Hz at the present loading condition. The specifications for the VFD A/C #7 components are provided in the table below.

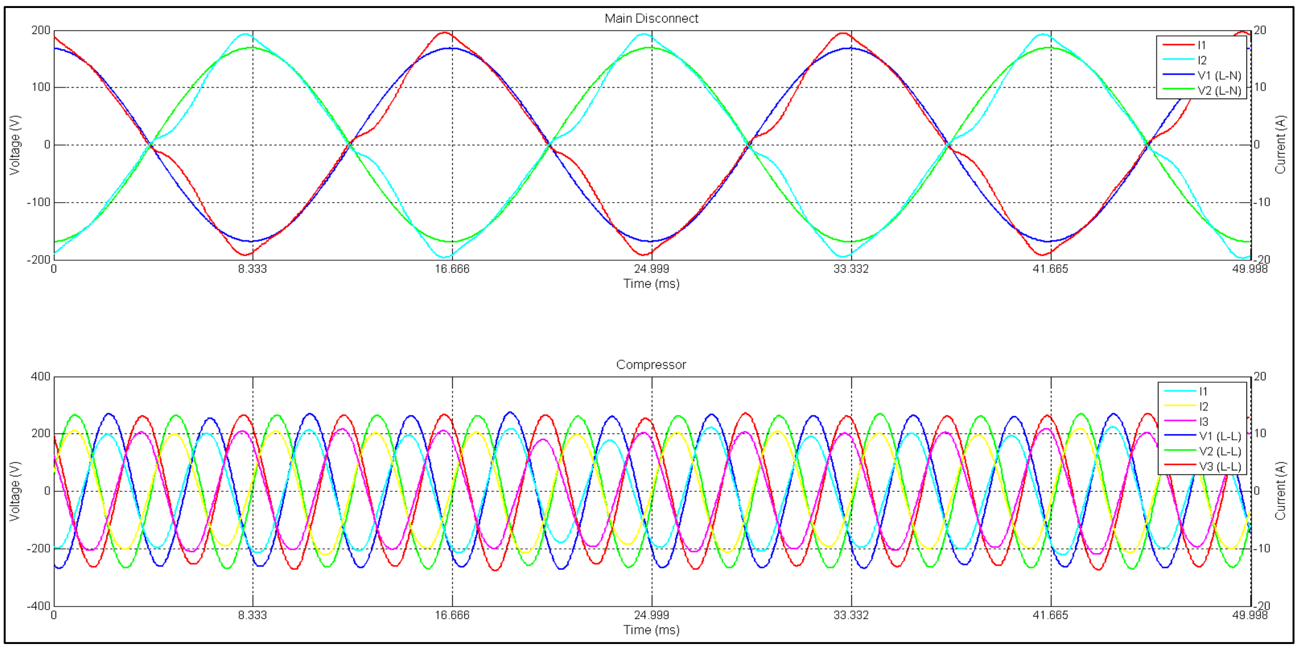

Figure 9.0.1 VFD A/C #7 Voltage and Current Waveforms

Manufacturer	LG
Voltage (V)	230
Refrig.	R-410A
SEER	16.1
Compressor, Model #	LG GJT240MBA
Compressor, RLA (Amps)	14.6
Compressor, LRA (Amps)	-
Outdoor Fan Motor, FLA (Amps)	0.25
Indoor Fan Motor, FLA (Amps)	0.50
Design Pressure High (PSI)	450
Design Pressure Low (PSI)	240

Table 9.0.1 VFD A/C #7 Specifications

9.1 Compressor Shutdown

VFD A/C #7 was shut down during normal operation using the programmable thermostat remote for the indoor blower unit. The figure below displays the measurements taken at the main terminal connections of the entire A/C unit.

After adjusting the thermostat, the indoor unit, outdoor unit, and compressor shut down right away. The delay time for air conditioner current to ramp down is approximately 2.4 cycles. While in standby mode, the device's power consumption is less than 0.65 Amps.

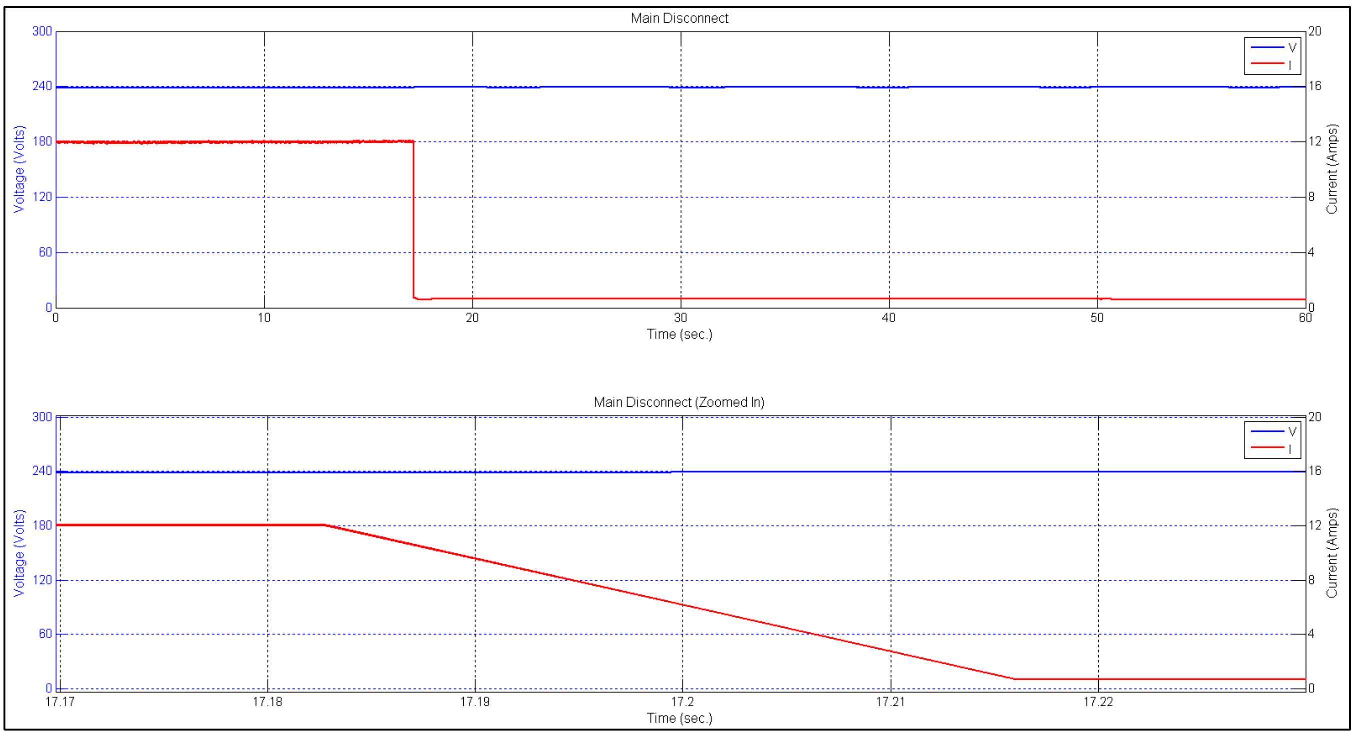

Figure 9.1.1 VFD A/C #7 Compressor Shutdown

9.2 Inrush Current

After starting up the VFD A/C unit via the programmable thermostat remote, the device does not initially display any sign of significant inrush current. The unit slowly ramps up over the course of approximately 27 seconds until the unit is drawing a minimum of 3.6 Amps. A spike in current 5.6 Amps, is observed at the end of the current ramp up. The VFD controlled compressor will increase in intervals over the course of several minutes to meet temperature demand until the unit is more heavily loaded. The room temperature was approximately 79 degrees Fahrenheit and the unit would typically operate between 11 and 12 Amps steady state.

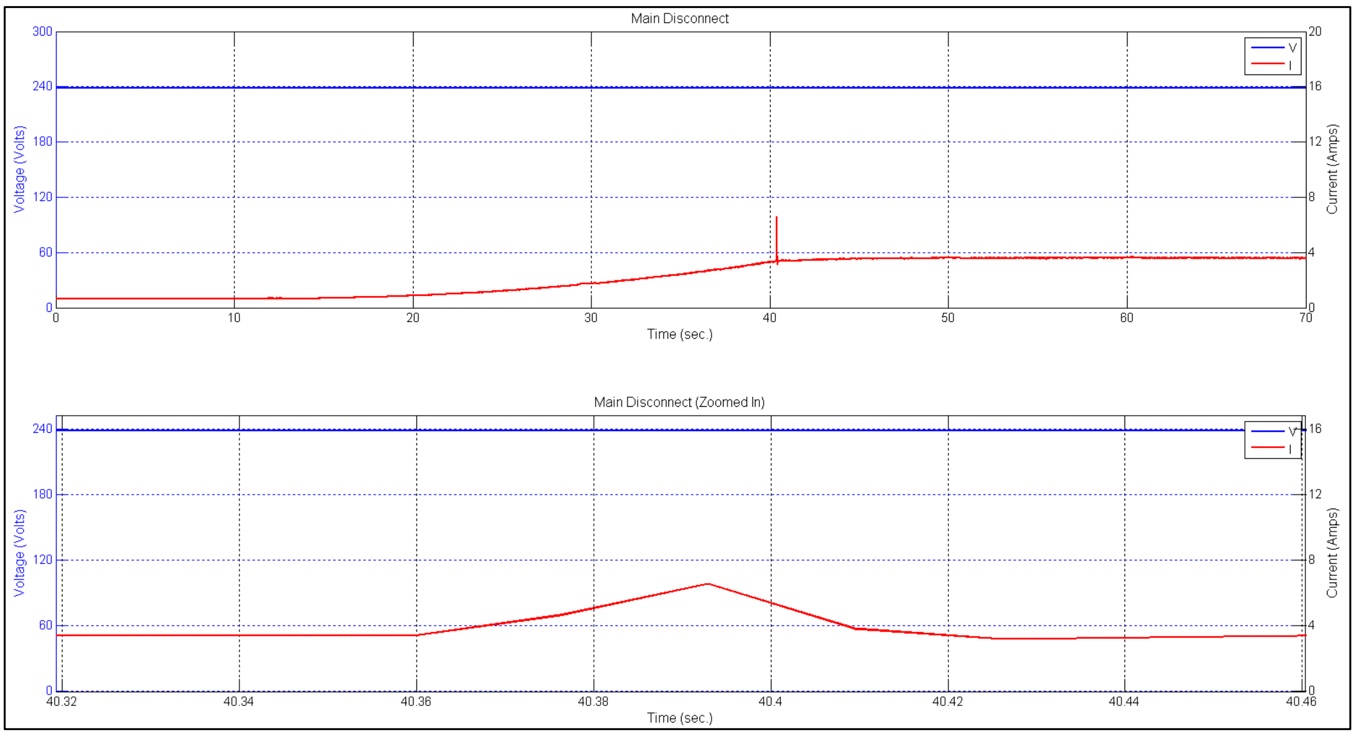

Figure 9.2.1 VFD A/C #7 Inrush Current

9.3 Balanced & Unbalanced Under-voltages

After performing various under-voltages on VFD A/C #7 in decrements of 10%, the compressor is observed disconnecting at different voltage magnitudes depending on the duration of the under-voltage transient. Longer voltage sags with a duration of 130 cycles to 9 cycles caused the compressor to shut down consistently at 60% nominal voltage. Voltage sags with a duration time of 6 and 3 cycles typically caused the compressor to disconnect at 50% nominal voltage. Finally, voltage sags with a duration time of 1 cycle typically caused the compressor to disconnect at 40% nominal voltage. The VFD A/C unit often disconnects the compressor up to 1.2 cycles after voltage recovered for the quicker voltage sags as shown in Table 9.3.1. This may be caused by the sudden increase in current as voltage returns to nominal or logic on the PCB controller.

Data captured several seconds after the disconnection of the compressors did not reveal restarting behavior and therefore reclose times were not captured. This indicates that there must be a protective relay and associated delay times programmed into the local controller of the VFD A/C unit to prevent immediate restarting. The compressor would only restart approximately 5 minutes or so after tripping occurred.

The following figure visually displays one of these balanced tests where the under-voltage sags have a duration time of 130 cycles. The compressor is observed being disconnected towards the beginning of the 60% voltage sag, within 15 cycles. The following table provides additional details regarding the compressor operation during a variety of balanced under-voltage transient tests including the voltage where the unit was tripped (V_{trip}) as well as the time it took for the unit controls to trip it offline after the start of the voltage sag (t_{trip}).

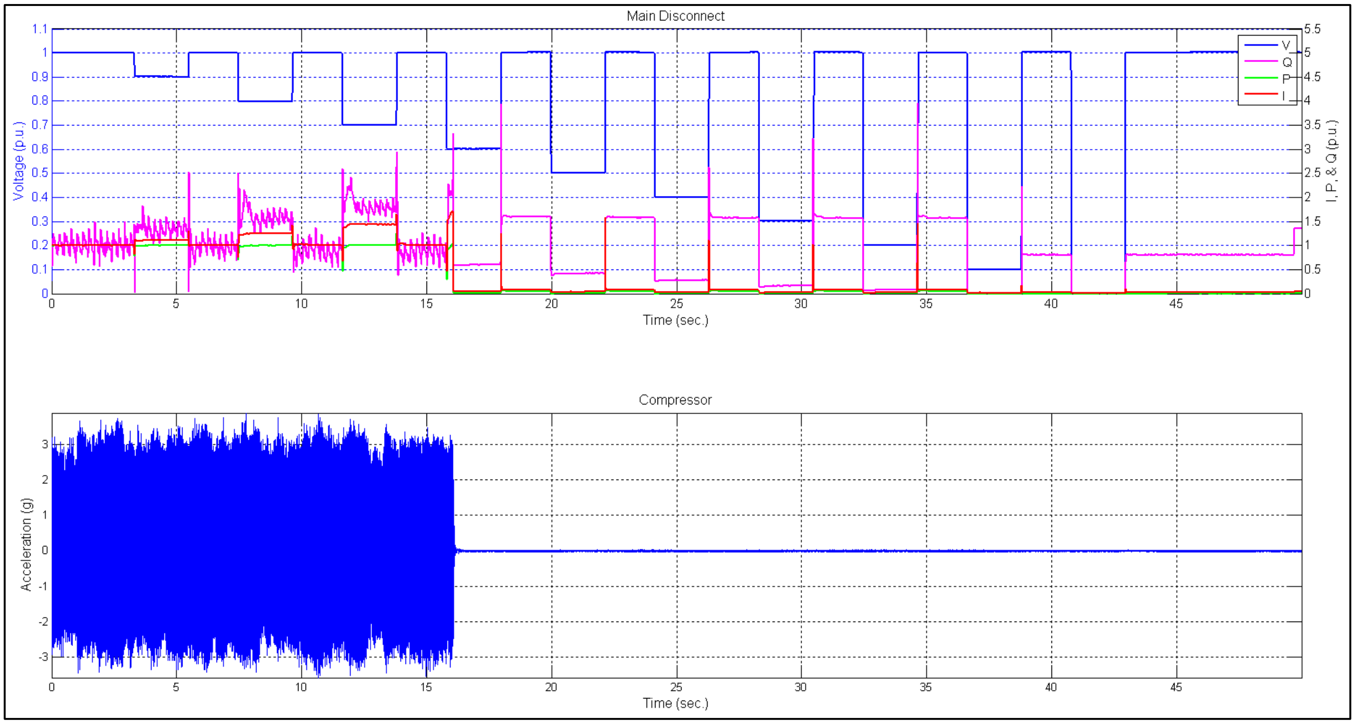

Figure 9.3.1 VFD A/C #7 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	60%	15
		60%	13.8
		60%	11.4
100%, 90%, 80%,... 0%	12	60%	10.2
		50%	7.2
		50%	10.2
100%, 90%, 80%,... 0%	9	60%	10.2
		60%	9.6
		60%	9.6
100%, 90%, 80%,... 0%	6	50%	7.2
		50%	6
		50%	6.6
100%, 90%, 80%,... 0%	3	50%	4.2
		50%	4.2
		50%	4.2
100%, 90%, 80%,... 0%	1	40%	1.4
		10%	1.4
		40%	1

Table 9.3.1 VFD A/C #7 Balanced Under-voltages in 10% Decrements Results

The specific voltage where the compressors are disconnected and/or the controls dropped were identified by performing additional balanced under-voltage tests in decrements of 1% nominal voltage. Most tests showed that the compressor could begin tripping off for voltage sags between 62% and 60% nominal voltage. Under-voltage transients lasting 3 cycles revealed tripping at 54% nominal voltage and 1 cycle transients revealed tripping at 49% nominal voltage. In each test, the compressor was tripped either at the end of the voltage sag or within 1.2 cycles after the voltage had already recovered. This could be caused by the inrush current at the end of the voltage sag or possibly the controller PCB to preventing loss of load until voltage is at or near steady state. The following table provides the details of the compressor disconnection behavior during these 1% voltage decrement tests.

Under-Voltage Transient		**Compressor**	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
70%, 69%, 68%,…	130	62%	129.6
70%, 69%, 68%,…	12	60%	12
70%, 69%, 68%,…	9	62%	10.2
70%, 69%, 68%,…	6	62%	7.2
60%, 59%, 58%,…	3	54%	4.2
60%, 59%, 58%,…	1	49%	1.9

Table 9.3.2 VFD A/C #7 Balanced Under-voltages in 1% Decrements Results

The unbalanced under-voltages on VFD A/C #7 resulted in compressor trip voltages and trip times similar to those observed during balanced under-voltage conditions with respect to the line-to-line voltage. Although the unit does not trip until one line under-voltage sags with a duration of 3 to 130 cycles reach either 20% or 10% line-to-neutral, this is equivalent to 60% or 55% line-to-line nominal voltage. The 1 cycle voltage sags were similarly consistent tripping at 50% line-to-line nominal voltage. These results suggest that the power electronic controls that operate the compressor of this particular VFD unit rely on the voltage potential across both lines.

The following figure shows an example of these unbalanced cases (Line 2 under-voltages for 130 cycles) where the compressor is disconnected at 20% line-to-neutral nominal voltage 18.6 cycles after the beginning of the voltage sag. The following table provides the unbalanced voltage transients performed at the main terminals of the VFD A/C unit. Please note that many of the unbalanced tests shown in the table exhibit tripping either at the end of the voltage sag or after voltage recovers to nominal, similar to some of the balanced under-voltage tests.

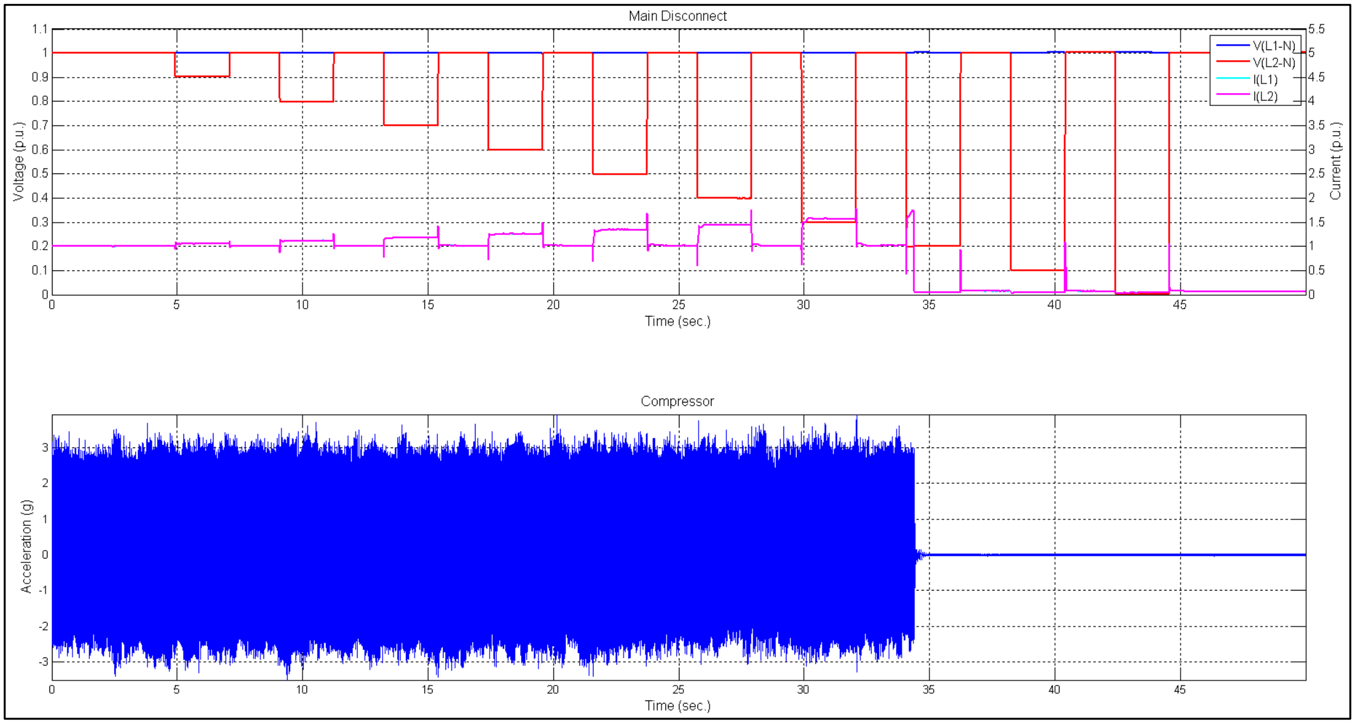

Figure 9.3.2 VFD A/C #7 Unbalanced Under-voltage Response (Line 1, 130 cycles)

Under-Voltage Transient			**Compressor**		
Lines	**Volt Range**	**Duration (cyc)**	**$V_{trip\ L\text{-}N}$ (%)**	**$V_{trip\ L1\text{-}L2}$ (%)**	**t_{trip} (cyc)**
L1	100%, 90%, 80%,... 0%	130	10%	55%	15
		12	20%	60%	12.6
		6	20%	60%	6
		3	20%	60%	3
		1	0%	50%	1.8
L2	100%, 90%, 80%,... 0%	130	20%	60%	18.6
		12	20%	60%	12
		6	20%	60%	6
		3	10%	55%	3
		1	0%	50%	2.4

Table 9.3.3 VFD A/C #7 Unbalanced Under-voltage Results

9.4 Balanced & Unbalanced Over-voltages

VFD A/C #7 was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve to avoid damaging any voltage sensitive equipment. These tests include multiple voltage swells performed in 2% increments for up to 120% nominal voltage to identify any tripping behavior. No over-voltage protection was observed during any of these tests, only voltage ride-through. The following figure shows a sample over-voltage test and the following table specifies the types of tests performed.

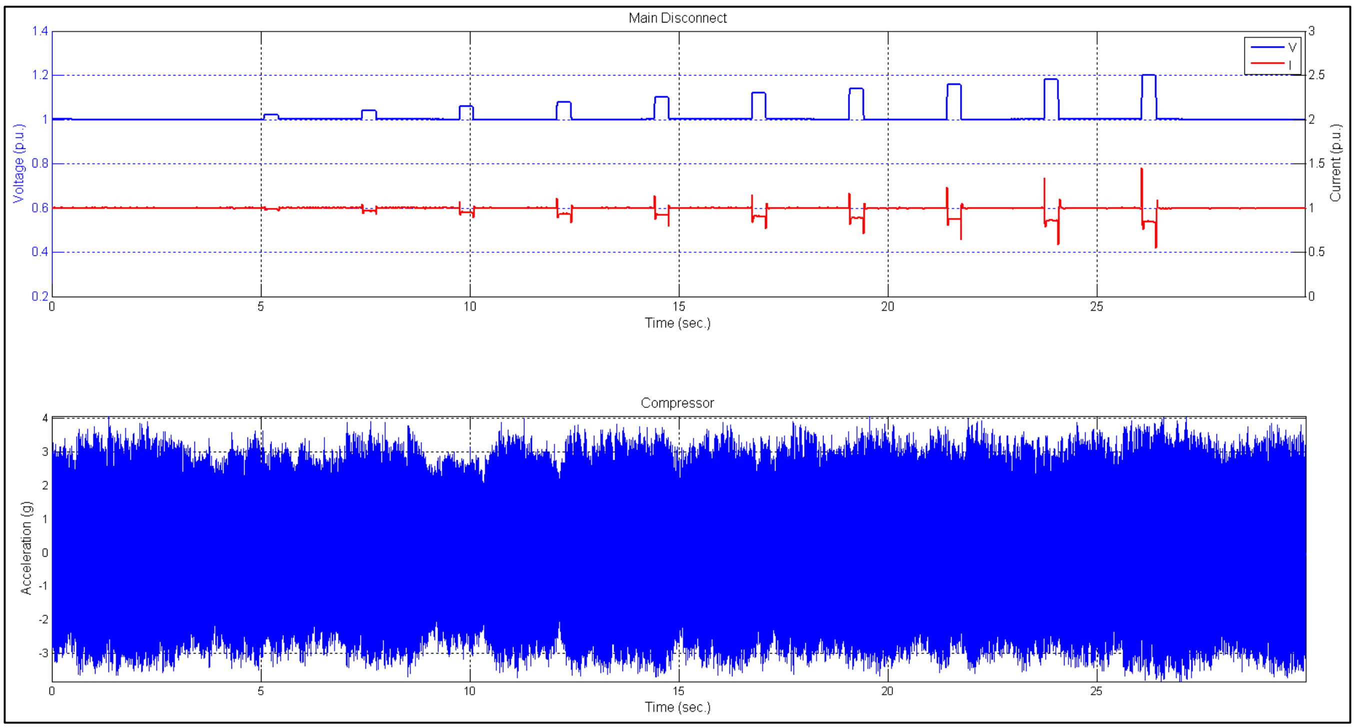

Figure 9.4.1 VFD AC #7 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		
Lines	Volt Range	Duration (cyc)	$V_{trip\ L\text{-}N}$ (%)	$V_{trip\ L1\text{-}L2}$ (%)	t_{trip} (cyc)
L1 & L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L1	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A
L2	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A

Table 9.4.1 VFD A/C #7 Balanced & Unbalanced Over-voltage Results

9.5 Voltage Oscillations

The following figure shows the performance of VFD A/C #7 during voltage oscillations between 100% and 90% nominal voltage for a variety of swing frequencies or oscillation rates.

The VFD appears to be maintaining the speed and consumption of the compressor motor. Current at the main terminals of the unit oscillates in the opposite direction of voltage, between 10% and 11% above nominal, to minimize any oscillations or deviations in real power for all swing frequencies. The consumption of real power remains relatively constant within 3% of nominal during the voltage oscillations. However, deviates further from steady state at higher swing frequencies.

Reactive power consumption is very low since the power factor is greater than 0.99 for the device. Therefore any minor change in reactive load, even during steady state, results in drastic changes to the per unit values. As a result, reactive power was not included in the figure below.

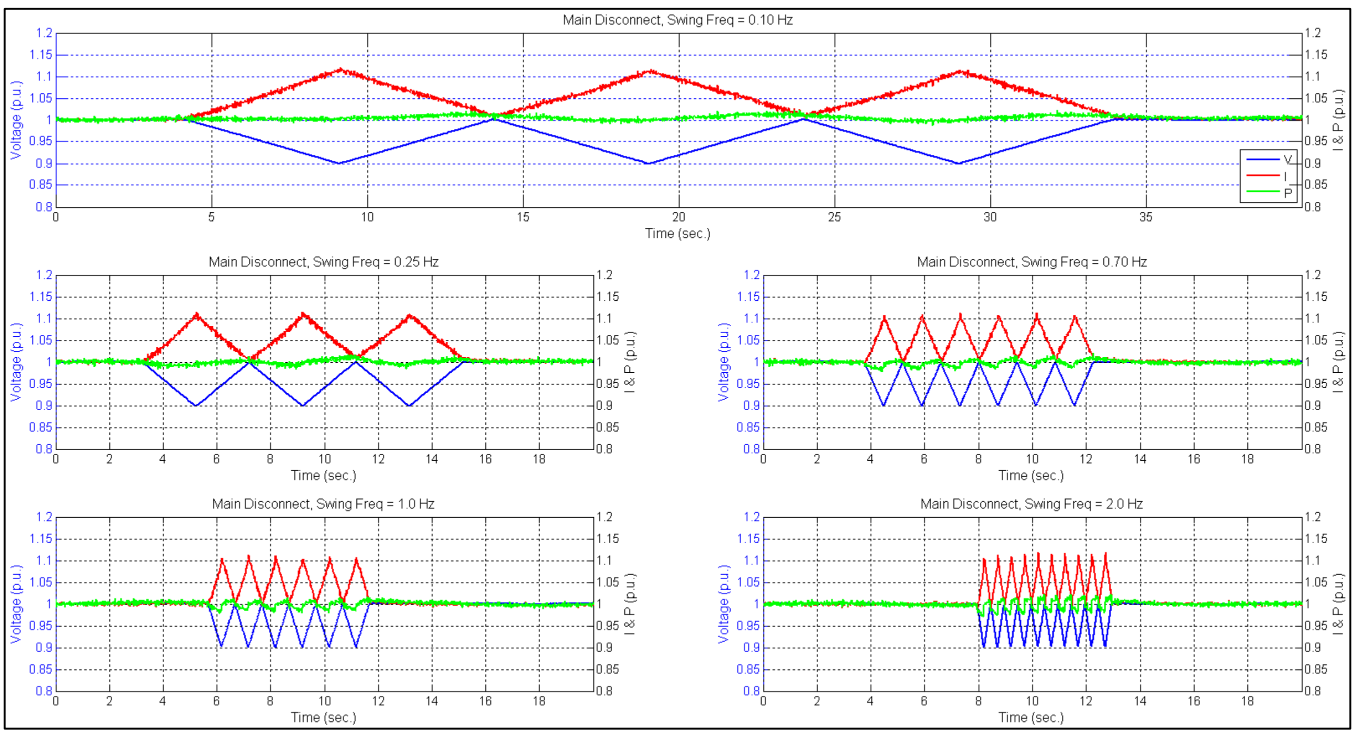

Figure 9.5.1 VFD AC #7 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

9.6 Under-frequency Events

After subjecting VFD A/C #7 to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection while operating between 60 Hz and 58 Hz. The device simply rides through these under-frequency conditions. The constant current suggests the VFD is also maintaining frequency at the motor. The following figure and table identify the magnitude and duration of the frequency transient tests that were performed.

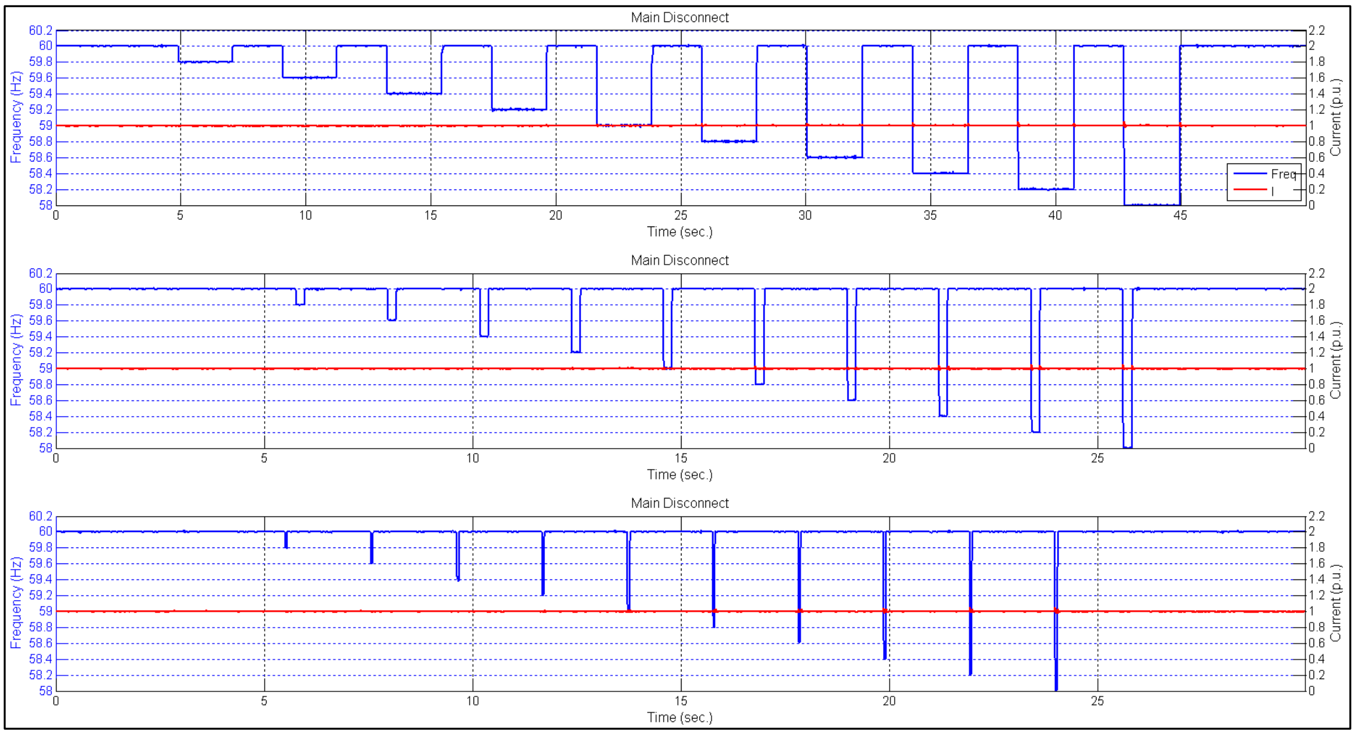

Figure 9.6.1 VFD A/C #7 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 9.6.1 VFD A/C #7 Under-frequency Test Results

9.7 Over-frequency Events

Similar to the under-frequency tests, VFD A/C #7 was subjected to over-frequency transients to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The motor frequency is maintained by the VFD. The following figure and table identify the magnitude and duration of the specific over-frequency tests that were performed.

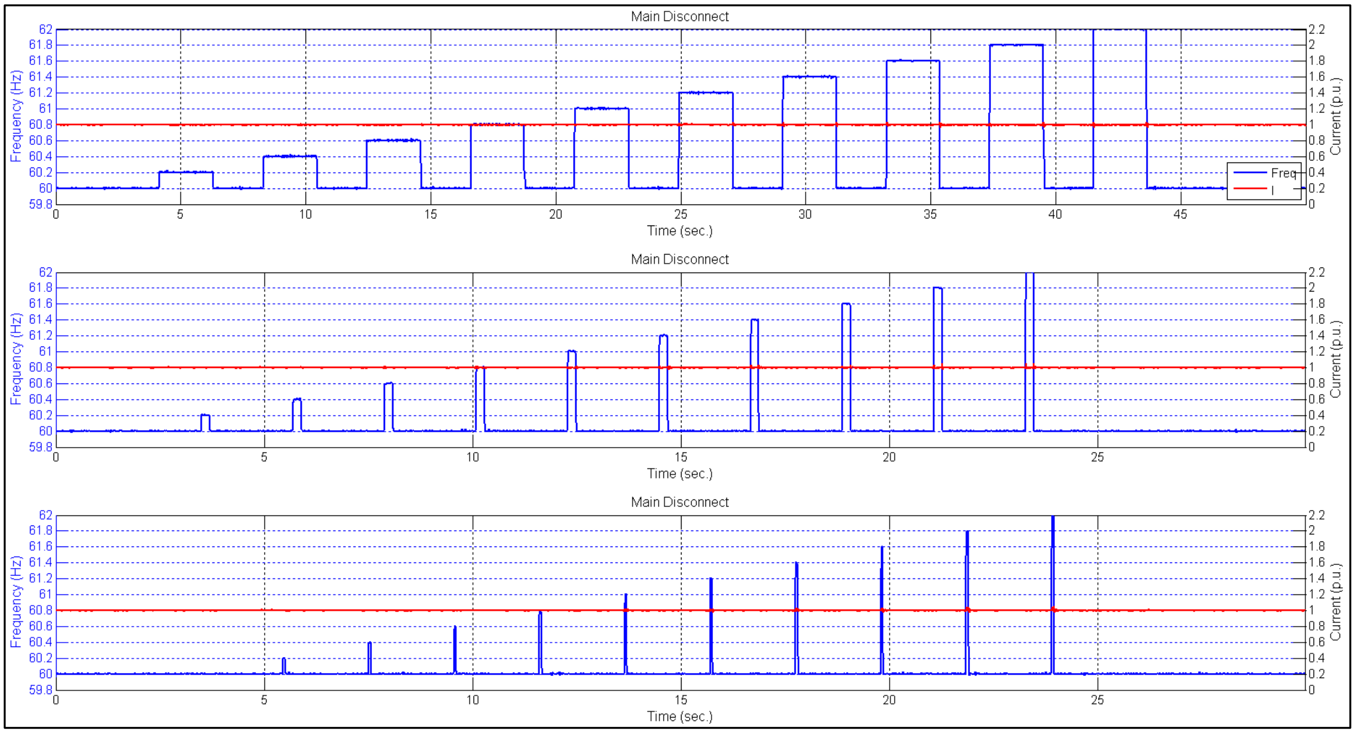

Figure 9.7.1 VFD A/C #7 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A

Table 9.7.1 VFD A/C #7 Over-frequency Test Results

9.8 Frequency Oscillations

The following figure shows the performance of VFD A/C #7 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates (0.10, 0.25, 0.70, 1.0, and 2.0 Hz).

Motor consumption is held near constant by the performance of the VFD. Current does not oscillate or deviate in response to frequency oscillations at the main terminals of the A/C unit. The active power consumption remains constant as well, within ±1% of its steady state value along with current for all swing frequencies or oscillation rates.

Reactive power was not included in the figure below because of its low consumption (power factor is greater than 0.99). Even minor deviations that naturally occur during steady state cause significant changes to the per unit values plotted.

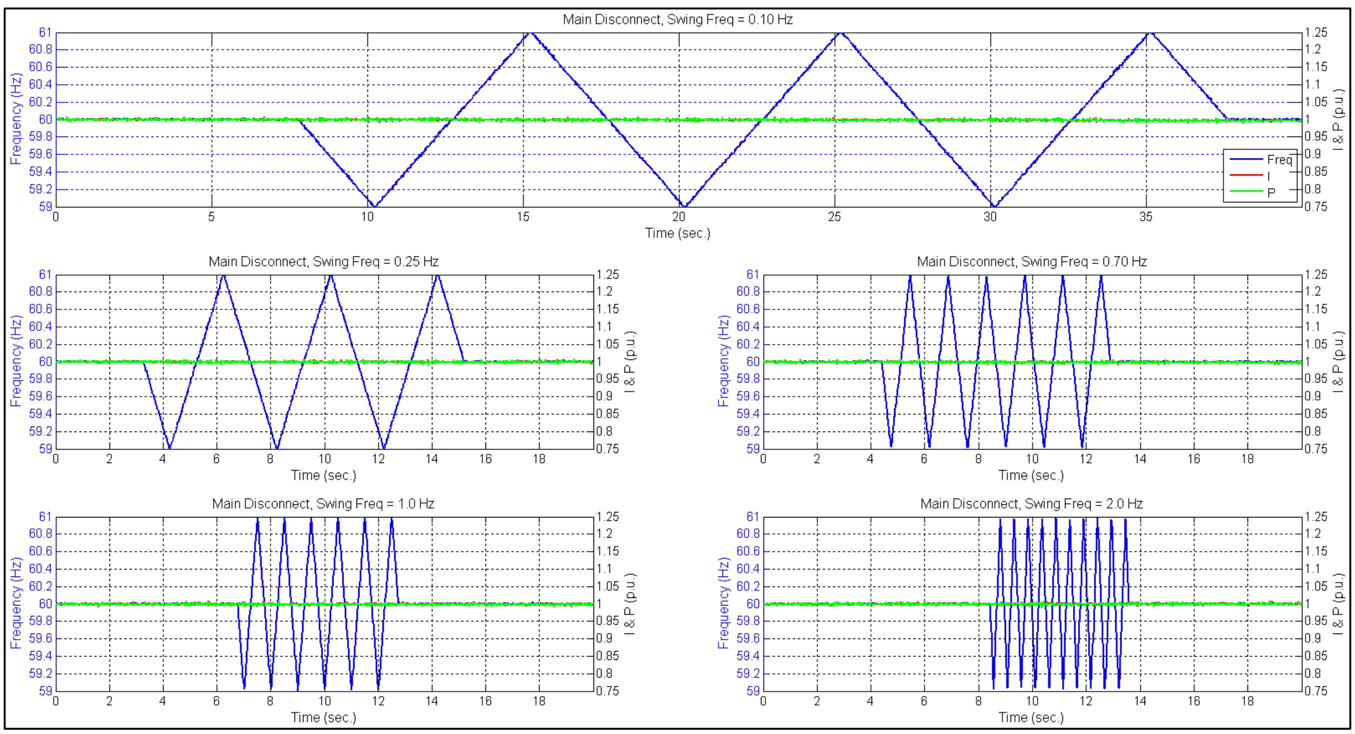

Figure 9.8.1 VFD A/C #7 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

9.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit tripped while ramping down to 60% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation (down to 70% nominal voltage).

The VFD is doing an excellent job managing the consumption and speed of the compressor motor. Current ramps up to approximately 45% above nominal while voltage ramps down to 30% below nominal. Real power consumption is held constant for both the 2 and 8 second voltage ramp tests, within ±3% of nominal. Reactive power consumption is low due to the large power factor, but it ramps up to nearly 80% above of its nominal value.

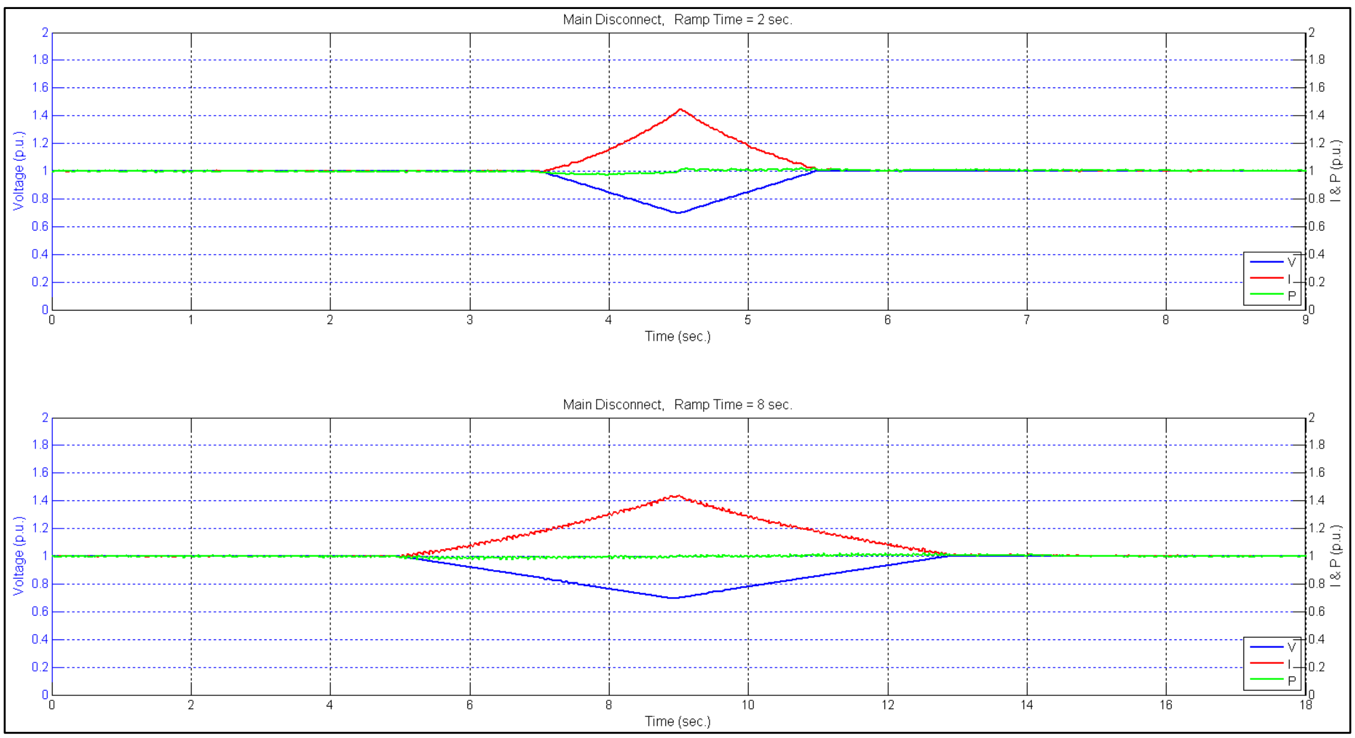

Figure 9.9.1 VFD A/C #7 Voltage Ramp Down to 70% (2 & 8 sec.)

Voltage was ramped up to 110% and back down steady state voltage at different ramp rates to demonstrate the load performance while operating at over-voltage values.

Similar to the under-voltage ramp test, motor speed is held constant by the VFD. Current is observed ramping down to nearly 10% below nominal in response to voltage. Real power consumption remain relatively close to nominal for most of the voltage ramp, within $\pm$2% of steady state. Reactive power ramps down to 35% below its nominal value. However, little reactive power is consumed during normal operation due to a large power factor.

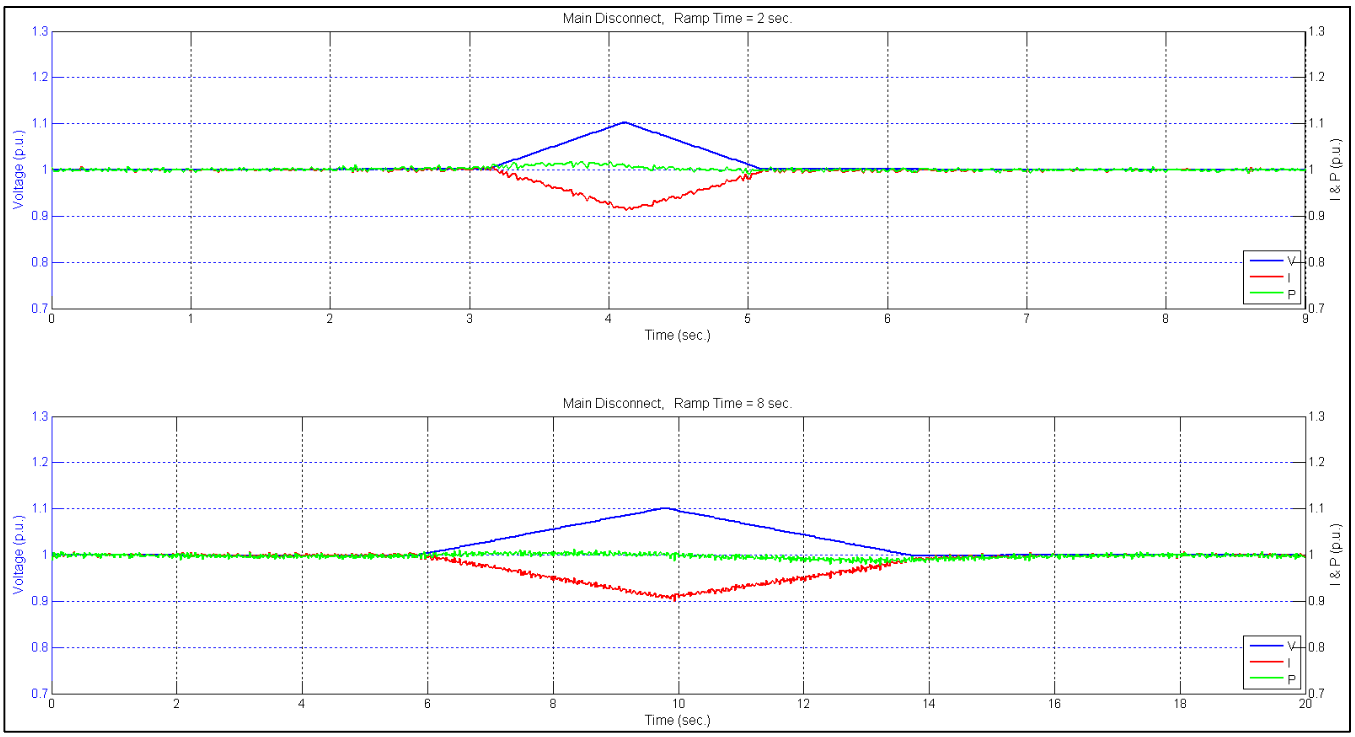

Figure 9.9.2 VFD A/C #7 Voltage Ramp Up to 110% (in 2 & 8 sec.)

9.10 Frequency Ramps

Frequency was ramped down to 50 Hz and back up to 60 Hz at different ramp rates to demonstrate the load performance while operating at lower frequency values as shown in the figure below.

Current and real power remain relatively constant throughout the entire under-frequency ramp, within ±2% of respective nominal values. Reactive power consumption is low, but does deviate by up to 8% from nominal.

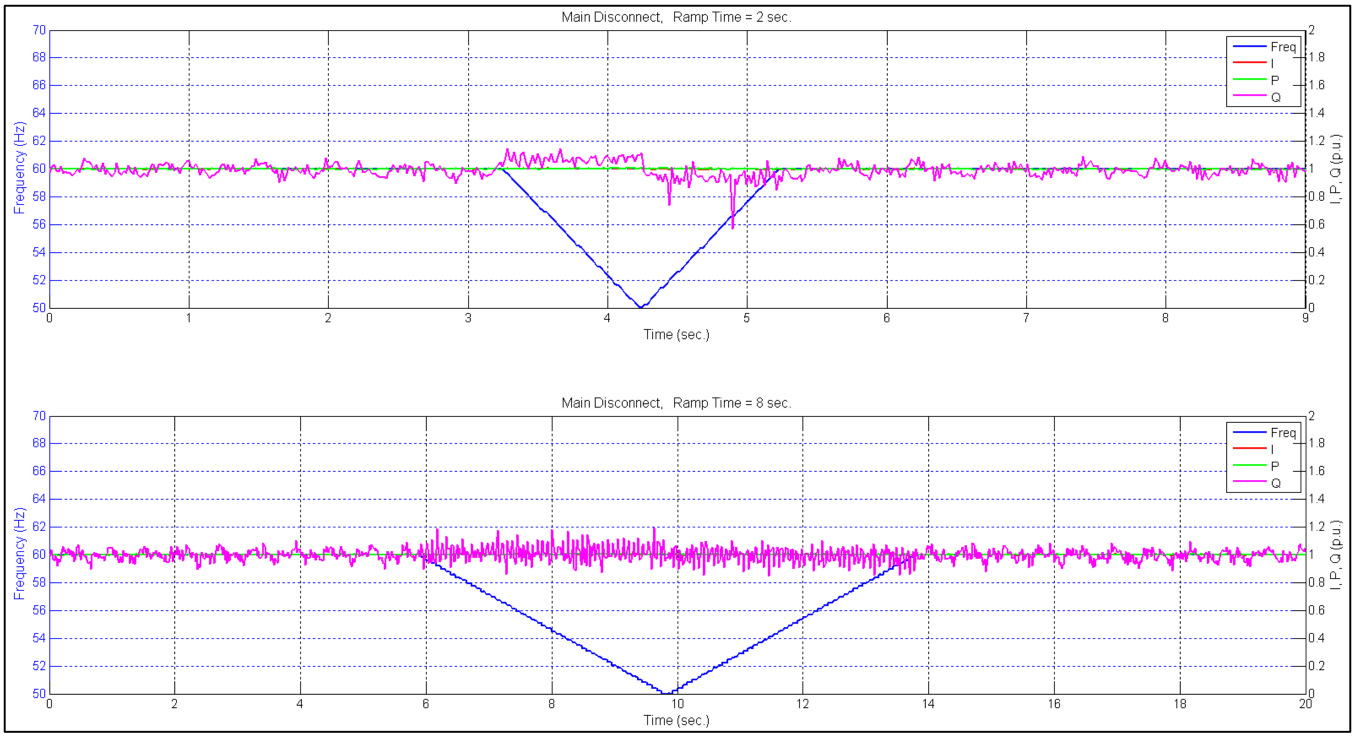

Figure 9.10.1 VFD A/C #7 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

Frequency was ramped up to 70 Hz and back down to 60 Hz at different ramp rates to demonstrate the load performance while operating at higher frequency values. However, VFD A/C #7 tripped at approximately 67.5 Hz and the test was redone ramping frequency up to 65 Hz as shown in the figure below.

Similar to VFD A/C #1, current stays constant at the beginning of the test until frequency reaches 64 Hz. At this point the current ramps up with frequency until peaking at 6% above nominal. Real power consumption is constant throughout the entire test. Reactive power, like current, begins ramping after frequency goes above 64 Hz and peaks at approximately 268% of nominal before ramping down. The device is operating at a power factor greater than 0.99 and therefore this amount of reactive power consumption is low.

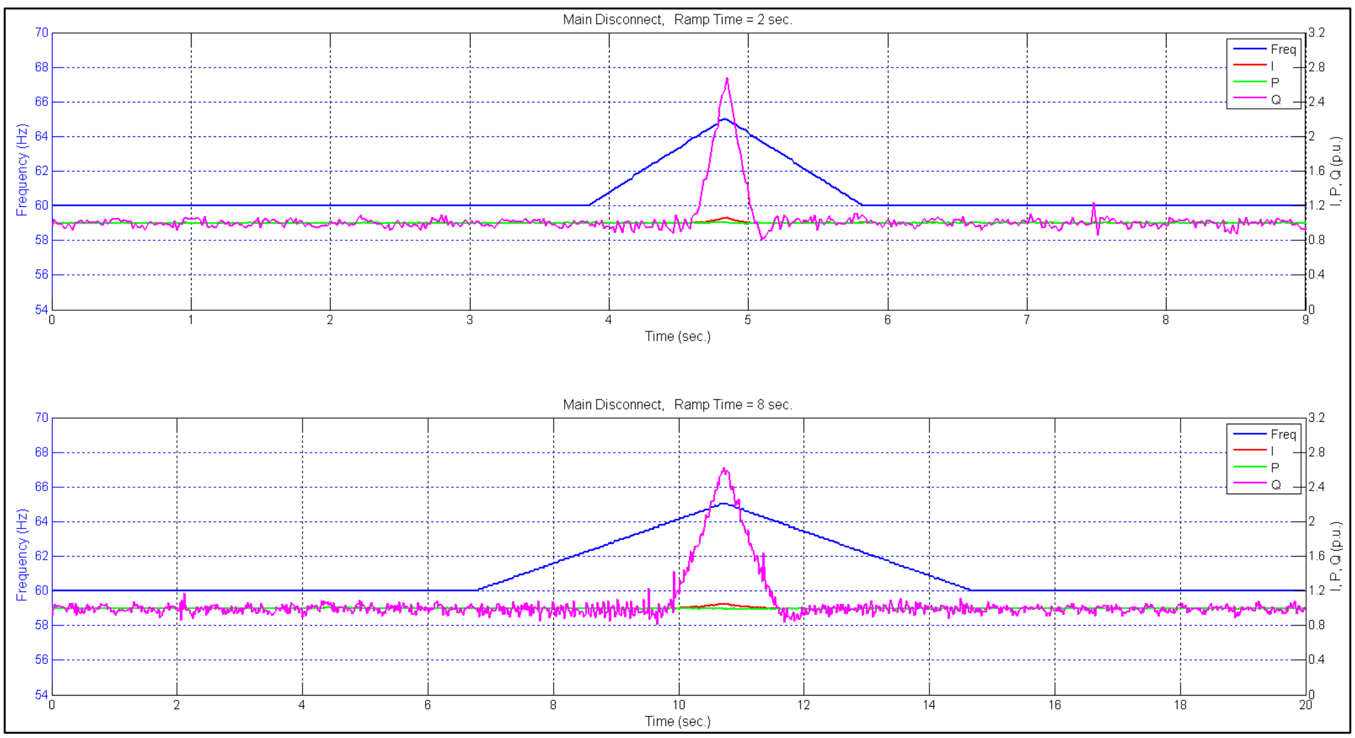

Figure 9.10.2 VFD A/C #7 Frequency Ramp Up to 65 Hz (in 2 & 8 sec.)

9.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times without scope filters to calculate the actual harmonic contribution of VFD A/C unit #7 to the grid. The maximum total harmonic distortion of current was calculated as 14.41% of the fundamental. The following table gives the total harmonic distortion calculations and the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)		
	$V_{(L1-L2)}$	$I_{(L1)}$	$I_{(L2)}$
1	0.48	14.36	14.41
2	0.47	14.30	14.34
3	0.46	14.21	14.26

Table 9.11.1 VFD A/C #7 Total Harmonic Distortion

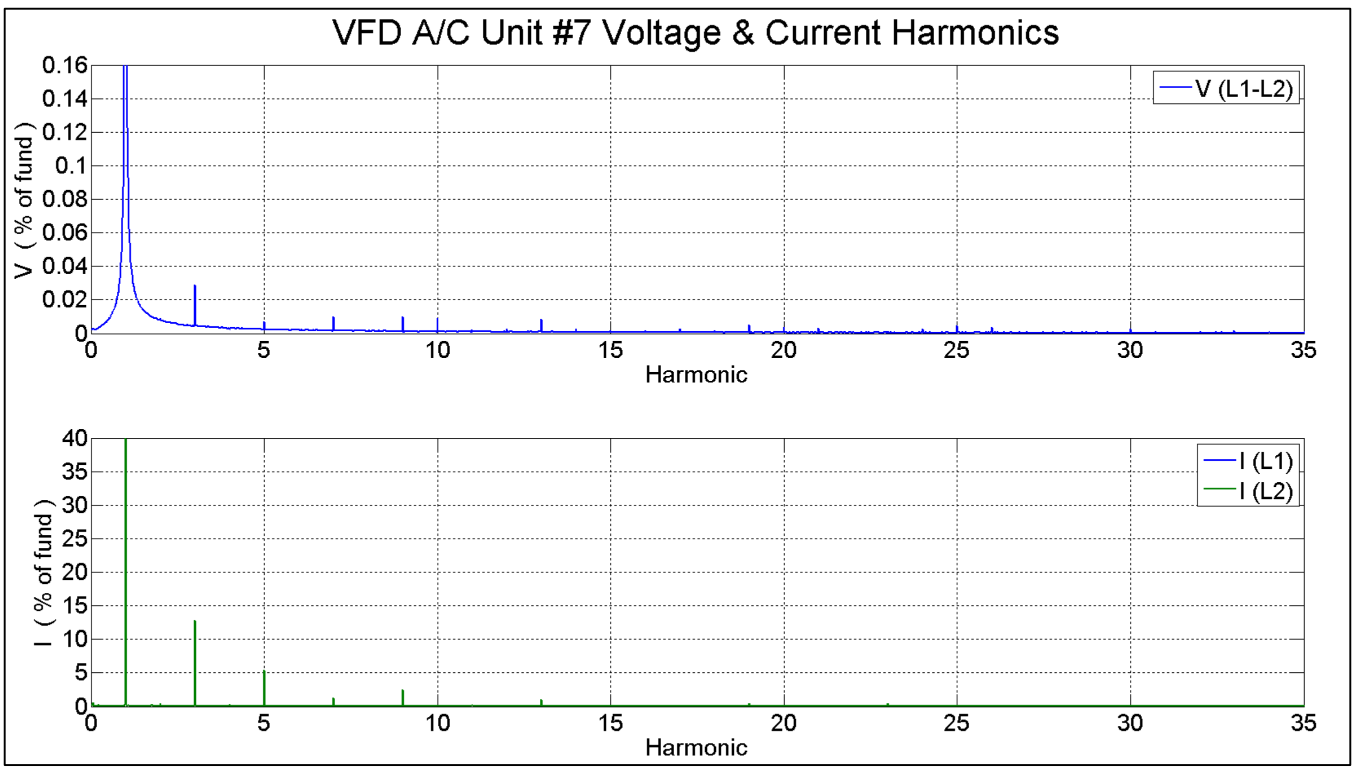

Figure 9.11.1 VFD A/C #7 Harmonics Contribution

9.12 Conservation Voltage Reduction

Voltage was decreased by 1% nominal voltage in 5 second intervals down to 90% before recovering back to steady state as shown in the figure below.

CVR will not be effective on this particular load based on the following results. Current increases by approximately 1.1% of nominal current for every 1% decrease in nominal voltage over the course of the CVR test. Therefore the real power consumption is nearly constant, within ±2% of nominal. Reactive power slowly increases over time, but the nominal consumption is still low due to high power factor.

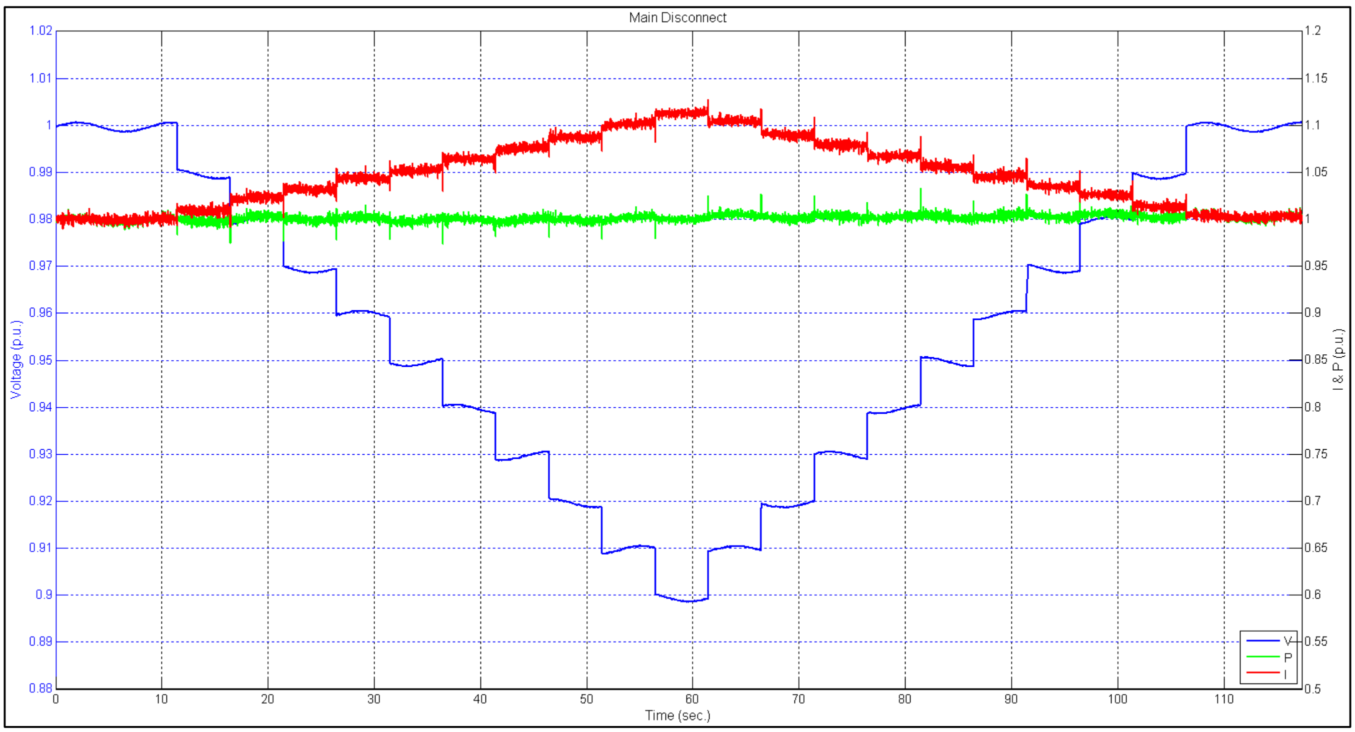

Figure 9.12.1   VFD A/C #7 CVR Response Down to 90% Voltage

Alternatively, the main terminal voltage at the VFD A/C unit was increased by 1% nominal voltage in 5 second intervals up to 105% before stepping back to steady state as shown in the figure below.

Again, CVR does not have a beneficial impact on the load consumption. The current decreases by approximately 1% of nominal for every 1% increase in nominal voltage. Therefore real power remains near its steady state consumption, with +2% of nominal. Reactive power consumption slowly decreases during the CVR test, but is consumption is low during steady state as well.

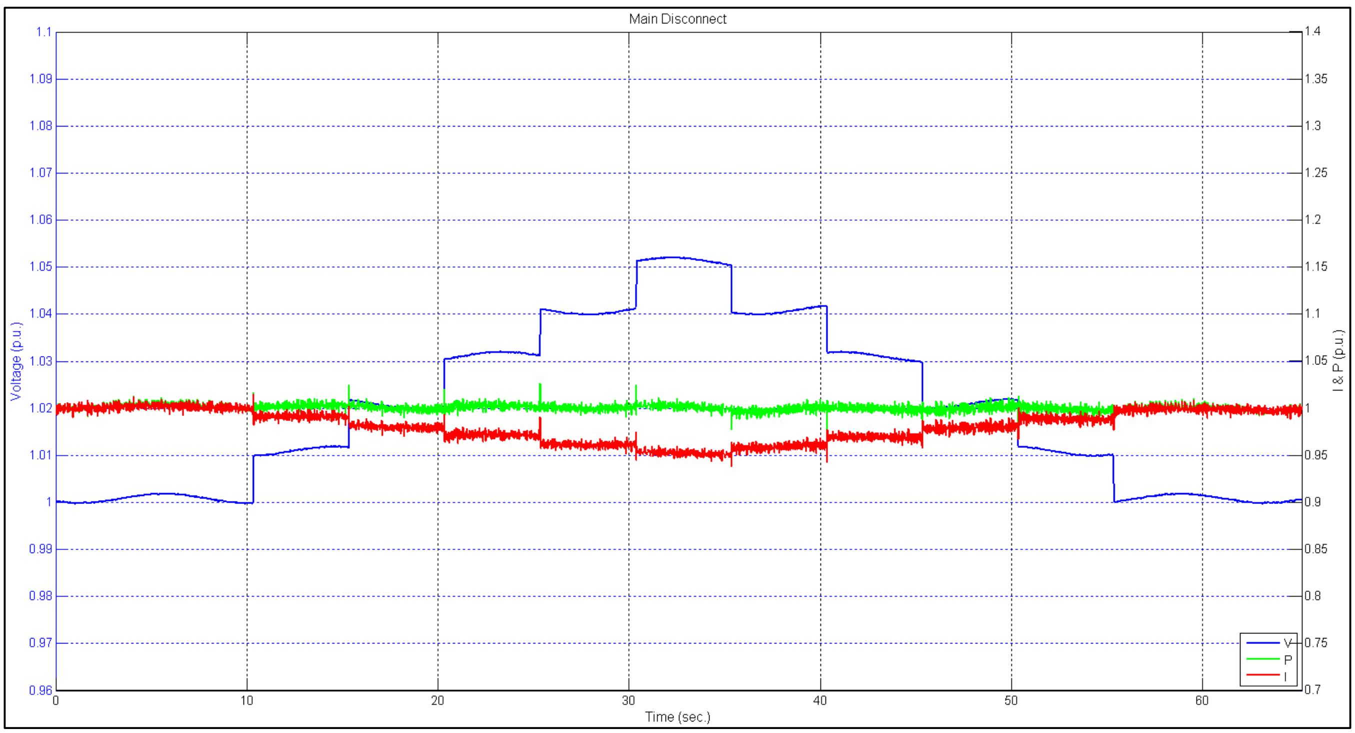

Figure 9.12.2 VFD A/C #7 CVR Response Up to 105% Voltage