SOUTHERN CALIFORNIA EDISON
An EDISON INTERNATIONAL® Company

Commercial 3-Phase Rooftop Air Conditioner Test Report

Prepared for:

Joe Eto

Lawrence Berkeley National Laboratory

Prepared by:

Steven Robles

Advanced Technology, Engineering & Technical Services, SCE

June 19, 2015

Southern California Edison (SCE), an Edison International company, is one of the nation's largest investor-owned utilities, serving more than 14 million people in a 50,000-square-mile service area within Central, Coastal and Southern California. The utility has been providing electric service in the region for more than 125 years.

SCE's service territory includes about 430 cities and communities with a total customer base of 4.9 million residential and business accounts. SCE is regulated by the California Public Utilities Commission and the Federal Energy Regulatory Commission.

In 2012, SCE generated about 25 percent of the electricity it provided to customers, with the remaining 75 percent purchased from independent power producers. One of the nation's leading purchasers of renewable energy, SCE delivered nearly 15 billion kilowatt-hours of renewable energy to its customers in 2012, enough to power 2.3 million homes.

Advanced Technology is the organization in SCE's Transmission and Distribution business unit and Engineering & Technical Services (E&TS) division that investigates advanced technologies and methodologies to support the utility's goals to provide safe, reliable and affordable energy while overcoming the challenges associated with the generation, transmission and distribution of electricity such as: the integration of variable energy resources, cascading outages and the effects of customer loads.

SCE DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

This report was created as a result of work sponsored by the U.S. Department of Energy through the Lawrence Berkeley National Laboratory and SCE's Research Development and Demonstration Balancing Account, which was initially established in 1988 as part of customer rates and performed by its Advanced Technology organization. This report has not been approved or disapproved by SCE nor has SCE verified the accuracy, adequacy, and safety of the information in this report.

Neither Advanced Technology, SCE, Edison International, nor any person working for or on behalf of any of these entities, makes any warranty or representation, express or implied, related to this report. Without limiting the foregoing, SCE expressly disclaims any liability associated with the following: (i) information, products, processes or procedures discussed in this report, including the merchantability and fitness for a particular purpose of these, (ii) use of the test procedure or that this use does not infringe upon or interfere with rights of others, including another’s intellectual property, and (iii) that this report is suitable to any particular user’s circumstance.

SCE follows OSHA and internal safety procedures to protect its personnel and encourages its partners and contractors to these safety practices as well.

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

LBNL DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

TABLE OF CONTENTS

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 and it is held until the A/C load trips itself off via internal thermal protection. In some cases, data captured on the electric grid from phasor measurement units (PMUs) has revealed instances where voltage recovery was delayed for up to 50 seconds.

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 which is well before they are disconnected due to power contactor dropout 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 commercial 3-phase rooftop A/C units during typical voltage and frequency deviations that occur on the grid. Unlike conventional residential systems, these packaged rooftop systems are equipped with either single or dual 3-phase scroll compressor motors. Some of the larger commercial units are even designed with multiple power contactors and/or relays to independently operate each motor and even use logic from printed circuit boards to handle the controls.

Unfortunately, there has been little or no research executed on these types of units during dynamic conditions despite their frequent use on commercial buildings throughout the electric system. Therefore the resulting test data may be used to support the validation of load models as well as the investigation of stalling solutions. The commercial A/C characteristics to be evaluated include:

- Compressor stalling criteria (or lack thereof)
- Inrush currents during startup
- Contactor/relay protection and dropout characteristics
- 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

All of the tested commercial A/C units experienced contactor and/or relay controls dropout before motor stalling could occur for balanced 3-phase voltage sags. The conditions required to cause dropout were fairly consistent for each A/C unit and were greatly dependent on the voltage magnitude and the duration time of the voltage sag. Generally dropout occurs during under-voltages between 50% and 60% nominal voltage in 2 to 10 cycles after the voltage sag begins.

Unit	Compressor Motors	
	$V_{trip\ /\ dropout}$ (%)	$t_{trip\ /\ dropout}$ (cyc)
A/C #1	58% - 61%	2 - 14
A/C #2	60% - 70%	2 - 10
A/C #3	50% - 58%	2 - 59
A/C #4	58% - 60%	2 - 21
A/C #5	50% - 59%	2 - 22
A/C #6	51% - 59%	2 - 80
A/C #7	50% - 59%	2 - 67

Table 1.3.1 Contactor/Relay Controls Dropout

The test data also showed that the contactor would often chatter during the voltage step change before opening during the actual voltage sag. Although contactors and/or relays would usually dropout during the actual under-voltage condition, there were a few instances where this occurred after voltage had already recovered. Restart times appeared to be the same regardless of the voltage when the compressor motor was disconnected.

Data captured several seconds after the compressor was disconnected did not reveal immediate restarting behavior for nearly all under-voltage tests and therefore reclose times were not captured in the report. This indicates that there must be a protective relay and associated delay times either on the thermostat or the local controller. The compressor motor would only restart approximately several minutes after tripping/dropout occurred, outside the range of the data captured. However, there were a handful of instances where the power contactor reclosed in 1.2 cycles after voltage recovered from a sag, only to re-open within several cycles and remain open until the unit restarted minutes later.

Compressor motor stalling only occurred during specific unbalanced voltage sags where two phases were reduced to 30% - 10% nominal voltage. However, unlike residential A/C units, the compressor motors did not stall immediately and took anywhere from 10.8 to 60 cycles to stop rotating, depending on the voltage magnitude. The compressor motor stalled quicker at lower phase voltages. Additionally the current, real power, and reactive power consumption during stalling was reduced at lower stall voltages. After compressor stalling occurred, each motor would restart in approximately 5 cycles after voltage recovered to nominal.

Unit	Under-Voltage Transient			Compressor Response	
	Φ	**Volt Range**	**Duration (cyc)**	**V_{stall} (%)**	**t_{stall} (cyc)**
A/C #3	AB	100%, 90%, 80%,... 0%	130	20%	24
			130	10%	12.6
	BC	100%, 90%, 80%,... 0%	130	20%	20.4
			130	10%	13.2
A/C #4	BC	100%, 90%, 80%,... 0%	130	20%	27
	CA	100%, 90%, 80%,... 0%	130	20%	32
A/C #5	BC	100%, 90%, 80%,... 0%	130	30%	24
			130	20%	10.8
	CA	100%, 90%, 80%,... 0%	130	30%	24.6
			130	20%	13.8
A/C #6	BC	100%, 90%, 80%,... 0%	130	20%	30.1
	CA	100%, 90%, 80%,... 0%	130	20%	60
A/C #7	BC	100%, 90%, 80%,... 0%	130	20%	16.2

Table 1.3.2 Motor Stalling During Unbalanced Conditions

None of the units stalled during unbalanced single-phase transients. A/C #1 has a phase monitor relay, designed to detect unbalanced conditions, which would trip before stalling could occur. A/C #2 did not stall because of a sensitive relay that dropped out at higher voltages than the other units.

Unbalanced under-voltage sags result in greater variety of trip voltages and trip times because contactor dropout is dependent on the voltage powering the device controls. Each unit supplies its controls using one of the line-to-line voltages from the A/C main terminals ($V_{\Phi A\text{-}\Phi B}$, $V_{\Phi B\text{-}\Phi C}$, or $V_{\Phi C\text{-}\Phi A}$). Therefore faults with specific phase combinations can affect contactor and/or relay dropout on each unit differently.

Generally, under-voltage deviations within 10% of steady state such as voltage oscillations or conservation voltage reduction resulted in the compressor motor maintaining constant real power and reducing reactive power indicating the motor was lightly loaded. While the A/C units were tested outdoors during both mild and warmer temperatures (78° – 95° F), the compressor motor would typically operate at 60% to 70% its rated load amperage.

In order to observe compressor stalling criteria during 3-phase balanced under-voltage conditions, some of the units were modified such that the controls were powered from a separate power supply to bypass contactor dropout. Various voltage sweep and voltage sag tests revealed that each of the tested units would begin stalling once all three phases decreased to 39% - 52% nominal voltage and would take nearly 33 to 84 cycles to completely stall at these voltages. All of the commercial rooftop A/C units tested should experience contactor dropout before reaching these conditions, but the 3-phase compressor motor characteristics at these lower voltages may be useful for model validation purposes.

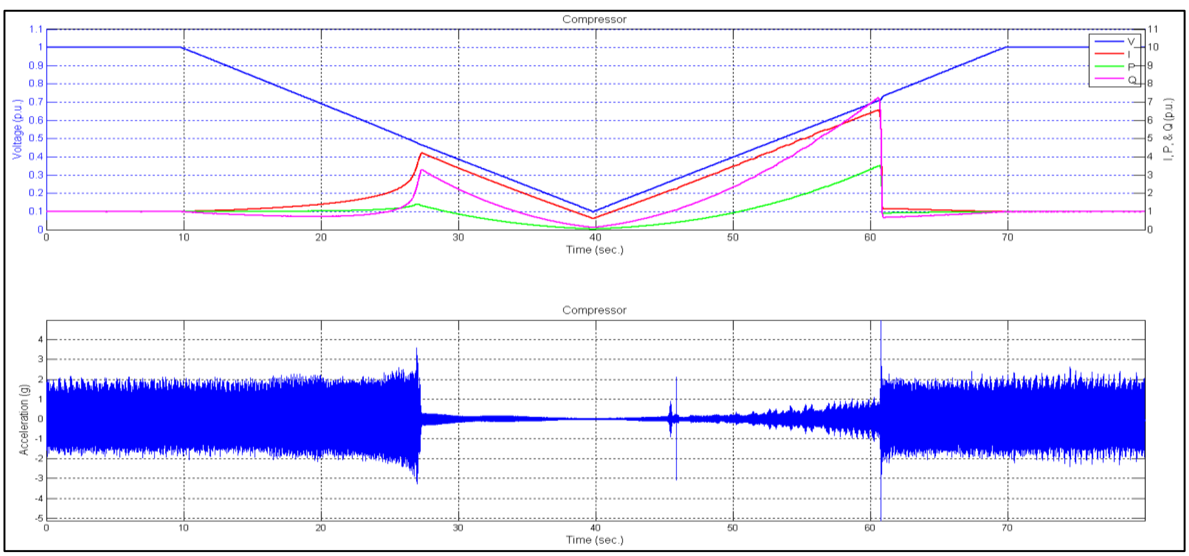

Figure 1.3.1 Sample Voltage Sweep of 3-Phase Compressor Motor

2.0 EQUIPMENT SETUP & MEASUREMENTS

While testing the performance of the seven commercial A/C units, the sinusoidal voltages and currents were measured at the compressor motor(s), the outdoor fan (condenser) motor, the indoor fan (blower) motor, and at the main disconnect terminals. These sinusoidal waveforms were used to calculate the RMS equivalent voltage/current values along with real power, reactive power, and frequency. In addition to these electrical measurements, accelerometers were placed on the A/C compressor motor to observe their mechanical vibration and serve as an indicator when stalling had occurred. Finally, transducers and thermocouples were placed at the return and supply ducts of the unit to capture air flow and temperature.

A/C #	Mfg	Model	Voltage	Ton	Comp.	Refrig.	EER	Comments
1	York	XP120C00NA4AAA5	460	10	SC	R410a	11	2 compressors
2	Coleman	B6HZ048A25	208	4	SC	R410a	11	
3	Rheem	RQPLB049CK015	208	4	SC	R410a	11.5	
4	Lennox	KHA048S4DN	208	4	SC	R410a	10.7	
5	Goodman	CPH0480153DAXX	208	4	SC	R410a	11.3	
6	Carrier	50TCQD12A2A6-0A0A0	460	10	SC	R410a	11	2 compressors
7	Trane	WSC120E4R0A	460	10	SC	R410a	11.2	2 compressors

Table 2.0.1 Commercial 3-Phase A/C Units Tested

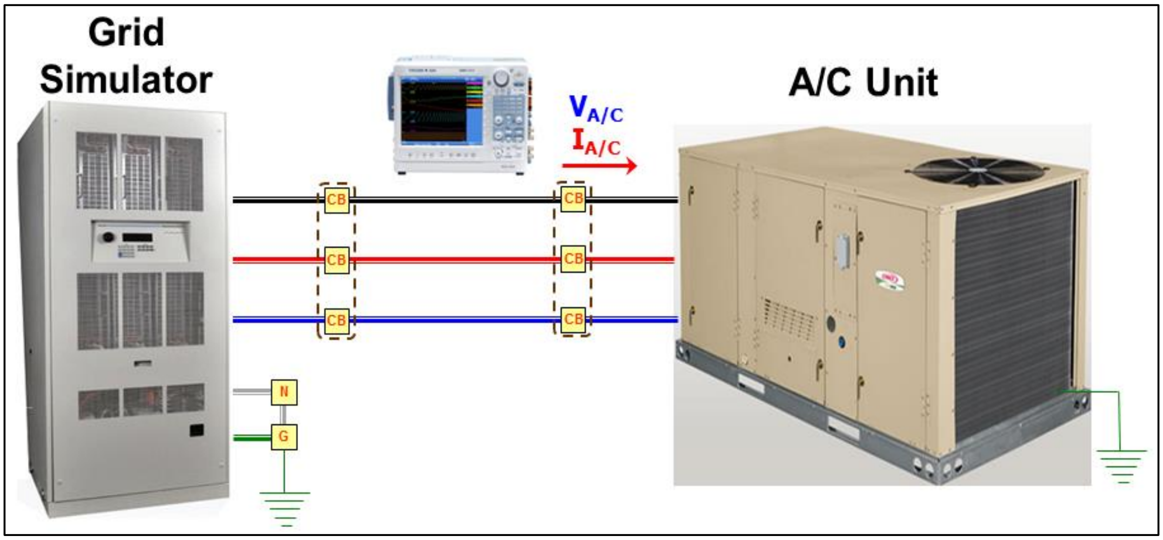

Figure 2.0.1 Commercial 3-Phase A/C Test Setup

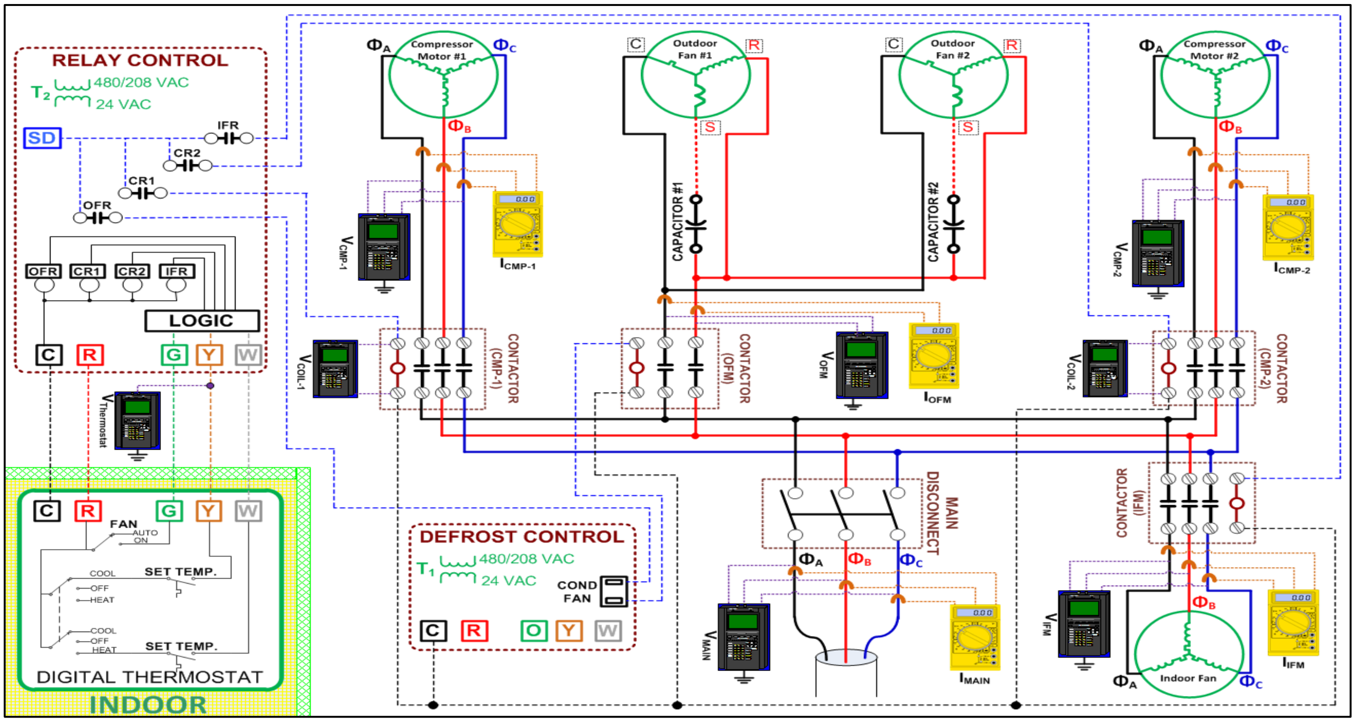

Figure 2.0.2 Typical A/C Wiring Diagram (10-ton Unit)

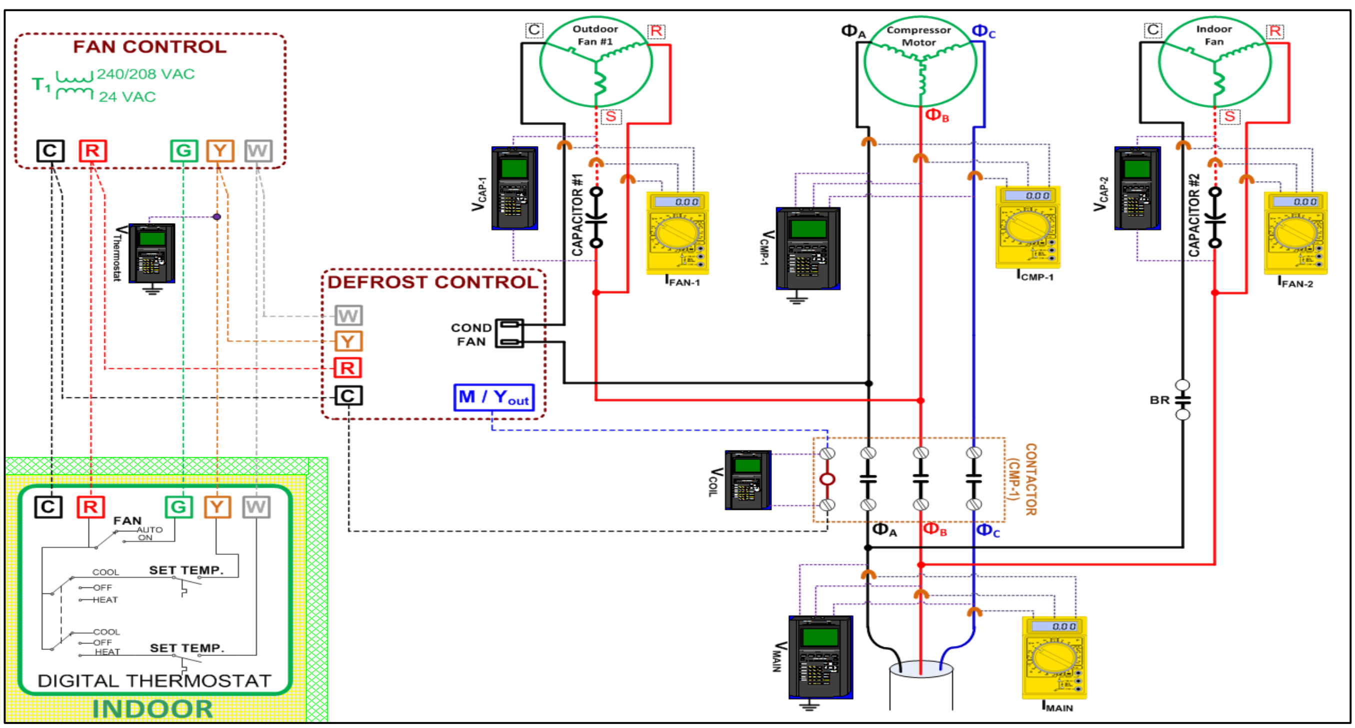

Figure 2.0.3 Typical A/C Wiring Diagram (4-ton Unit)

3.0 AIR CONDITIONER #1 TEST RESULTS

The first air conditioner tested is a 10-ton unit operated at 480 V line-to-line. The unit is comprised of an indoor blower fan motor, two outdoor fan motors, and two compressor motors. Both compressor motors were monitored individually (voltage, current, and acceleration) due to the fact that each compressor is connected with its own power contactor for operational purposes. The specifications for the individual components of A/C #1 are provided in the table below.

Main System		Compressors	
Manufacturer	York	Manufacturer	Danfoss
Model	XP120C00NA4AAA5	Model	HRH051U4LP6
Size (Tons)	10	Type	Scroll
Voltage (V)	460	Quantity	2
Refrig.	R-410A	RLA (Amps)	9.6
SEER	-	LRA (Amps)	70
EER	11	Test Press. High (PSI)	445
IEER	11.6	Test Press. Low (PSI)	236
Condenser Fan		**Blower Motor**	
Drive Type	Direct	Type	Belt
Quantity	2	Quantity	1
Motor HP	1/3	Motor HP	3
RPM	850	RPM	1725
FLA (Amps)	0.8	FLA (Amps)	5.3
Miscellaneous Components			
Contactor(s)	Hartland Controls, HCC-3XQ02CJ271	Capacitor(s)	CSC Electronics, 320-573131440
Transformer	Tyco Electronics, 4001-10j15AE15	Phase Balance Relay	ICM Controls, ICM 401

Table 3.0.1 A/C #1 Specifications

3.1 Compressor Shutdown

A/C #1 was shut down during normal operation using the connected thermostat. The figure below displays the measurements taken at the main service connections as well as the behavior of the various internal components.

The two compressors and outdoor fan motors shut down at the same time, immediately after managing the thermostat. The only power consumption after the compressors shut down was from the indoor fan motor operating at 3-phase 480 V with approximately 4.8 amps per phase (total of 2.7 kW or 3.9 kVA). However, this motor shuts down within 30 seconds of the other components.

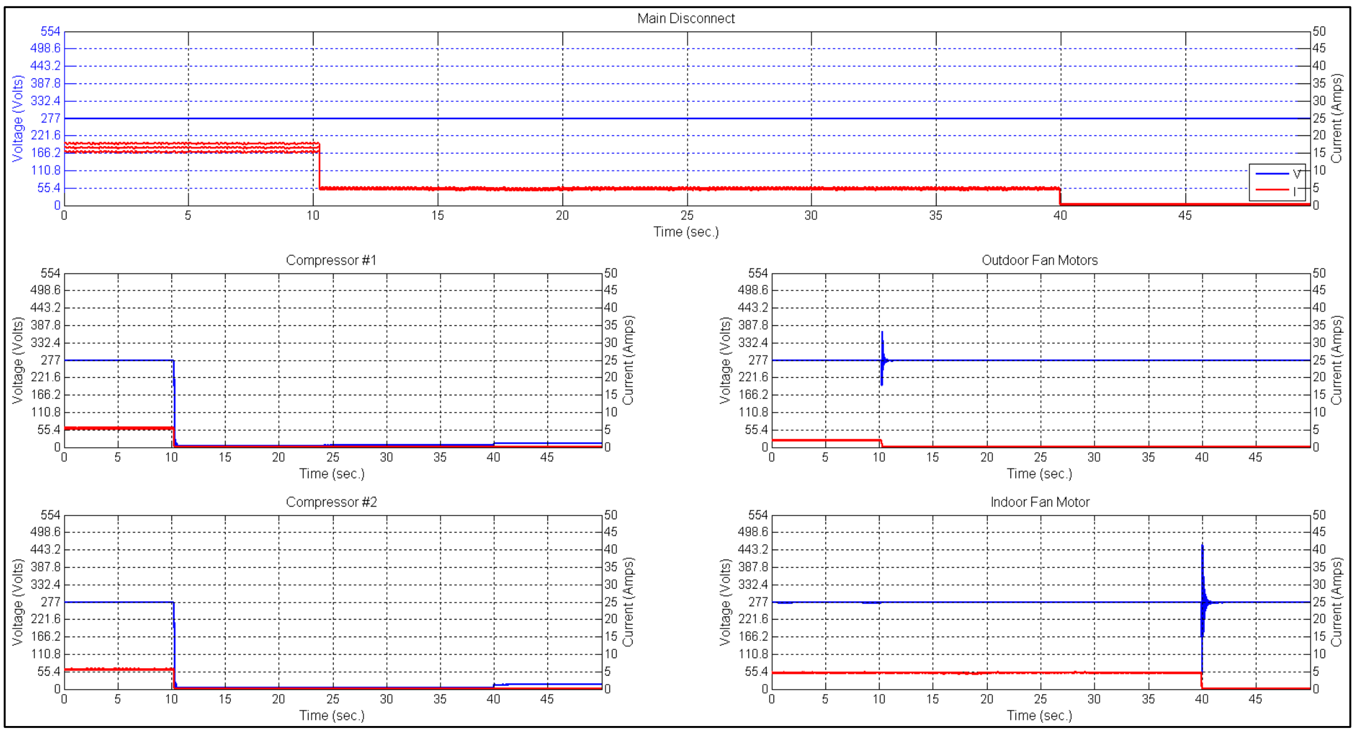

Figure 3.1.1 A/C #1 Compressor Shutdown

3.2 Inrush Current

Upon starting up the A/C unit via the programmable thermostat one compressor and the outdoor fan motors start up at the same time followed shortly by the indoor fan motor approximately 19 cycles later. Finally after an additional 29 seconds, the 2nd compressor turns on accordingly. The two significant inrush values observed at the main disconnect of the unit withdrew a maximum of 86.9 Amps and 68.5 Amps while lasting approximately 4 cycles.

Compressor #1 Inrush: Maximum of 56.5 Amps and duration of 4 cycles

Compressor #2 Inrush: Maximum of 58.5 Amps and duration of 4.2 cycles

Outdoor Fan Motors Inrush: Maximum of 5.5 Amps and duration of 61 cycles

Indoor Fan Motors Inrush: Maximum of 31.1 Amps and duration of 6/33 cycles

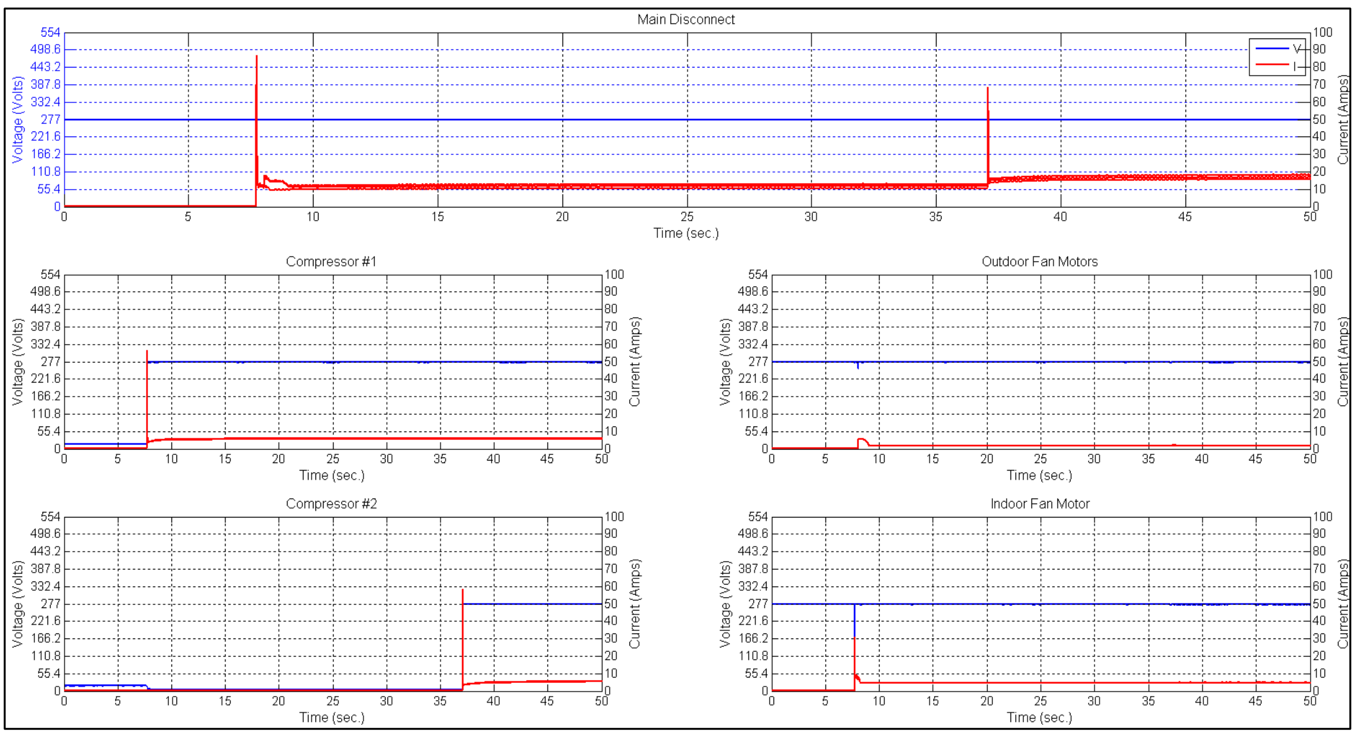

Figure 3.2.1 A/C #1 Inrush Current

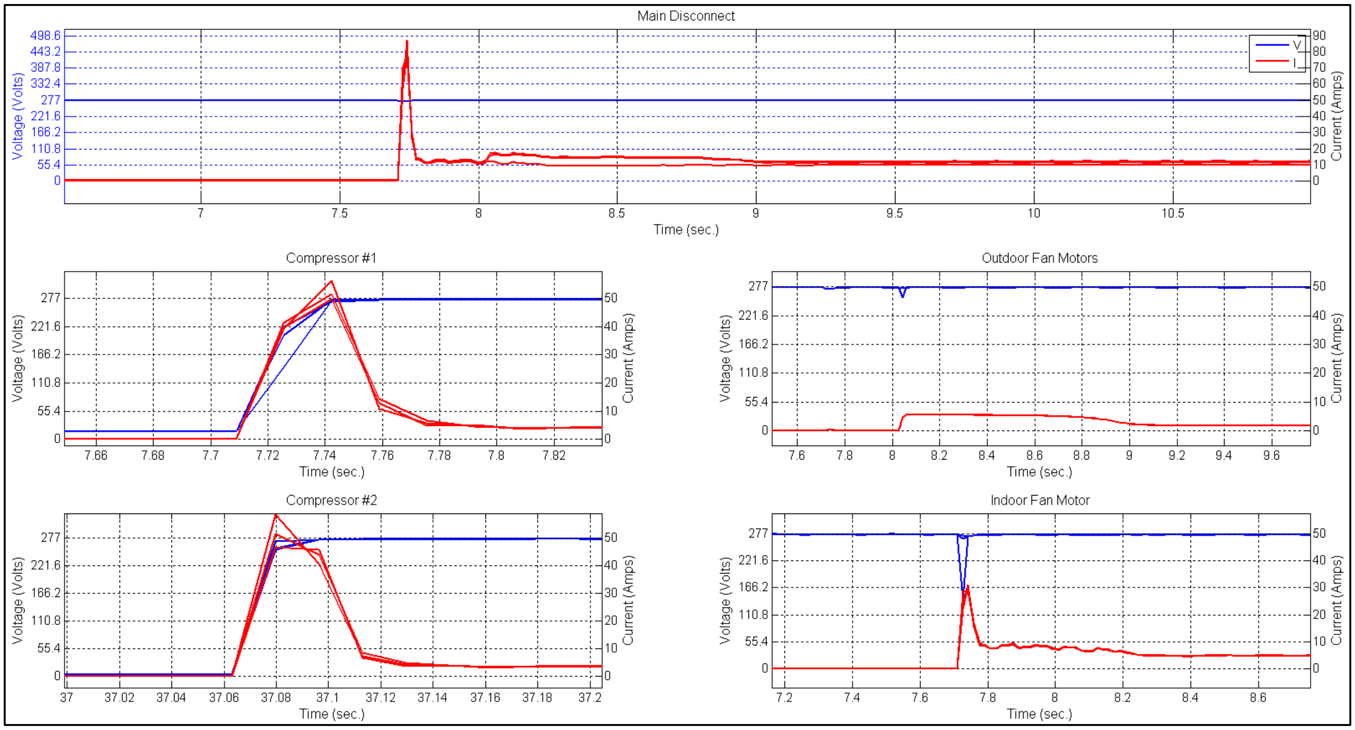

Figure 3.2.2 A/C #1 Inrush Current [Zoom In]

3.3 Balanced & Unbalanced Under-voltages

No stalling behavior was observed during any of the balanced or unbalanced under-voltage tests performed while operating under normal conditions. The contactors would open before reaching a voltage magnitude that would induce stalling behavior. Contactor chattering was sometimes observed during the voltage step changes and during the voltage sag tests as well. Data captured several seconds after the compressors were disconnected showed that the contactors did not reclose immediately after the voltage recovered for most cases. This is due a relay located at the thermostat or local controller. Reclosing typically occurred several minutes later as the A/C unit began startup operations.

After implementing balanced voltage sags on all three phases in decrements of 10%, the power contactors for each compressor typically opens at either 60% or 50% nominal voltage for under-voltage transients in the range of 3 to 130 cycles. Contactors were found to open between 3 and 19 cycles after the start of the voltage sag. One of the 3 cycle duration transients resulted in a delayed tripping behavior where the contactor began chattering but would not open until up to 12 cycles after the voltage already recovered to steady state (15 cycles after the start of the voltage sag). Only the 3 cycle transients showed the contactors reclosing immediately (within 1.2 cycles) following voltage returning to nominal, but would re-open after another 10 cycles and remain open until the unit restarted several minutes later.

The only case where the contactor remained closed and the compressor motor rode through all balanced under-voltage sags (down to 0%) was during switching transients with a duration time of 1 cycle. “N/A” or “not applicable” is placed in the following tables under “Compressor #1” and “Compressor #2” to represent these ride through situations where there is no trip voltage or trip time available.

The following figure gives a visual representation of these tests, specifically one of the longer duration voltage sags. The following table provides additional test details including the voltage where the compressor contactors opened (V_{trip}) as well as the time it takes for the contactors to open after the start of the voltage sag (t_{trip}).

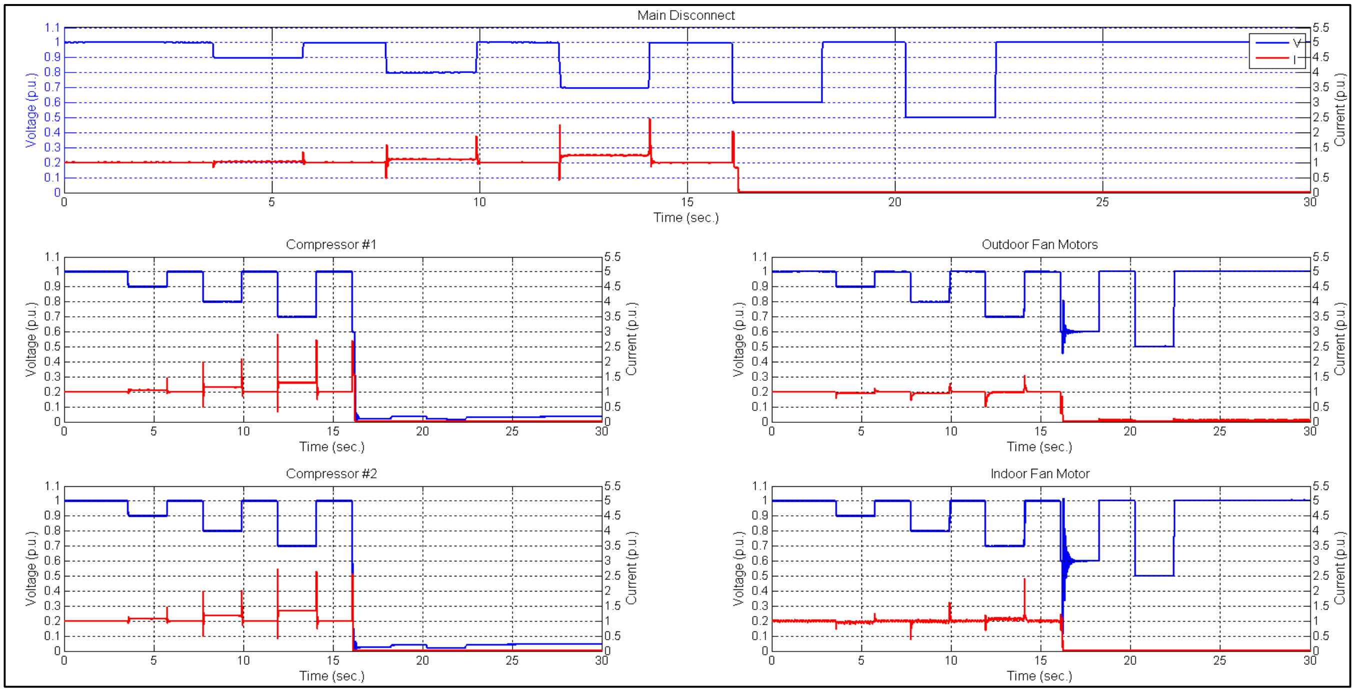

Figure 3.3.1 A/C #1 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor #1		Compressor #2	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	50%	12	50%	12
		60%	8	60%	3
		60%	19	60%	19
		60%	9	60%	4
		60%	8	60%	3
		60%	3	60%	3
100%, 90%, 80%,... 0%	6	60%	3	60%	3
		60%	3	60%	3
		50%	3	50%	3
		50%	3	50%	3
		50%	3	50%	3
100%, 90%, 80%,... 0%	3	50%	14	50%	15
		60%	2	60%	2
		50%	2	50%	2
		50%	3	50%	3
		60%	2	60%	2
100%, 90%, 80%,... 0%	1	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A

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

In order to narrow down the voltage where the compressors are disconnected, additional balanced under-voltage tests were performed in decrements of 1% nominal voltage. The results of multiple tests revealed that the contactors would start opening between 58% and 61% voltage. Measuring the 24 V across the coils of the contactors indicated that this operation was the result of contactor dropout since the compressor voltage was often “chattering” or would begin dissipating even before the contactor coil voltage de-energized. The following figure visually displays the compressor and coil voltages during an under-voltage test while the following table provides the details (V_{trip} and t_{trip}) of the 1% voltage decrements.

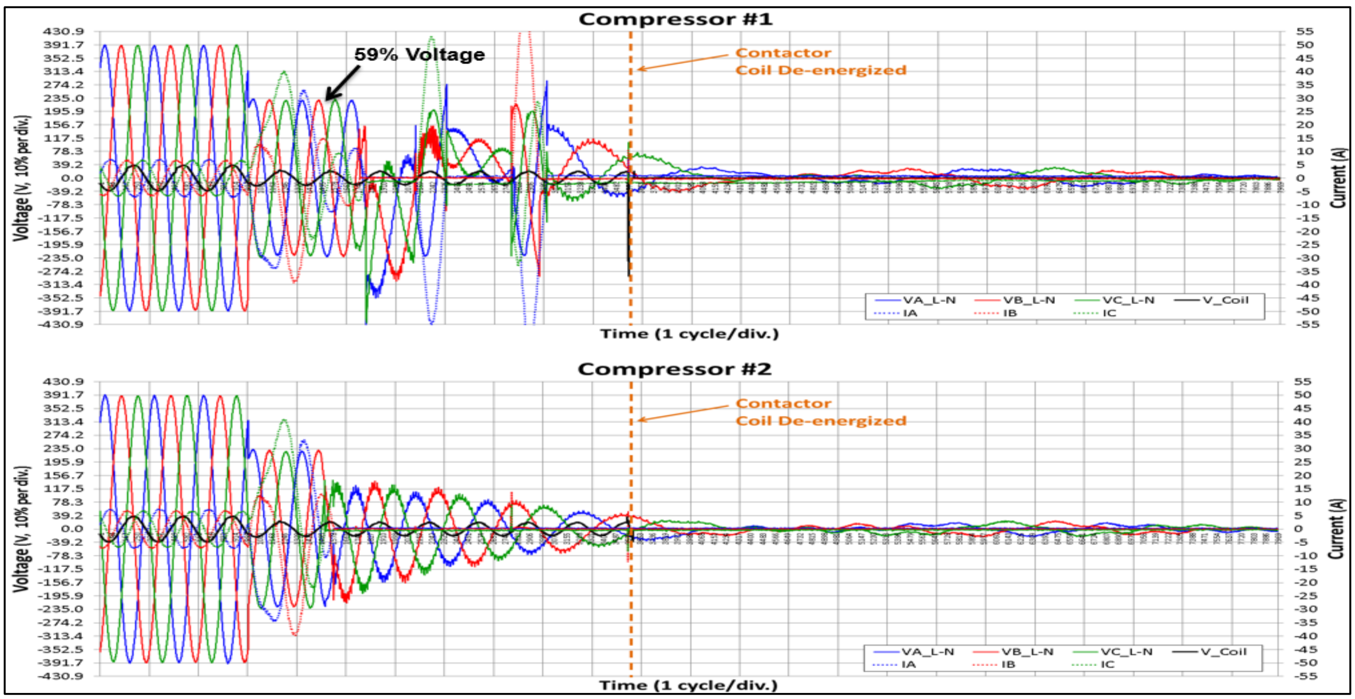

Figure 3.3.2 A/C #1 Compressor Contactor Dropout

Under-Voltage Transient		Compressor #1		Compressor #2	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
65%, 64%, 63%,…	120	60%	9	60%	2
65%, 64%, 63%,…	120	59%	2	59%	2
65%, 64%, 63%,…	120	61%	6	61%	2
65%, 64%, 63%,…	120	58%	14	58%	14
65%, 64%, 63%,…	120	61%	11	61%	11

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

Unbalanced under-voltages on this A/C unit resulted in a greater variety of trip voltages and trip times when the compressors were disconnected, as opposed to balanced conditions. One of the reasons for this is because the controls and the contactor coils are energized using the line-to-line supply voltage, phase C to phase A. Therefore phase C to A under-voltages yield similar results to those of balanced under-voltages. Also, any voltage sag observed on phase B does not contribute to dropout behavior from the controls or the individual contactors.

The A/C unit is equipped with a phase monitor relay designed to detect any imbalance between the different phases. Most unbalanced under-voltage tests (A, B, C, AB, and BC) with a duration between 130 and 30 cycles result in the A/C unit tripping off due to this phase monitor relay. It appears that voltage sags with a duration of 20 cycles or less are not detected by the relay based on the results of the phase B voltage sags. Under-voltages on phase B alone within 20 cycles resulted in the ride through behavior for all voltage magnitudes down to 0% voltage.

Contactors and relays did not reclose immediately upon voltage recovery after tripping or dropout had occurred. Reclosing would not occur until several minutes later due to the operations of the thermostat. The following table provides more details on the tripping/dropout behavior during the unbalanced transients including voltage where contactors opened and how long it took for the contactors to open after the start of the voltage sag.

Under-Voltage Transient			Compressor #1		Compressor #2		Controls Xfrmer
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	$V_{trip\ (PhA\text{-}PhC)}$ (%)
A	100%, 90%, 80%,... 0%	130	40%	115	40%	115	72%
		60	30%	52	30%	52	69%
		30	10%	27	10%	27	62%
		20	0%	2	0%	2	59%
		6	0%	2	0%	2	59%
		3	N/A	N/A	N/A	N/A	N/A
B	100%, 90%, 80%,... 0%	130	40%	110	40%	110	72%
		60	30%	52	30%	52	69%
		30	10%	28	10%	28	62%
		20	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A
C	100%, 90%, 80%,... 0%	130	40%	88	40%	88	72%
		60	30%	59	30%	59	69%
		30	10%	27	10%	27	62%
		20	0%	10	0%	10	59%
		6	0%	6	0%	6	59%
		3	0%	3	0%	3	59%
AB	100%, 90%, 80%,... 0%	130	40%	105	40%	105	72%
		60	30%	59	30%	59	69%
		6	10%	6	10%	6	62%
		3	N/A	N/A	N/A	N/A	N/A
BC	100%, 90%, 80%,... 0%	130	40%	81	40%	81	72%
		60	30%	48	30%	48	69%
		6	10%	6	10%	6	62%
		3	N/A	N/A	N/A	N/A	N/A
CA	100%, 90%, 80%,... 0%	130	50%	3	50%	3	50%
		60	50%	3	50%	3	50%
		6	60%	3	60%	3	60%
		3	50%	>3	50%	>3	50%

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

3.4 Balanced & Unbalanced Over-voltages

In order to avoid damaging any voltage sensitive A/C equipment, the unit was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve up to 120% nominal voltage. No over-voltage protection was observed during these tests as the A/C unit rode through all of the voltage transients and continued operating normally as shown in the following figure and table.

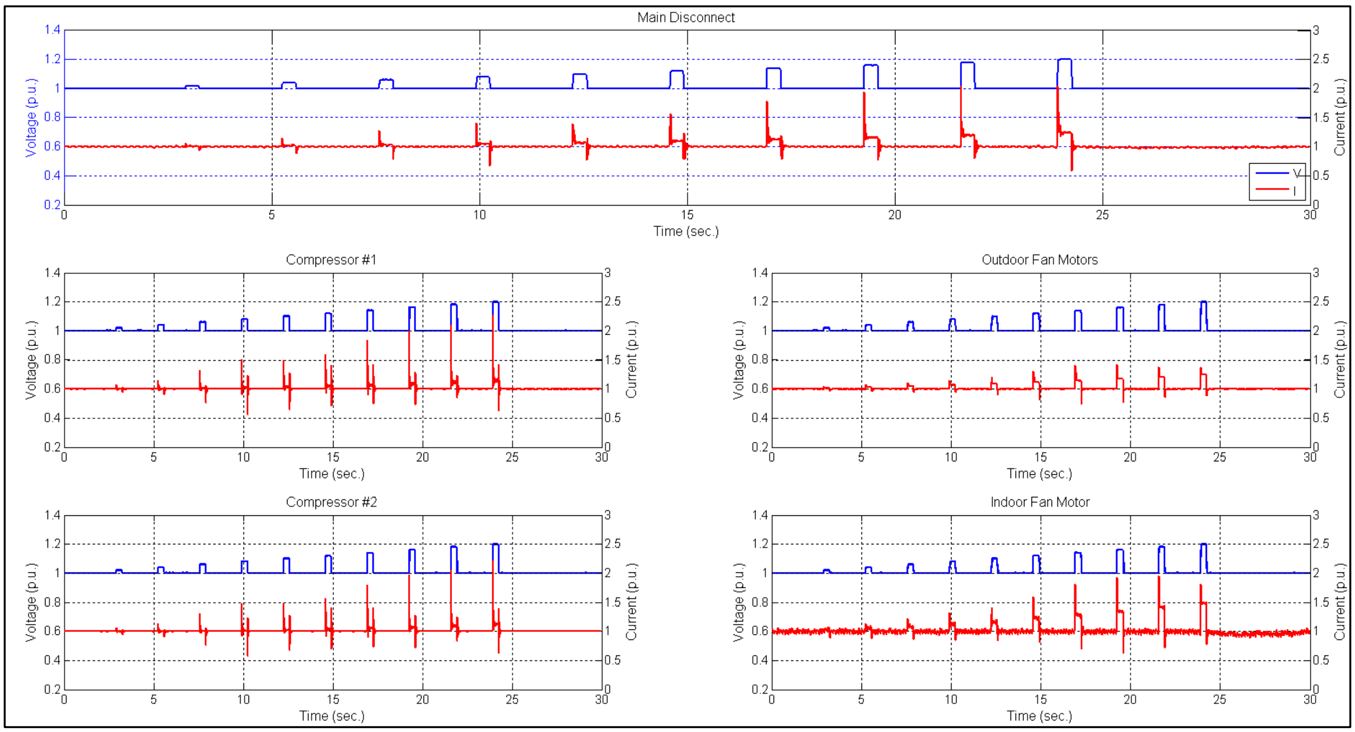

Figure 3.4.1 AC #1 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor #1		Compressor #2	
Φ	**Volt Range**	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
ABC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A
A	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A
B	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A
C	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A
AB	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A
BC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A
CA	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A

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

3.5 Voltage Oscillations

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

Current and real power remain relatively at steady state condition, typically oscillating within +3% of their nominal values. The A/C currents oscillate in the opposite direction of voltage (+2%) with slightly larger deviations occurring at 1 and 2 Hz voltage oscillations. On the other hand, real power consumption marginally oscillates with voltage (-2% to -3%).

Reactive power consumption experiences the largest impact (-12% to -16% deviation) oscillating in the same direction as voltage. Similar to current and real power, the larger deviations from steady state occur as the swing frequency or rate of oscillation increases.

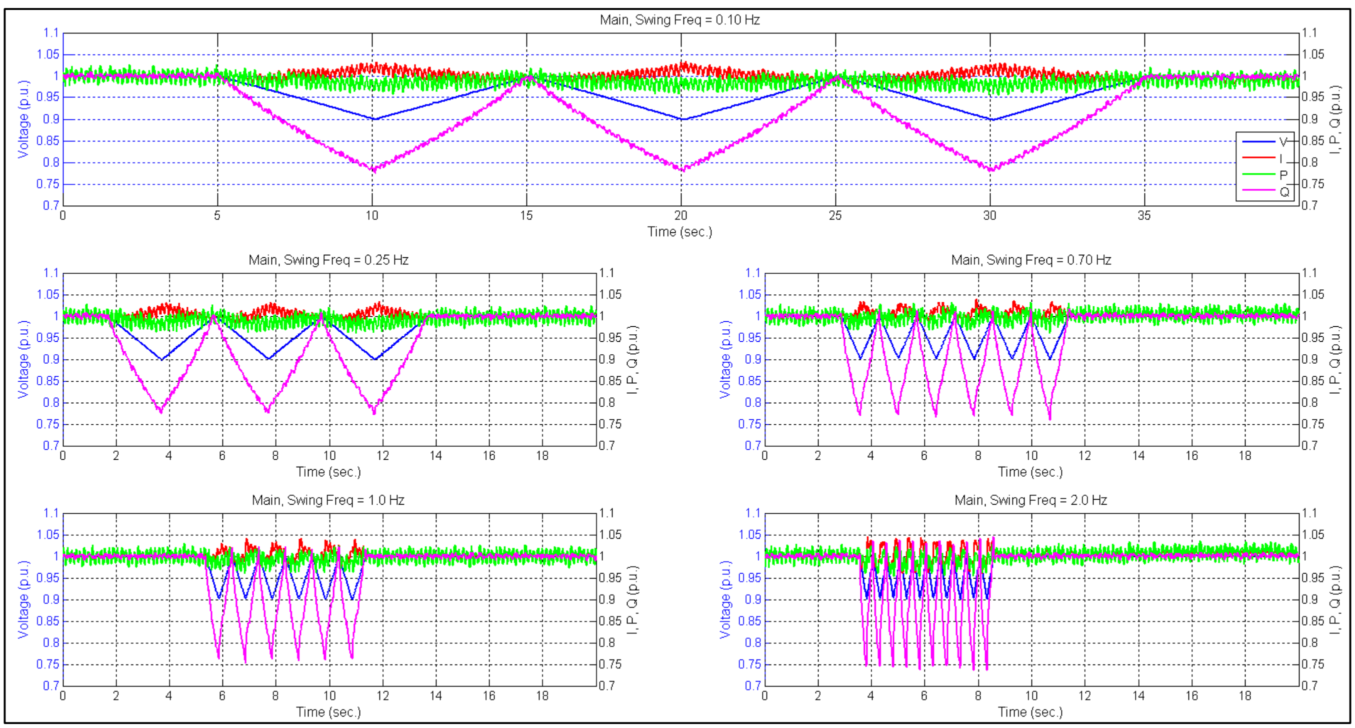

Figure 3.5.1 AC #1 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

3.6 Under-frequency Events

After subjecting this A/C to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection down to 58 Hz. The device simply rides through these frequency conditions. The following figure and table identify the tests that were performed.

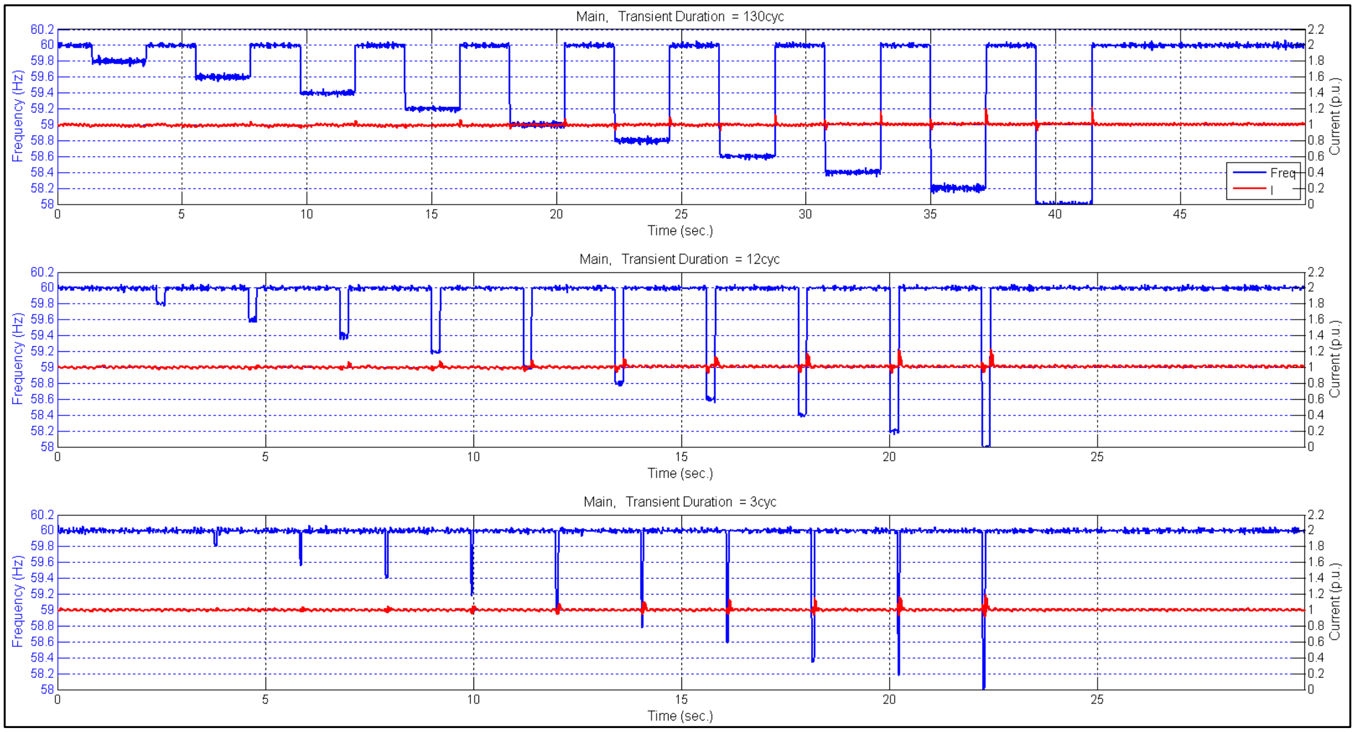

Figure 3.6.1 A/C #1 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor #1		Compressor #2	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 59.8Hz, 59.6Hz,... 58Hz	130	N/A	N/A	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	12	N/A	N/A	N/A	N/A
60Hz, 59.8Hz, 59.6Hz,... 58Hz	3	N/A	N/A	N/A	N/A

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

3.7 Over-frequency Events

Similar to the under-frequency tests, the A/C unit was subjected over-frequency transients with different duration times up to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The following figure and table identify the over-frequency tests that were performed.

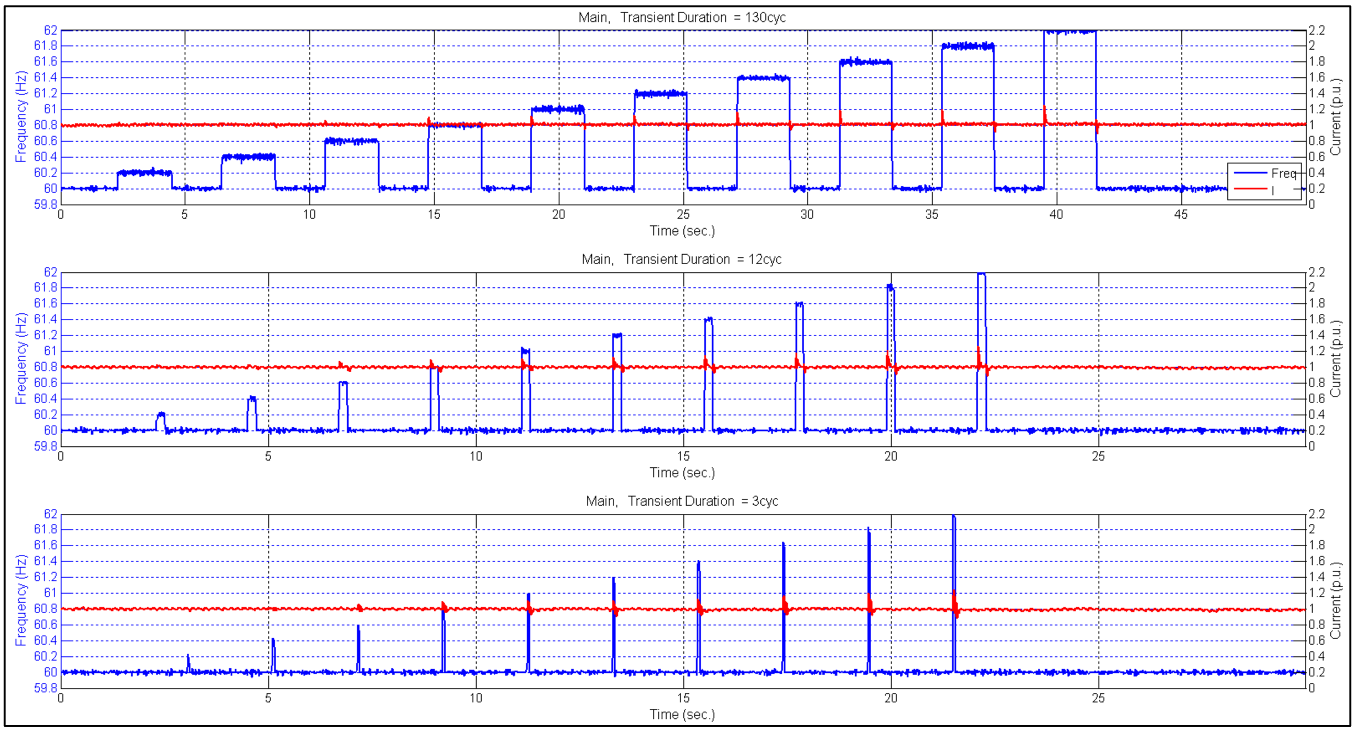

Figure 3.7.1 A/C #1 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor #1		Compressor #2	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 60.2Hz, 60.4Hz,... 62Hz	130	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	12	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	3	N/A	N/A	N/A	N/A

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

3.8 Frequency Oscillations

The following figure shows the performance of the A/C unit during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates.

Current does not appear to change very much (within +1%) during oscillations for swing frequencies up to 0.70 Hz. Even at a swing frequency of 1 Hz or 2 Hz, current only deviates up to +3% from its nominal current output.

Real and reactive power consumption deviates up to +5% from steady state during these frequency oscillations. However, the real power appears to oscillate with frequency while reactive power oscillates in the opposite direction of frequency.

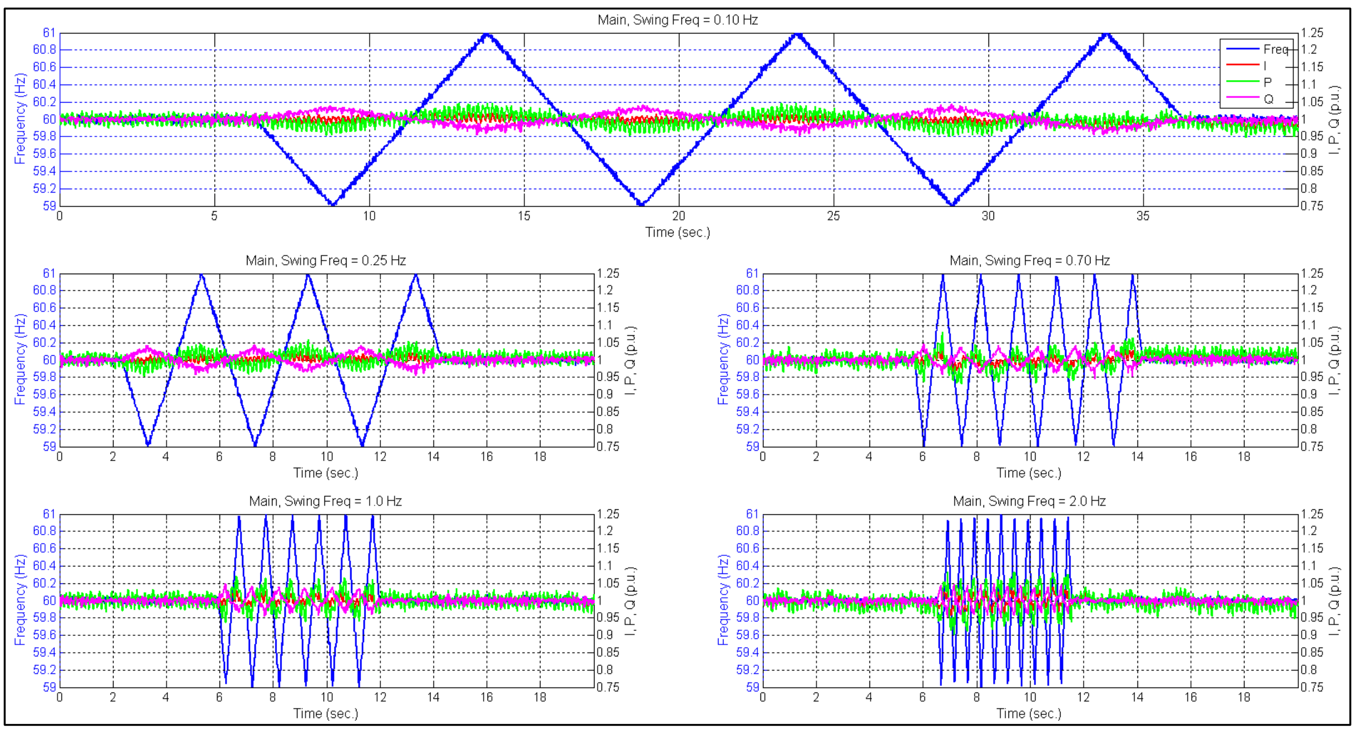

Figure 3.8.1 A/C #1 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

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).

Current ramps up to approximately 40% above nominal, mitigating a large reduction in real power consumption. As a result, real power only deviates roughly 6% below its nominal value at steady state. Reactive power is reduced significantly ramping as low as 50% of normal consumption.

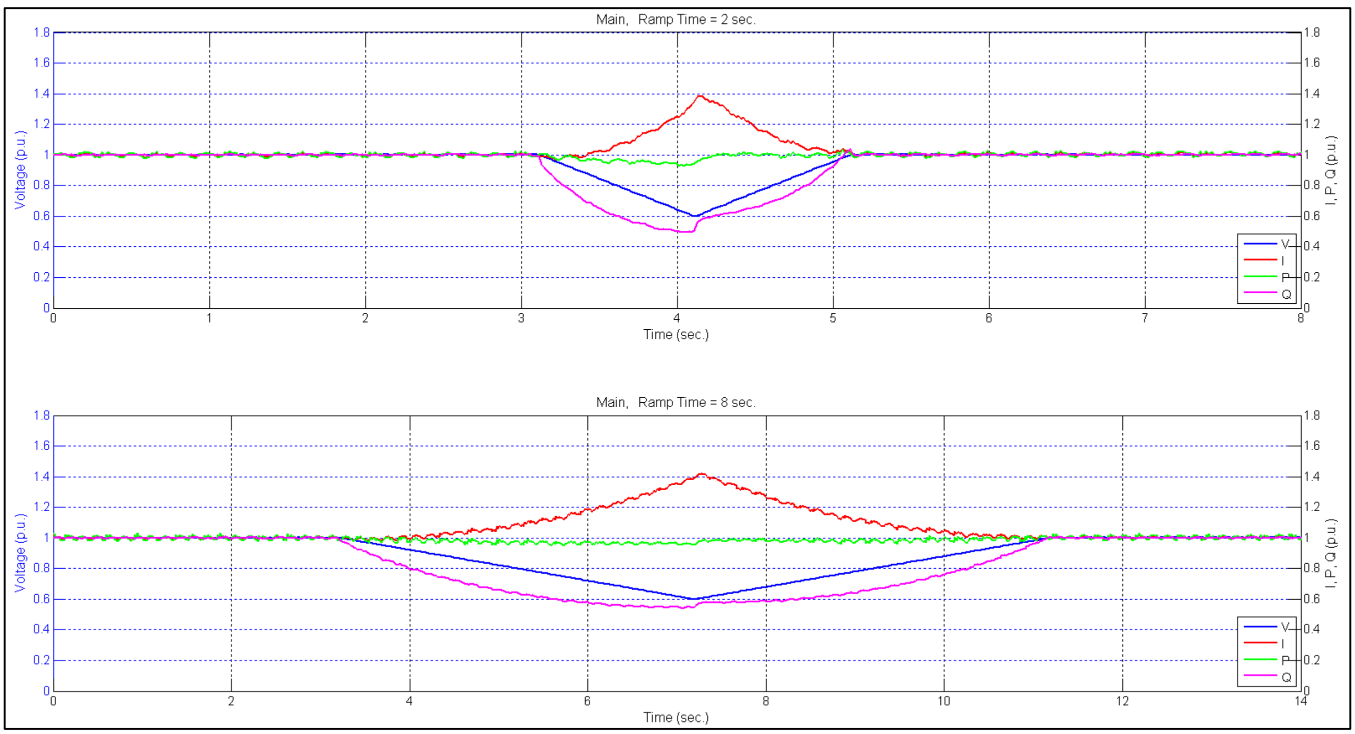

Figure 3.9.1 A/C #1 Voltage Ramp Down to 60% (2 & 8 sec.)

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.

Current is observed uniformly ramping up to approximately 10% above nominal. Real power ramps with voltage as well but only deviating by 5% above steady state. Finally, reactive power has the most significant deviation by nearly ramping up to 40% above of normal consumption.

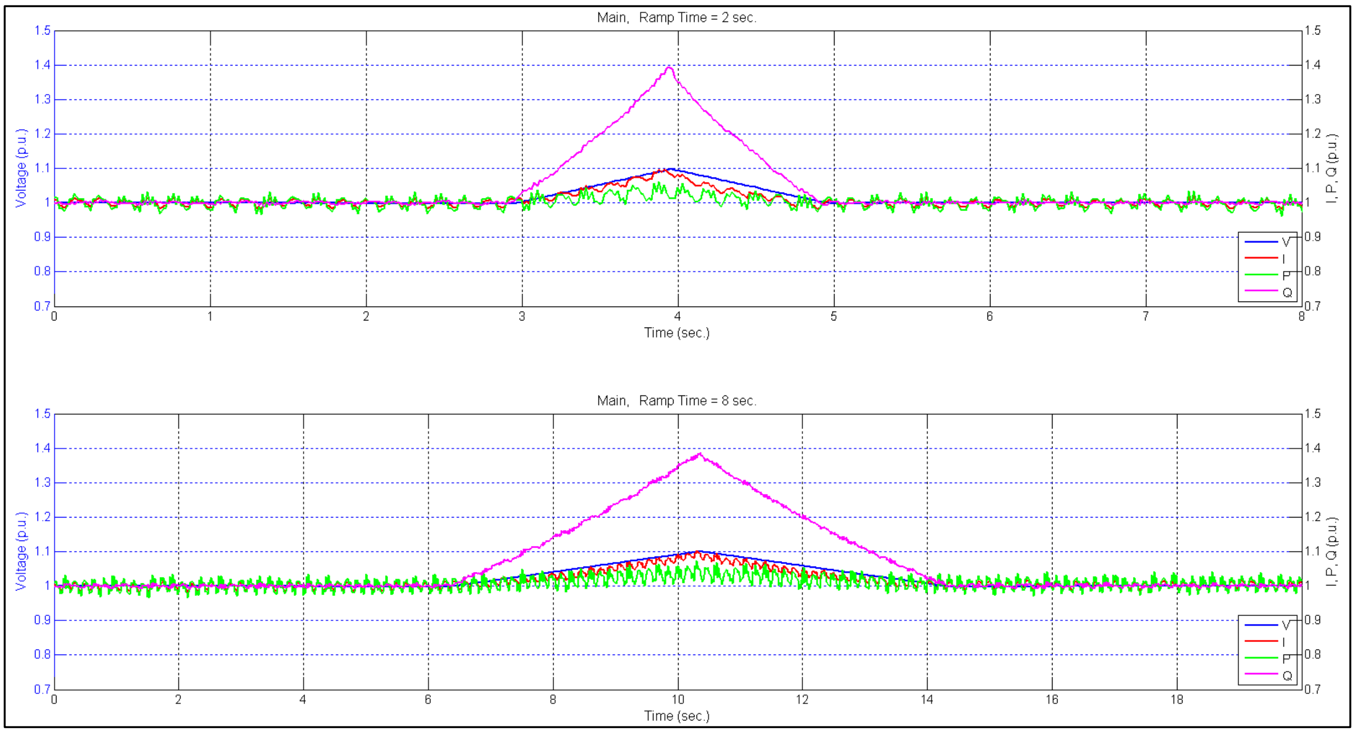

Figure 3.9.2 A/C #1 Voltage Ramp Up to 110% (in 2 & 8 sec.)

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 ramps up to 25% above its nominal output. Real power consumption is reduced during the under-frequency condition dipping to nearly 20% below steady state. Reactive power increases the most, in terms of percentage, ramping to as high as 66% above of normal consumption.

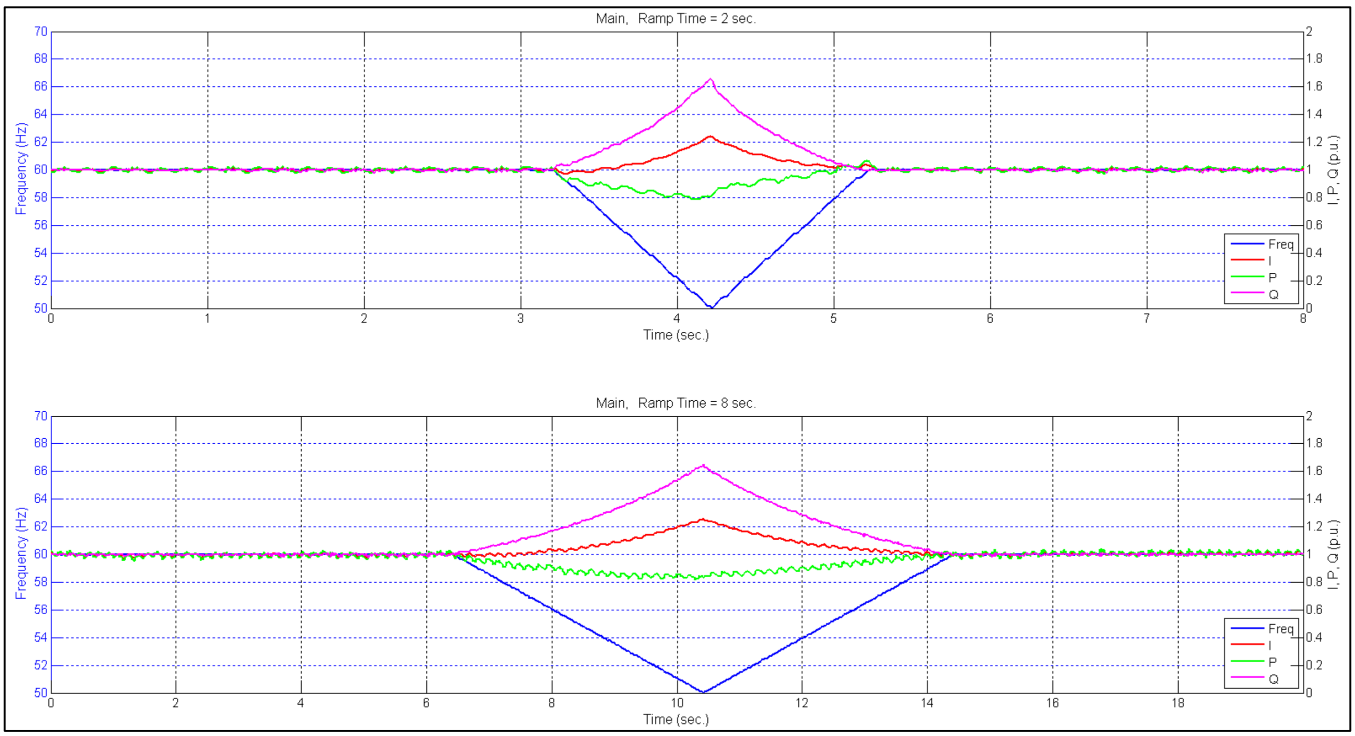

Figure 3.10.1 A/C #1 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

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 as shown in the figure below.

Current is observed ramping up to approximately 12% to 15% above its normal current output. Real power consumption is actually increased ramping up to 14% above steady state. Reactive power ramps in the opposite direction of frequency to 18% below its nominal value.

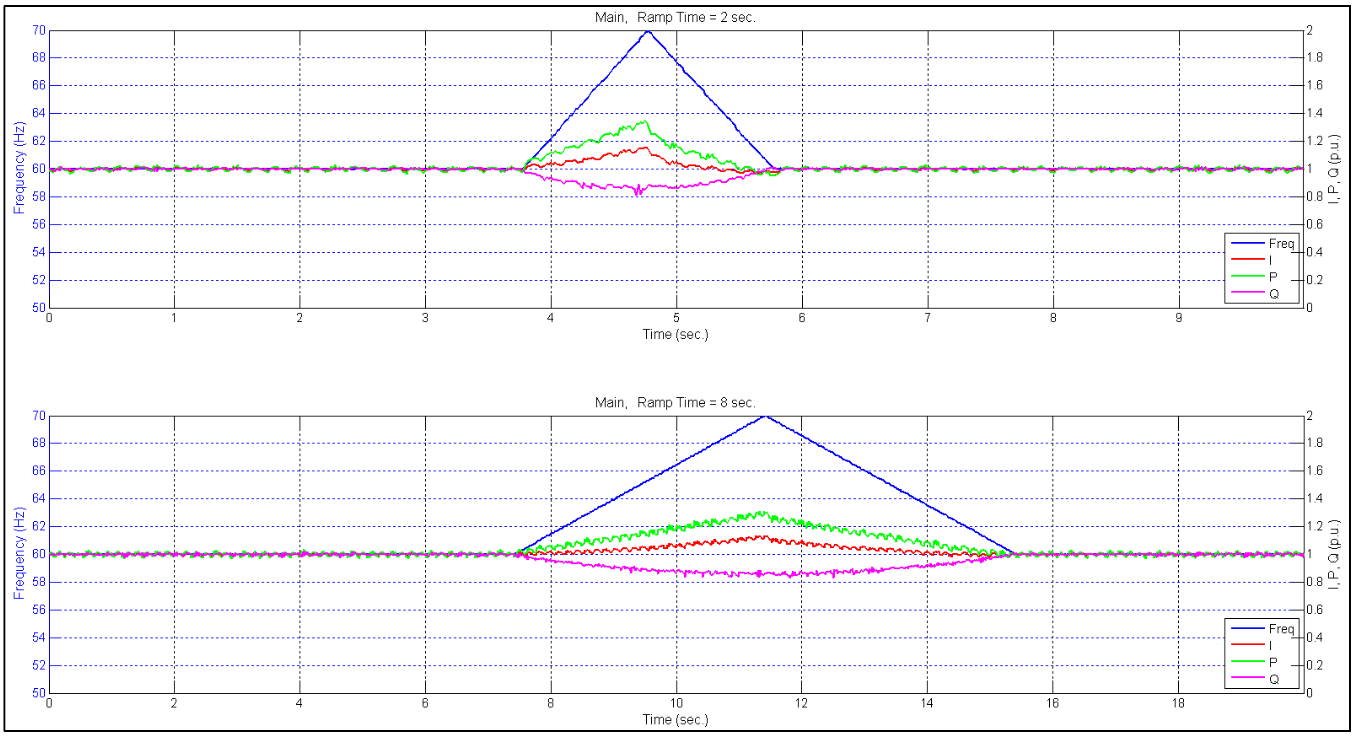

Figure 3.10.2 A/C #1 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

3.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times to calculate the harmonic contribution of A/C unit #1 to the grid. The total harmonic distortion of current was determined to be less 2% of the fundamental. The following table gives the total harmonic distortion for each phase ad the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)					
	$V_{A\ (L\text{-}N)}$	$V_{B\ (L\text{-}N)}$	$V_{C\ (L\text{-}N)}$	I_A	I_B	I_C
1	0.08	0.09	0.09	1.67	1.36	1.87
2	0.08	0.09	0.09	1.68	1.38	1.88
3	0.08	0.09	0.09	1.73	1.42	1.93

Table 3.11.1 A/C #1 Total Harmonic Distortion

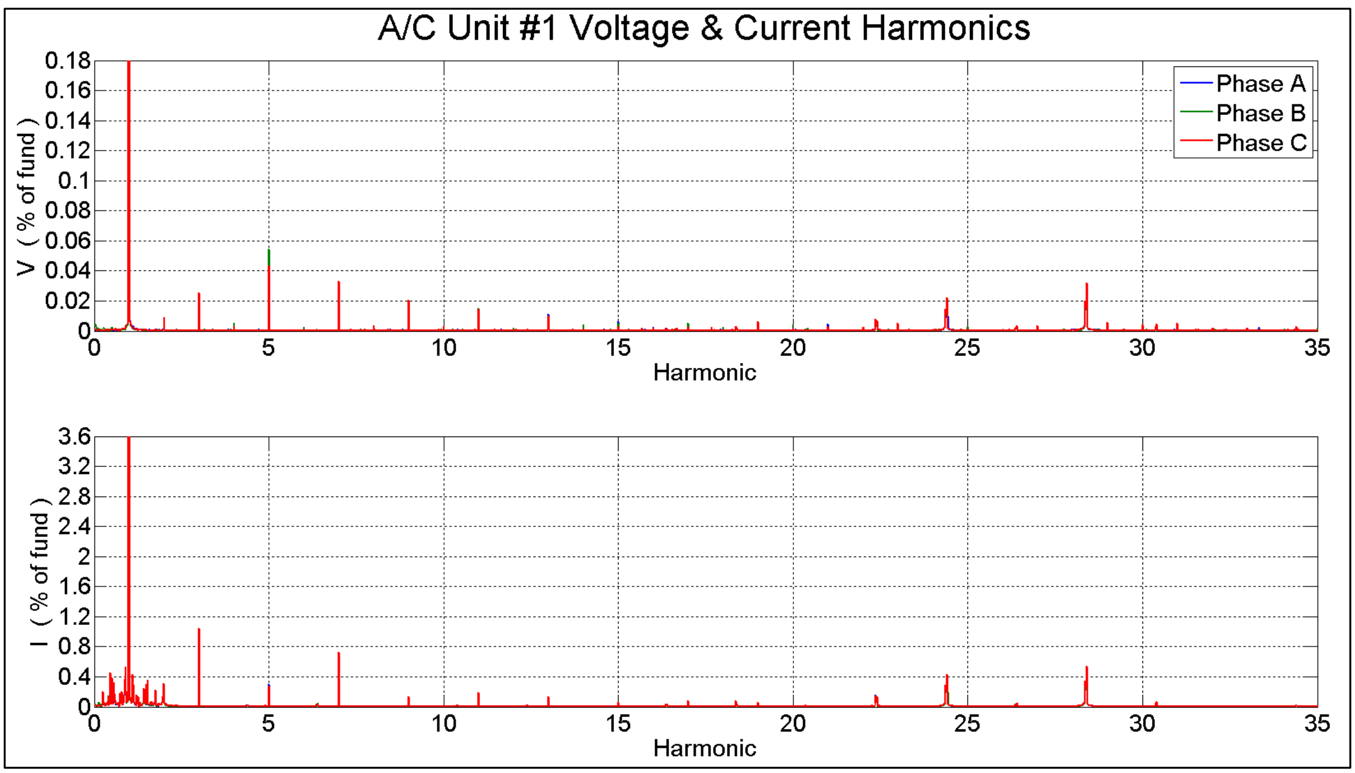

Figure 3.11.1 A/C #1 Harmonics Contribution

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. Outdoor conditions resulted in mild loading of the dual compressors operating at approximately 60% of the rated load amps.

Current remains relatively constant throughout the test, only reducing by roughly 2% of the nominal output at most. Real power does not change much as well with approximately a 3% loss in power consumption during the course of CVR. Reactive power is observed stepping down with the voltage and drops as low as 24% below steady state. This translates to a decrease of 2.4% nominal reactive power for every 1% decrease in nominal voltage.

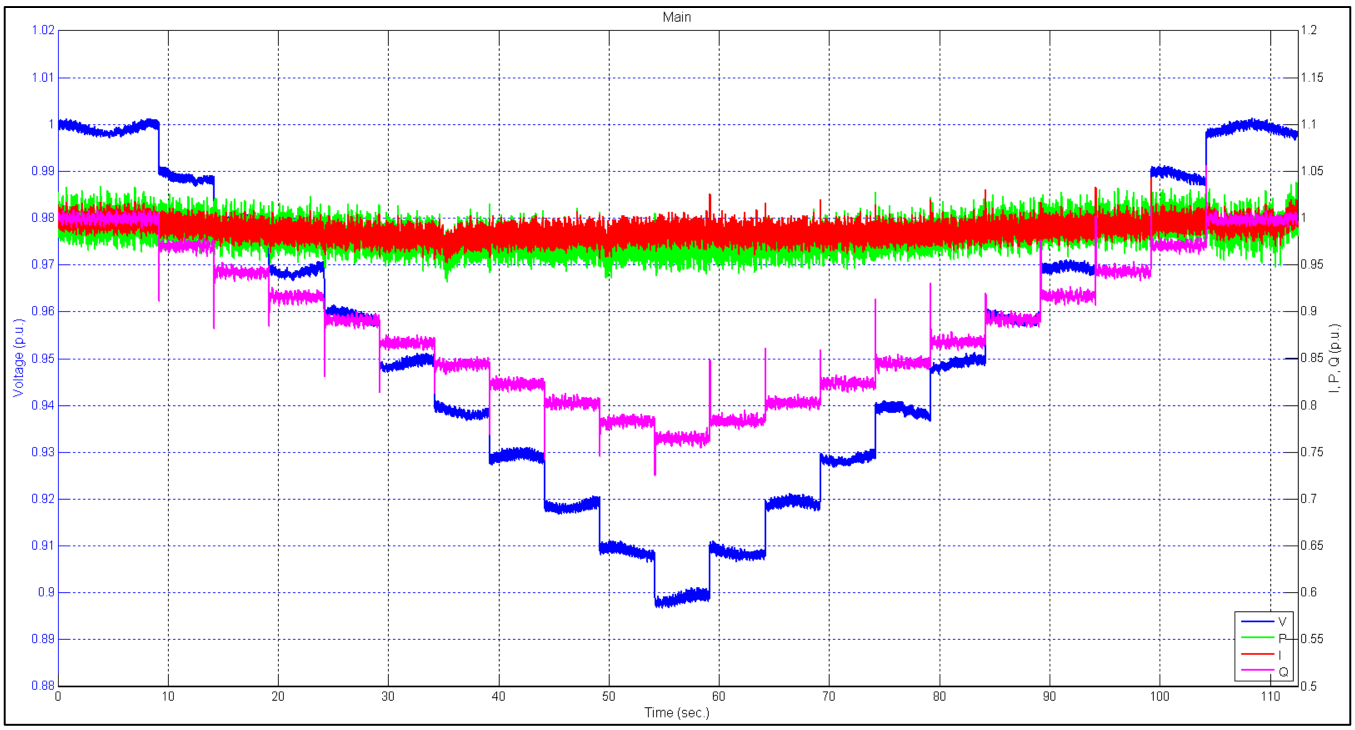

Figure 3.12.1 A/C #1 CVR Response Down to 90% Voltage

Alternatively, the service voltage at the 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 only slightly increases over the course of the test, deviating at most approximately 3% above its nominal value. Real power remains nearly constant as well varying within ±3% of the normal power consumption. Reactive power is observed stepping up with the voltage and increases as high as 16.5% above steady state. This translates to an increase of 3.3% nominal reactive power for every 1% increase in nominal voltage.

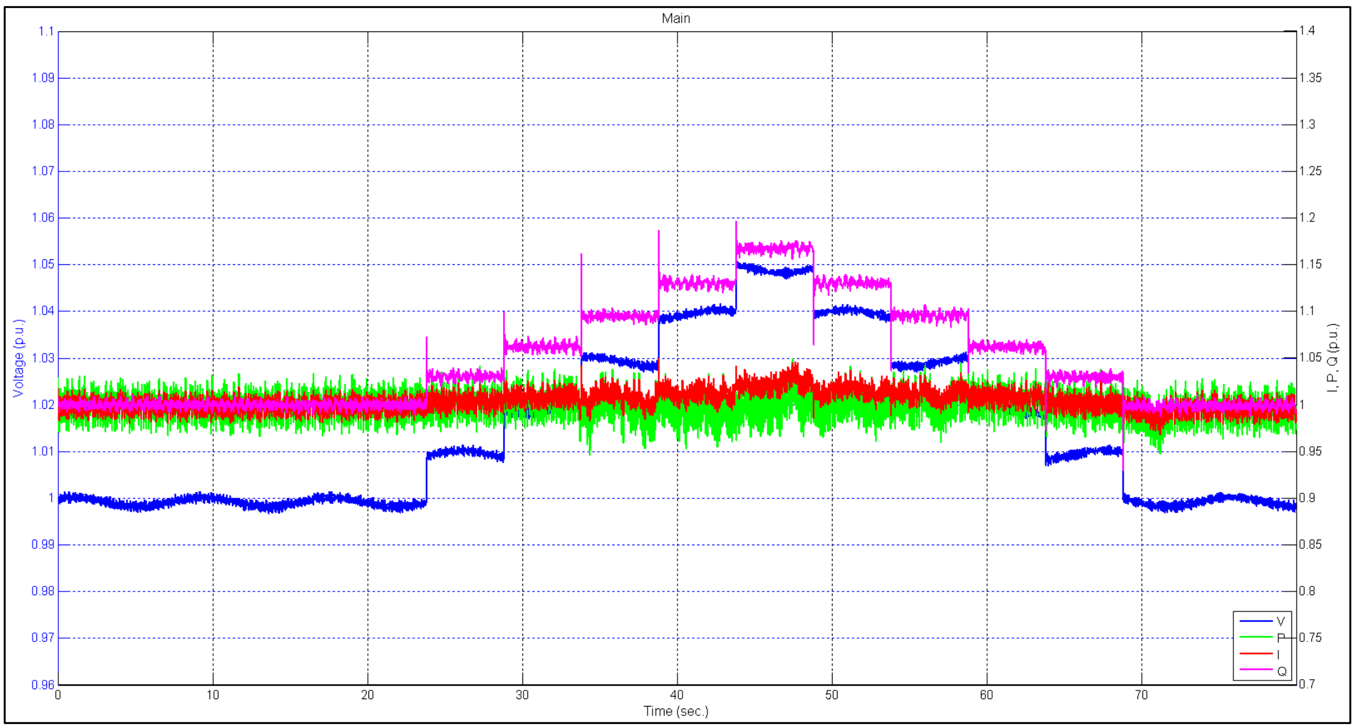

Figure 3.12.2 A/C #1 CVR Response Up to 105% Voltage

3.13 Compressor Stalling

A/C unit #1 did not display any signs of compressor stalling during any of the under-voltage transient tests performed. The contactors and/or controls typically dropped out or the phase monitor relay would trip the unit off. Reclosing would not occur until several minutes later at which time the unit started up normally. Therefore several additional undervoltage tests were performed after making modifications to the device controls in order to induce compressor stalling behavior. Rather than using the service voltage from the main terminals of the A/C unit to serve the step-down transformer (24 V output) and power the controls, a separate power supply was used to energize these controls (contactor coils, relays, thermostat, etc.) to bypass any dropout performance

Previous tests revealed that dropout had consistently occurred at 60% which was used as a starting point for these additional under-voltage tests. A series of under-voltage sags were performed in 1% voltage decrements with duration times of 3 seconds as shown in the following figures. Both compressor motors began stalling at the 39% voltage dip, but neither of them stalled immediately. Compressors #1 and #2 take approximately 47 and 33 cycles to reach their peak stalling current at these voltages. Notice that stalling was identified by the dramatic increase in current and reactive power as well as the reduced mechanical vibration of the compressor. Lower voltage magnitudes resulted in faster stalling behavior as witnessed when stalling occurs within approximately 9 cycles at 31% nominal voltage.

The compressors restarted from their stalling condition within 4 cycles after voltage returns to nominal. Both compressors consistently restart after each and every voltage sag performed.

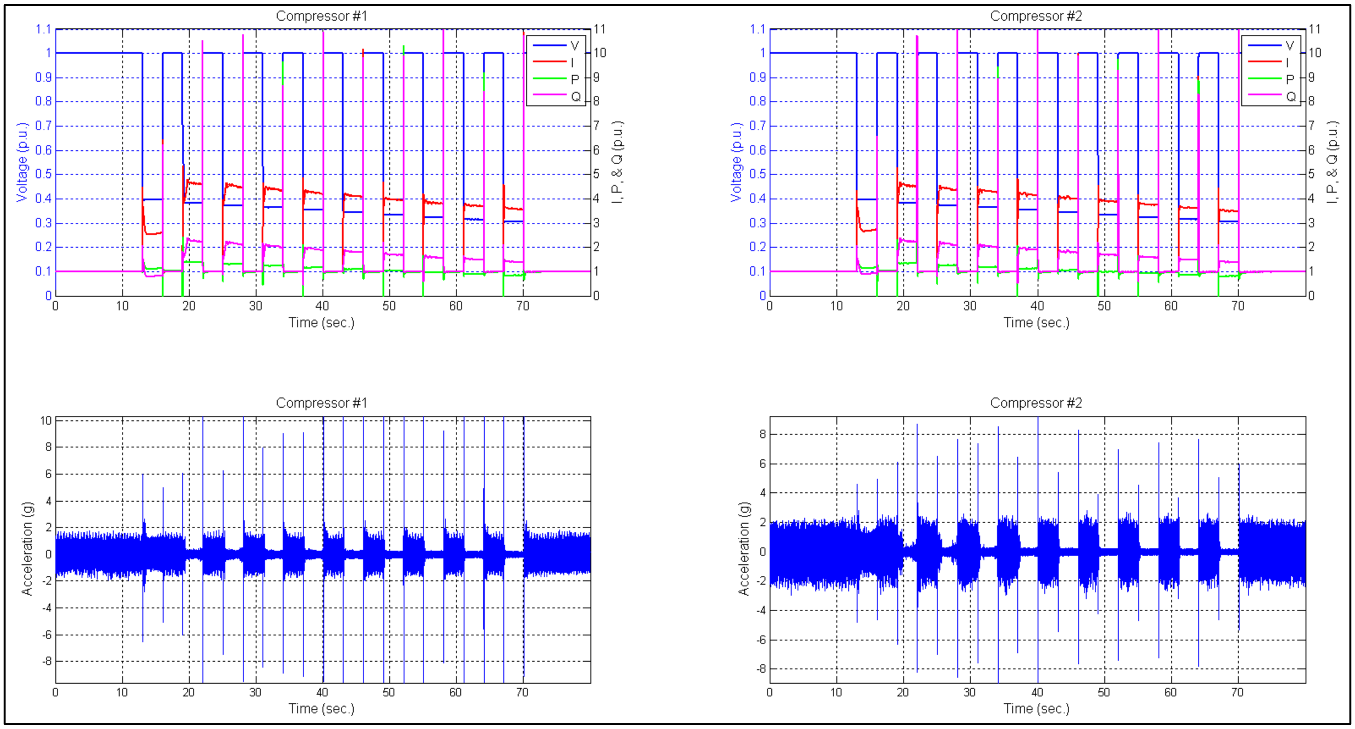

Figure 3.13.1 A/C #1 Compressor Stalling During Under-voltages (40% to 31% voltage)

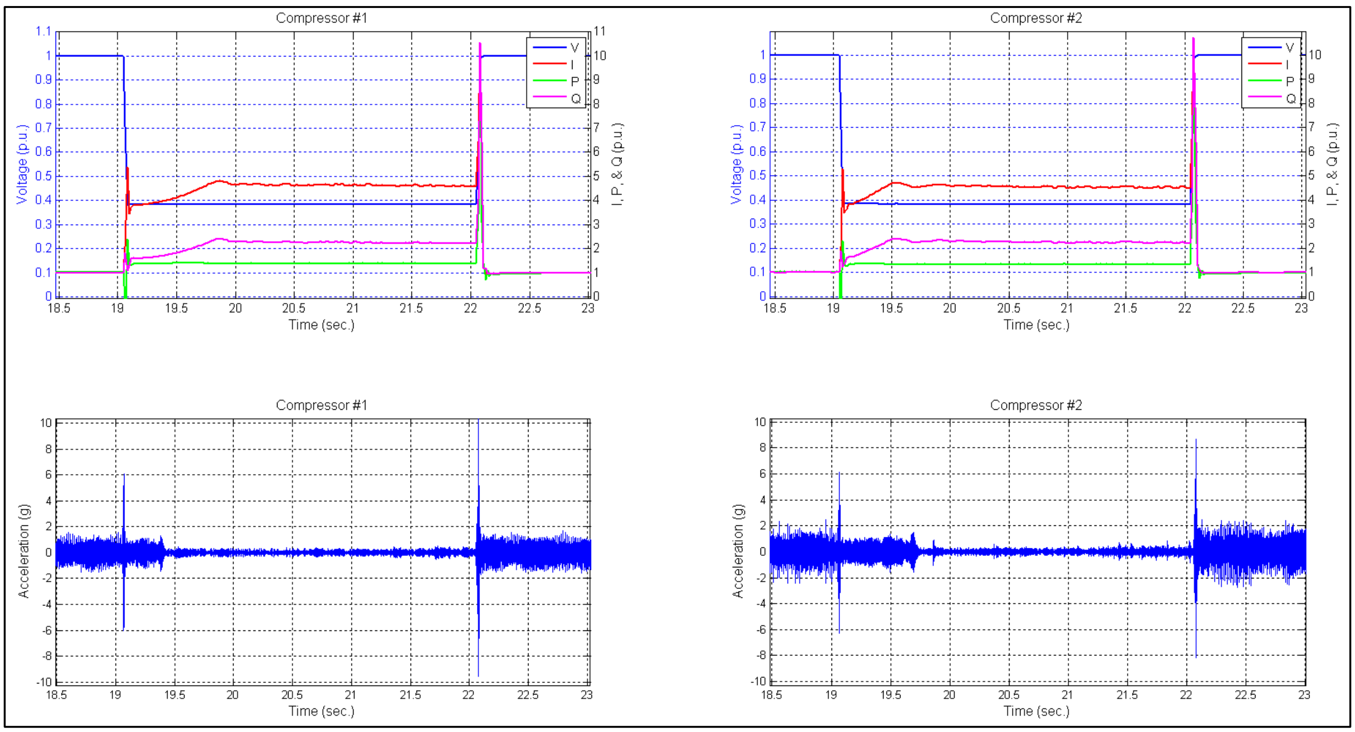

Figure 3.13.2 A/C #1 Compressor Stalling During Under-voltages (39% voltage)

Additionally, a voltage ramp test was performed to capture the dual compressor's current, real power, and reactive power consumption at different voltage levels as shown in the figure below. The stalling point for compressor #1 current, real power, and reactive power reached 4.5 pu, 1.3 pu, and 2.1 pu while the restarting points for the same parameters increased to as large as 4.0 pu, 1.3 pu, and 1.8 pu. The stalling point for compressor #2 current, real power, and reactive power reached 4.5 pu, 1.3 pu, and 2.2 pu while the restarting points for the same parameters increased to as large as 4.2 pu, 1.4 pu, and 2.0 pu.

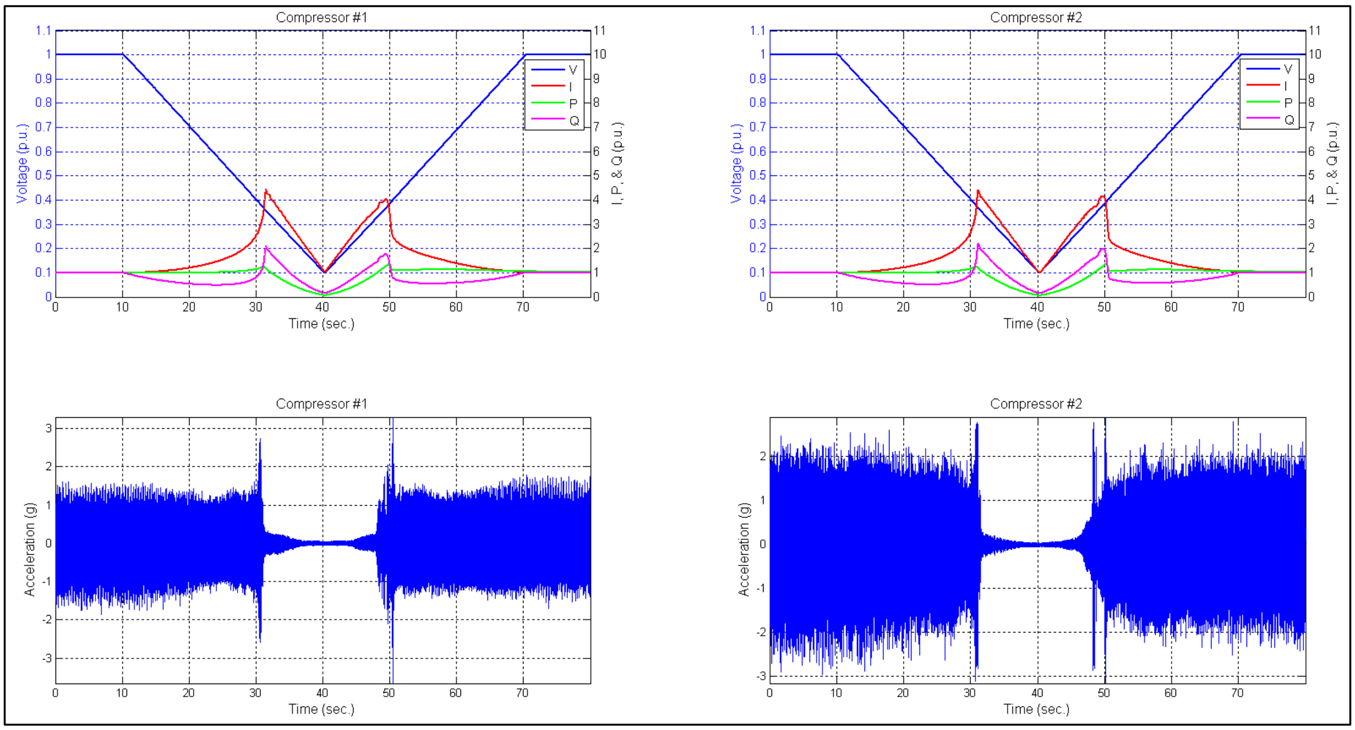

Figure 3.13.3 A/C #1 Compressor Stalling During Voltage Ramp

4.0 AIR CONDITIONER #2 TEST RESULTS

The second air conditioner tested is a 4-ton unit operated at 208 V line-to-line. The unit is comprised of a single indoor blower fan motor, outdoor fan motor, and a compressor motor. The specifications for the individual components of A/C #2 are provided in the table below.

Main System		**Compressors**	
Manufacturer	Coleman	Manufacturer	Copeland
Model	B6HZ048A25	Model	ZP42K5E-TF5-130
Size (Tons)	4	Type	Scroll
Voltage (V)	208	Quantity	1
Refrig.	R-410A	RLA (Amps)	13.7
SEER	13	LRA (Amps)	83
EER	11	Test Press. High (PSI)	445
IEER	-	Test Press. Low (PSI)	236
Condenser Fan		**Blower Motor**	
Drive Type	Direct	Type	Direct
Quantity	1	Quantity	1
Motor HP	1/4	Motor HP	3/4
RPM	850	RPM	Variable
FLA (Amps)	1.2	FLA (Amps)	6
Miscellaneous Components			
Contactor(s)	Hartland Controls, HCC-3XQ02CJ271	Capacitor(s)	CSC Electronics, 325P505H37A15A4X
Transformer	Tyco Electronics, 4001-46J15AE15	Phase Balance Relay	-

Table 4.0.1 A/C #2 Specifications

4.1 Compressor Shutdown

A/C #2 was shut down during normal operation using the connected thermostat. The figure below displays the measurements taken at the main service connections as well as the behavior of the individual motors.

The compressor and outdoor fan motor shut down at the same time shortly after triggering the thermostat. The only power consumption after the compressor shuts down was from the single-phase indoor fan motor that is pulling 2.1 Amps (total of 430 W or 500 VA). The indoor fan motor begin ramping down to zero approximately 40 seconds after the other components.

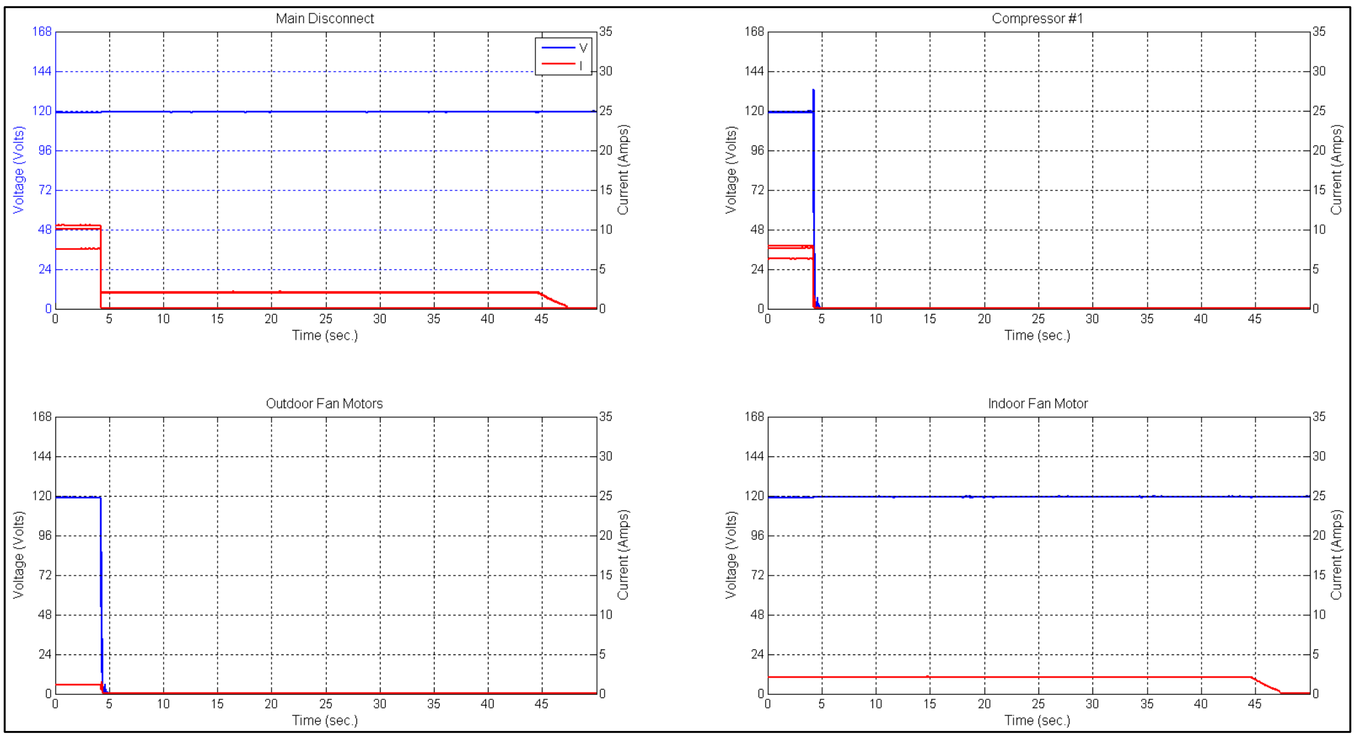

Figure 4.1.1 A/C #2 Compressor Shutdown

4.2 Inrush Current

The indoor fan motor began operating over a minute before the remaining motors turned on. Both the compressor and outdoor fan motor start up at the same time as shown in the figure below. The inrush currents observed at the main disconnect of the unit indicate a maximum value of 75.5 Amps and a duration time of 6 cycles.

Compressor Inrush: Maximum of 73.6 Amps and duration of 6 cycles

Outdoor Fan Motor Inrush: Maximum of 2.4 Amps and duration of 2.9 seconds

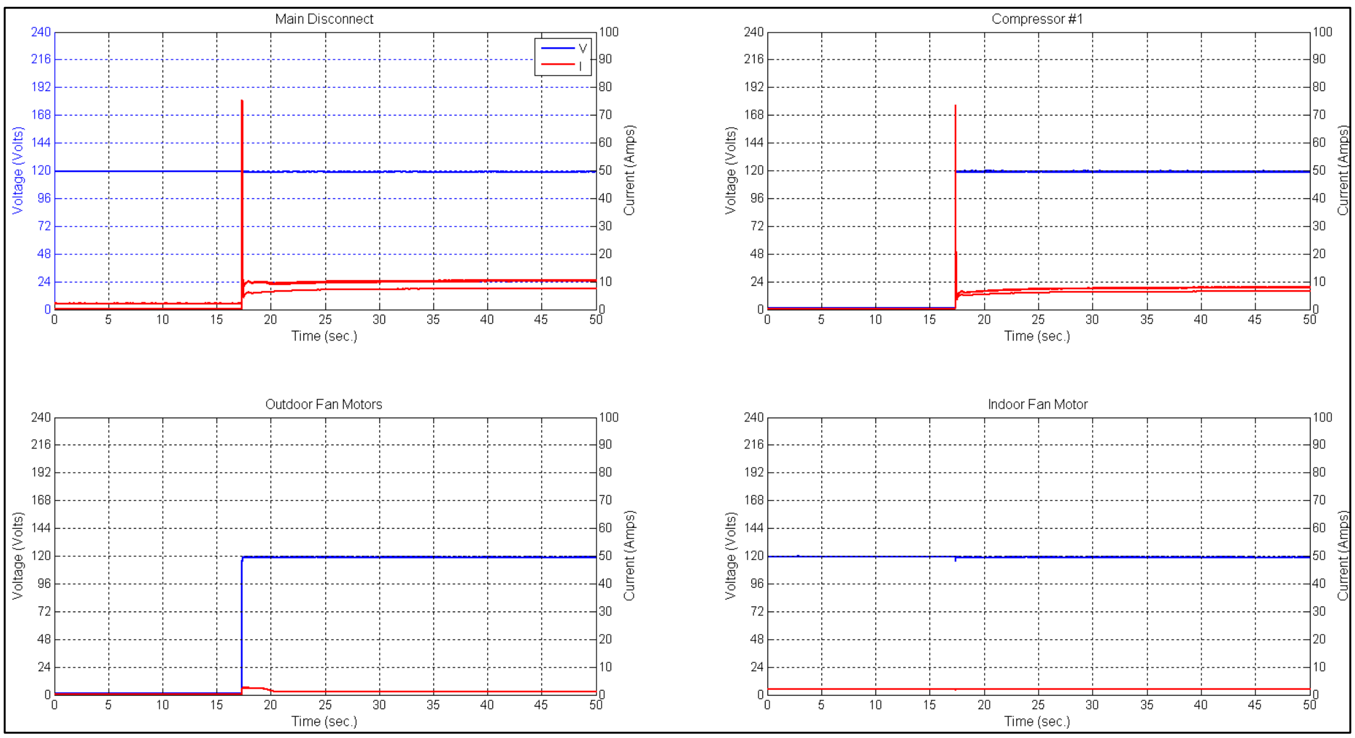

Figure 4.2.1 A/C #2 Inrush Current

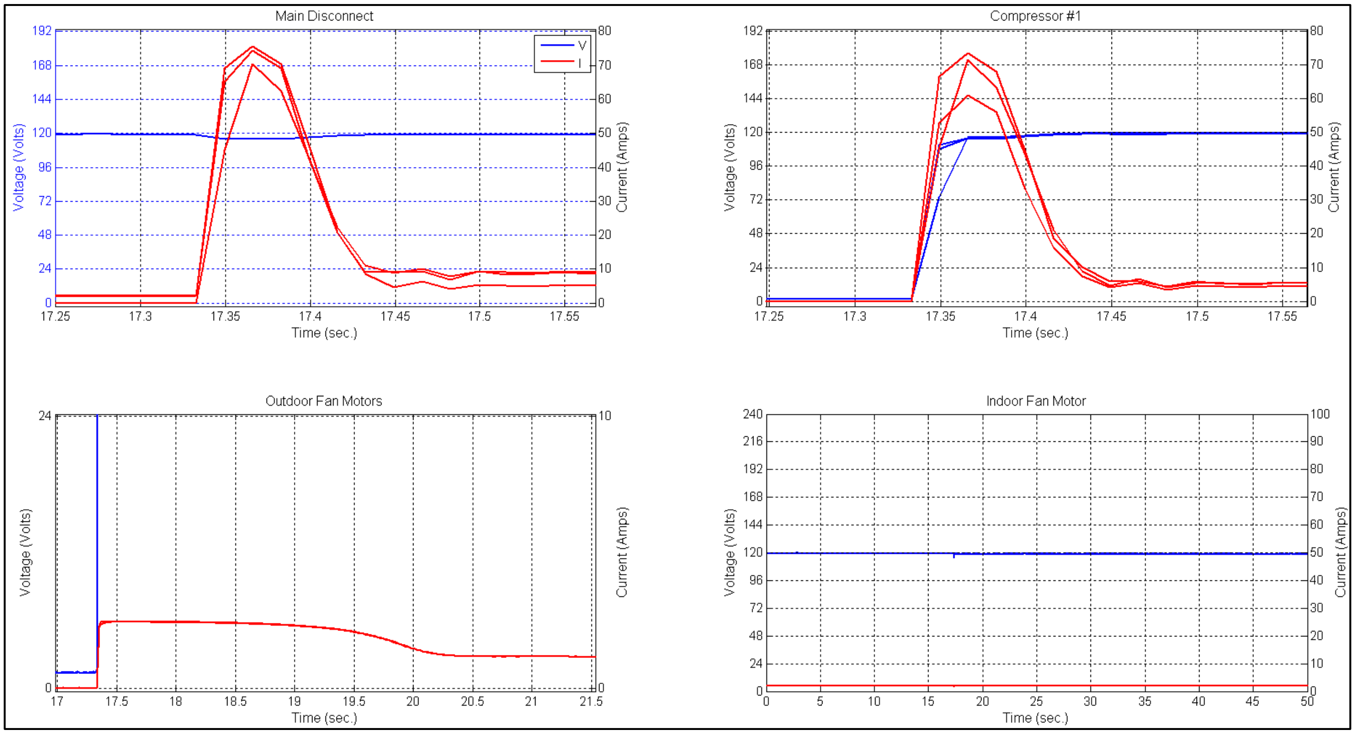

Figure 4.2.2 A/C #2 Inrush Current [Zoom In]

4.3 Balanced & Unbalanced Under-voltages

Control voltage measurements (24 V) were monitored at the thermostat output, pressure switch output, and contactor coil to help determine the root cause of compressor tripping during A/C #2 under-voltage tests. No stalling behavior was observed during any of these tests since the contactor opened before reaching a voltage that cause compressor stalling. At the beginning of a voltage sag contactor chattering can be observed during the step change, but it does not open until reaching the bottom of the under-voltage value. Data captured several seconds after the disconnection of the compressor did not reveal immediate contactor reclosing during most tests, except for special tests where the contactor control wiring was re-configured. Contactors would only reclose several minutes after voltage recovered to steady state, due to a relay located at the controller or even at the thermostat.

Balanced voltage sags on all three phases in decrements of 10% revealed that the compressor contactor would open at 70% nominal voltage for any under-voltage transient with a duration of 6 to 130 cycles. During these tests, the contactor would open in 7 to 10 cycles after the beginning of the voltage sag and it would not reclose immediately after the voltage sag had ended. In the case of the 6 cycle voltage sag, the contactor did not open until 2 cycles after voltage already recovered to steady state (8 cycles after the start of the voltage sag).

However, the controls voltage at the output of the thermostat and pressure switches did not trip until 60% voltage up to 7 cycles after the start of the voltage sag which suggested that a small relay on the defrost control board (located between the pressure switches and contactor coil) was tripping/dropping out. Further testing confirmed this when bypassing the defrost control board (connecting thermostat output directly to the contactor coil) resulted in compressor tripping at 60% nominal voltage. Therefore the control relay was dropping out at 70% voltage causing the contactor to prematurely open and without the relay, the contactor would dropout at 60% voltage within 8 cycles. Neither the relay nor the contactor reclosed immediately after the voltage recovered to nominal.

Additional tests on the unmodified A/C unit showed that the compressor contactor opened at 60% nominal voltage for 3 cycle under-voltage sags, suggesting the that the small relay did not detect these voltage transients. The contactor was observed opening either between 2 and 3 cycles after the start of the voltage sag. One instance resulted in the contactor reclosing in 1.2 cycles after voltage recovery only to immediately re-open. The contactor and compressor motor appeared to only ride through all under-voltage transients with a duration time of 1 cycle down to 0% voltage. The following figure visually displays one of the longer duration balanced under-voltage tests. The following tables provide the details regarding the compressor operation and control voltage measurements during the various tests.

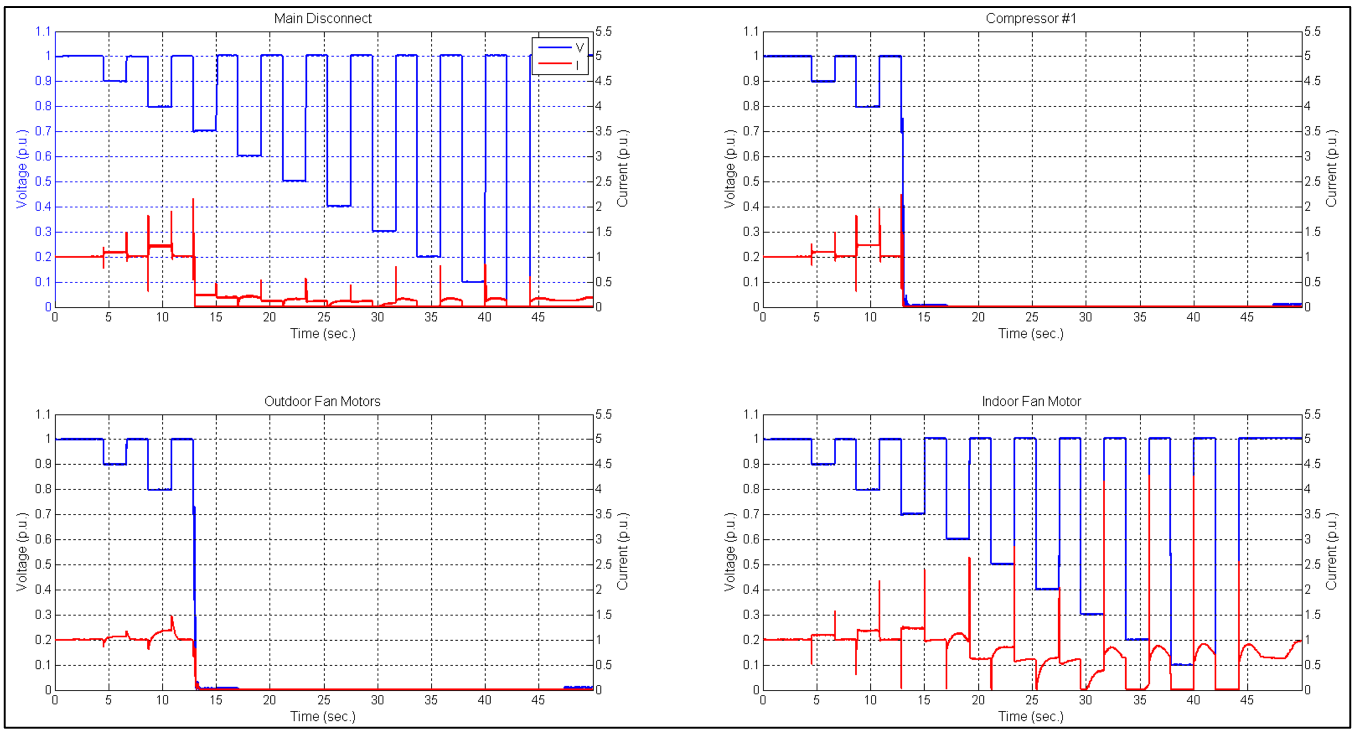

Figure 4.3.1 A/C #2 Balanced Under-voltage Response (130 cycles)

The following tables provide the details regarding the voltage sag where voltage disappears and time it takes for this tripping/dropout to occur after the start of the voltage sag based on the voltage/current measurements take at the compressor contactor as well as the control voltage measurements taken at the contactor coil, pressure switches and thermostat. "N/A" represents situations where dropout is not applicable and the unit rode through all under-voltage values.

Under-Voltage Transient		Compressor		Contactor Coil		Press. Switches		Thermostat (Y)	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
100%, 90%, 80%,... 0%	130	70%	7	70%	7	60%	6	60%	6
		70%	9	70%	9	60%	8	60%	8
		70%	10	70%	9	60%	9	60%	9
100%, 90%, 80%,... 0%	9	70%	9	70%	9	60%	6	60%	6
		70%	8	70%	7	60%	8	60%	8
		70%	9	70%	9	60%	6	60%	6
100%, 90%, 80%,... 0%	6	70%	8	70%	7	60%	7	60%	7
		70%	8	70%	8	60%	6	60%	6
		70%	8	70%	7	60%	6	60%	6
100%, 90%, 80%,... 0%	3	60%	2	60%	5	60%	5	60%	5
		60%	3	60%	3	60%	6	60%	6
		60%	2	60%	3	60%	6	60%	6
100%, 90%, 80%,... 0%	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

In order to narrow down the voltage where the compressors are disconnected and contactor/controls dropout occurs, additional balanced under-voltage tests were performed in decrements of 1% nominal voltage where the contactor coil is energized directly by the supply voltage using the step-down controls transformer. The results of these tests revealed that the contactors would start opening between 60% and 61% voltage within 1.8 to 2.4 cycles after the voltage sag started. The contactor took between 0.6 to 1.2 cycles to close after voltage recovered to nominal. The following table summarizes these details of the 1% voltage decrements.

Under-Voltage Transient		Compressor	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)
70%, 69%, 68%, …	120	61%	1.8
70%, 69%, 68%, …	120	61%	2.4
70%, 69%, 68%, …	120	60%	1.8

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

Unbalanced under-voltages on this A/C unit resulted in a greater variety of trip voltages and trip times, as opposed to balanced conditions, when the compressors were disconnected. One of the reasons for this is because the controls (including the contactor coil) are energized using one of the line-to-line supply voltages, phase A to phase B. Phase A to B under-voltages are therefore similar to the results of the balanced under-voltage tests.

As a result of the controls configuration, phase C under-voltage transients do not result in contactor dropout, only voltage ride-through. It's worth noting that the ride through performance during this voltage unbalance reveals an increase in mechanical vibration on the compressor motor as shown in the following figure.

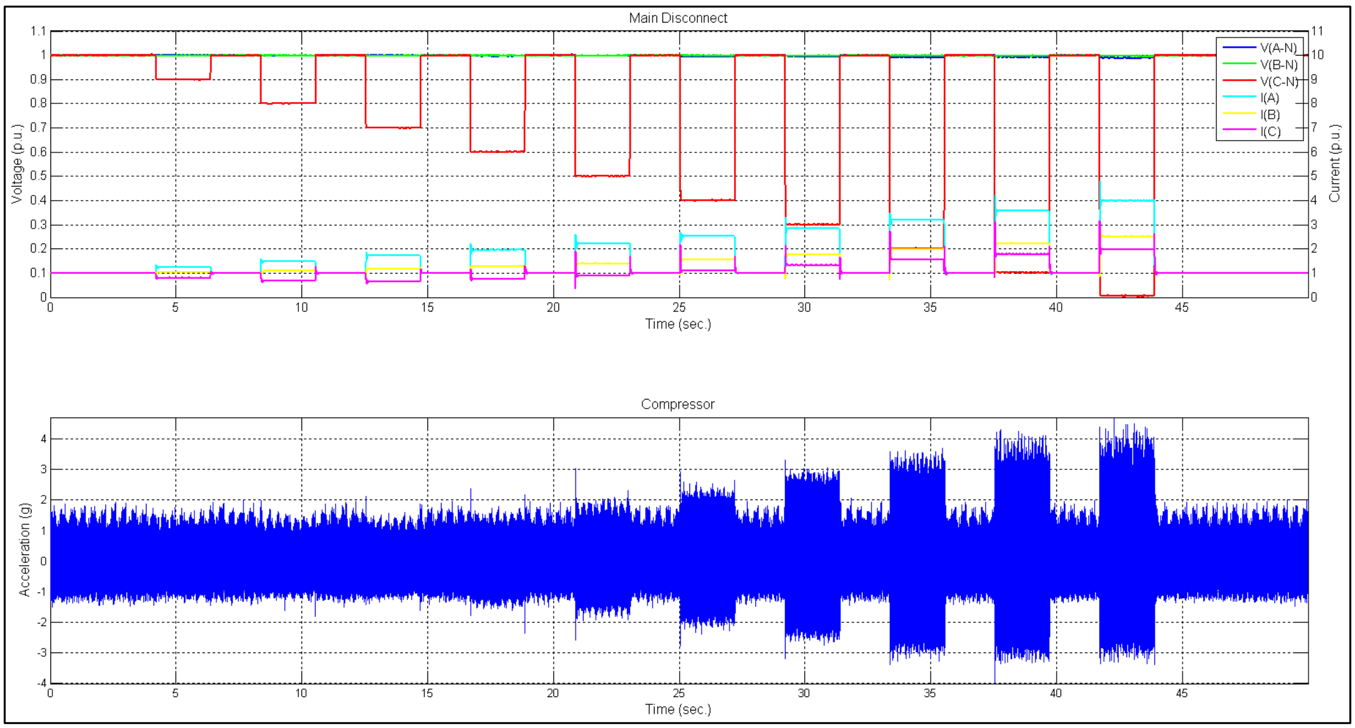

Figure 4.3.2 A/C #2 Unbalanced Under-voltage Response (Phase C, 130 cycles)

The following table provides the same dropout/tripping details as previous tables in this section, but this time for the results of the unbalanced under-voltage transients. Notice that there are several instances where the contactor opens a few cycles after the voltage has recovered from the sag.

Under-Voltage Transient			Compressor		Contactor Coil		Press. Switches		Thermostat (Y)	
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
A	100%, 90%, 80%,... 0%	130	30%	8	30%	7	10%	6	10%	6
		9	30%	9	30%	8	10%	7	10%	7
		6	30%	3	30%	5	10%	6	10%	6
		3	10%	6	10%	6	10%	6	10%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 90%, 80%,... 0%	130	30%	10	30%	9	20%	17	20%	17
		9	30%	7	30%	6	10%	6	10%	6
		6	30%	9	30%	9	10%	8	10%	8
		3	10%	3	10%	5	10%	6	10%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 90%, 80%,... 0%	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 90%, 80%,... 0%	130	70%	8	70%	8	60%	6	60%	6
		9	60%	2	60%	6	60%	7	60%	7
		6	60%	4	60%	3	60%	8	60%	8
		3	60%	10	60%	7	60%	7	60%	7
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 90%, 80%,... 0%	130	30%	7	30%	6	20%	20	20%	20
		9	30%	10	30%	9	10%	6	10%	6
		6	30%	10	30%	9	10%	7	10%	7
		3	30%	6	30%	5	10%	6	10%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 90%, 80%,... 0%	130	30%	9	30%	8	20%	19	20%	19
		9	30%	9	30%	8	10%	6	10%	6
		6	30%	10	30%	9	10%	6	10%	6
		3	20%	7	20%	6	10%	6	10%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 4.3.3 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. 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.

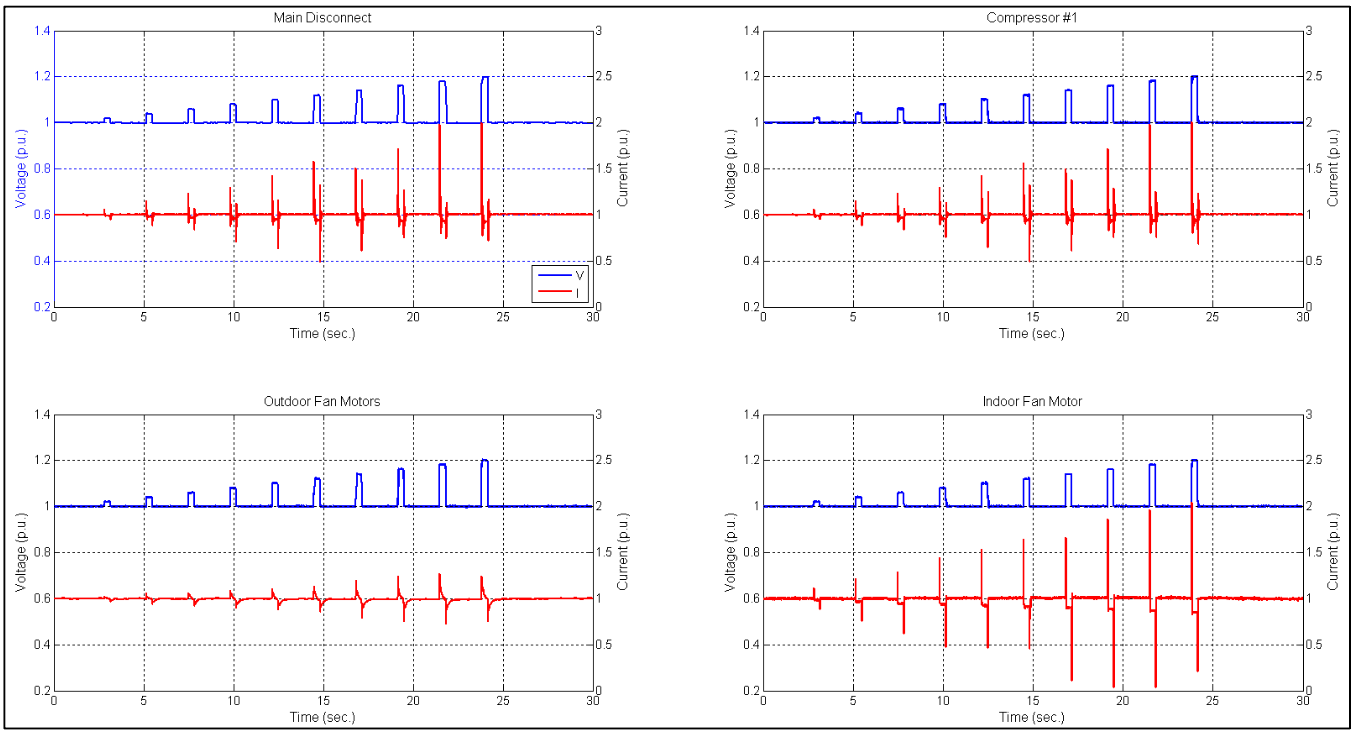

Figure 4.4.1 AC #2 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		Contactor Coil		Press. Switches		Thermostat (Y)	
Φ	**Volt Range**	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
ABC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

4.5 Voltage Oscillations

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

The currents oscillate in the opposite direction of voltage (+9%) for all swing frequencies tested. Real power remains relatively at steady state, typically oscillating within ±2% of the nominal power consumption. Real power also experiences larger deviations as the swing frequency or rate of oscillation increases.

Reactive power consumption experiences the largest impact (-15% to -25% deviation) oscillating in the same direction as voltage. Similar to real power, greater deviations from steady state occur for higher swing frequencies with an overshoot response occurring as reactive power recovers to nominal.

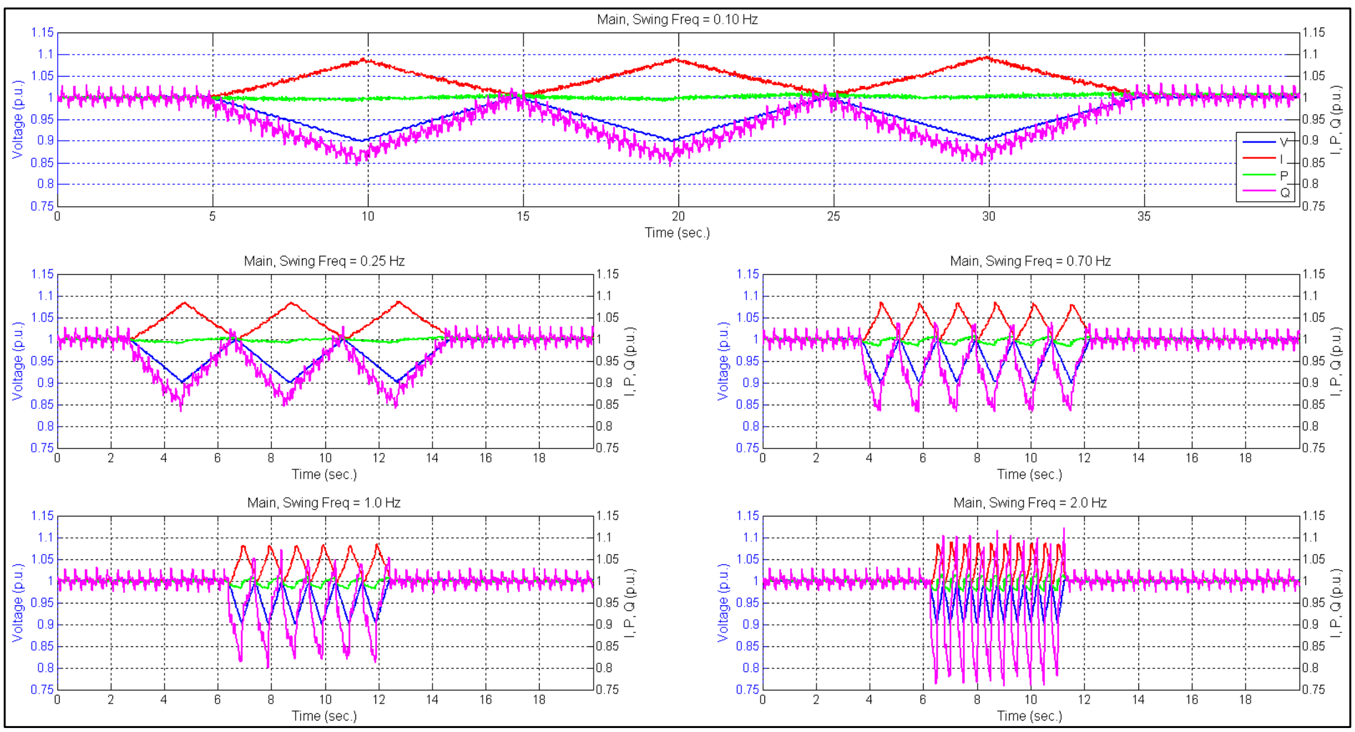

Figure 4.5.1 AC #2 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

4.6 Under-frequency Events

After subjecting A/C #2 to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection down to 58 Hz. The device simply rides through these frequency conditions. The following figure and table identify the tests that were performed.

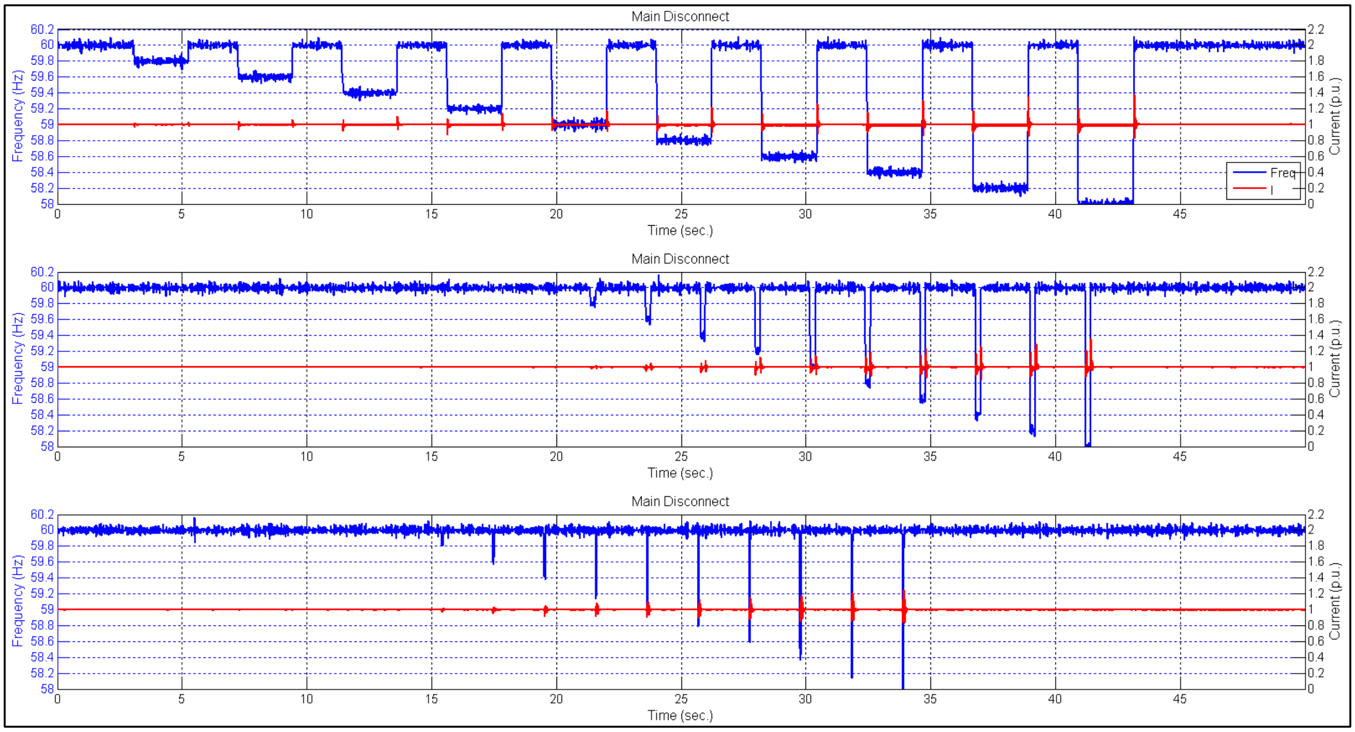

Figure 4.6.1 A/C #2 Under-frequency Response (130, 12, 3 cycles)

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

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

4.7 Over-frequency Events

Similar to the under-frequency tests, A/C #2 was subjected over-frequency transients with different duration times up to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The following figure and table identify the over-frequency tests that were performed.

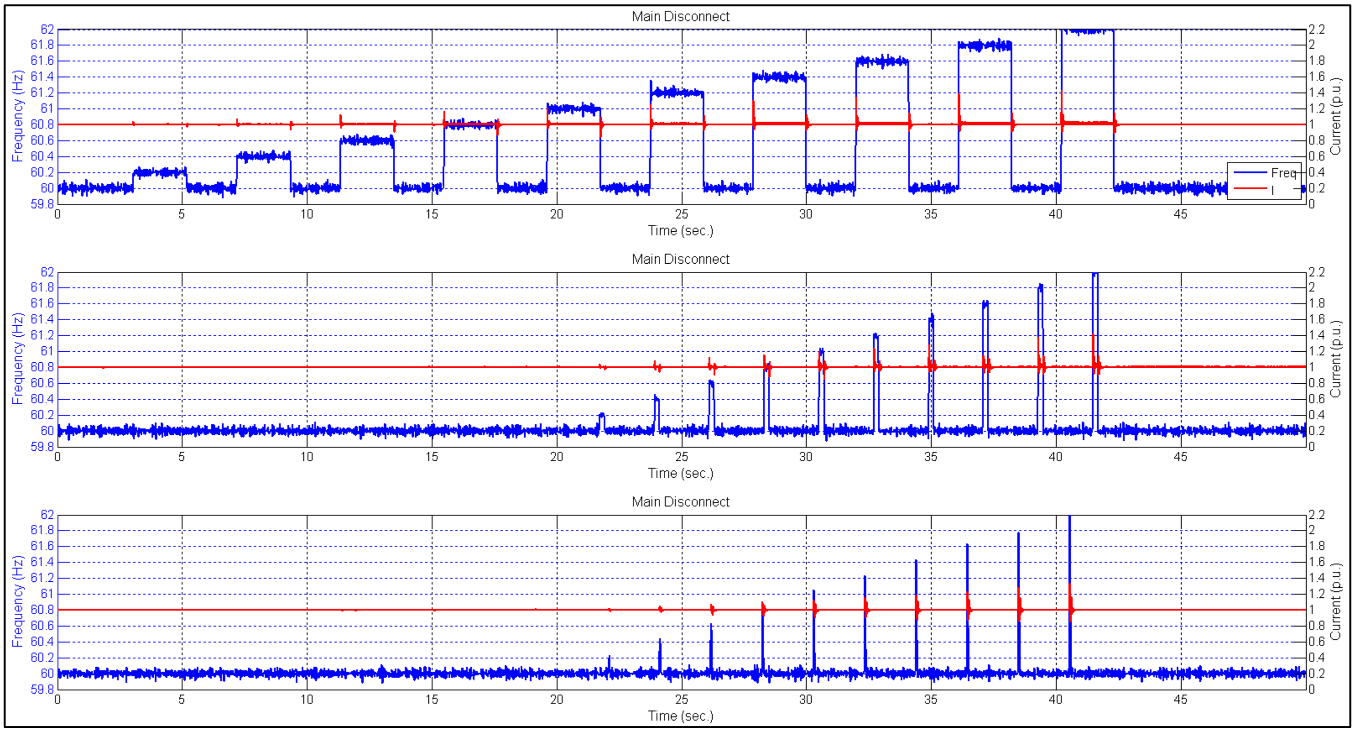

Figure 4.7.1 A/C #2 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor		Contactor Coil		Press. Switches		Thermostat (Y)	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 60.2Hz, 60.4Hz,... 62Hz	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

4.8 Frequency Oscillations

The following figure shows the performance of A/C unit #2 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates.

Current, real power, and reactive power remain relatively close to steady state, only deviating within +2% of their nominal values for swing frequencies up to 0.70 Hz. Even at a swing frequency of 1 Hz or 2 Hz, these values only deviate up to +3.5% from their nominal consumption values.

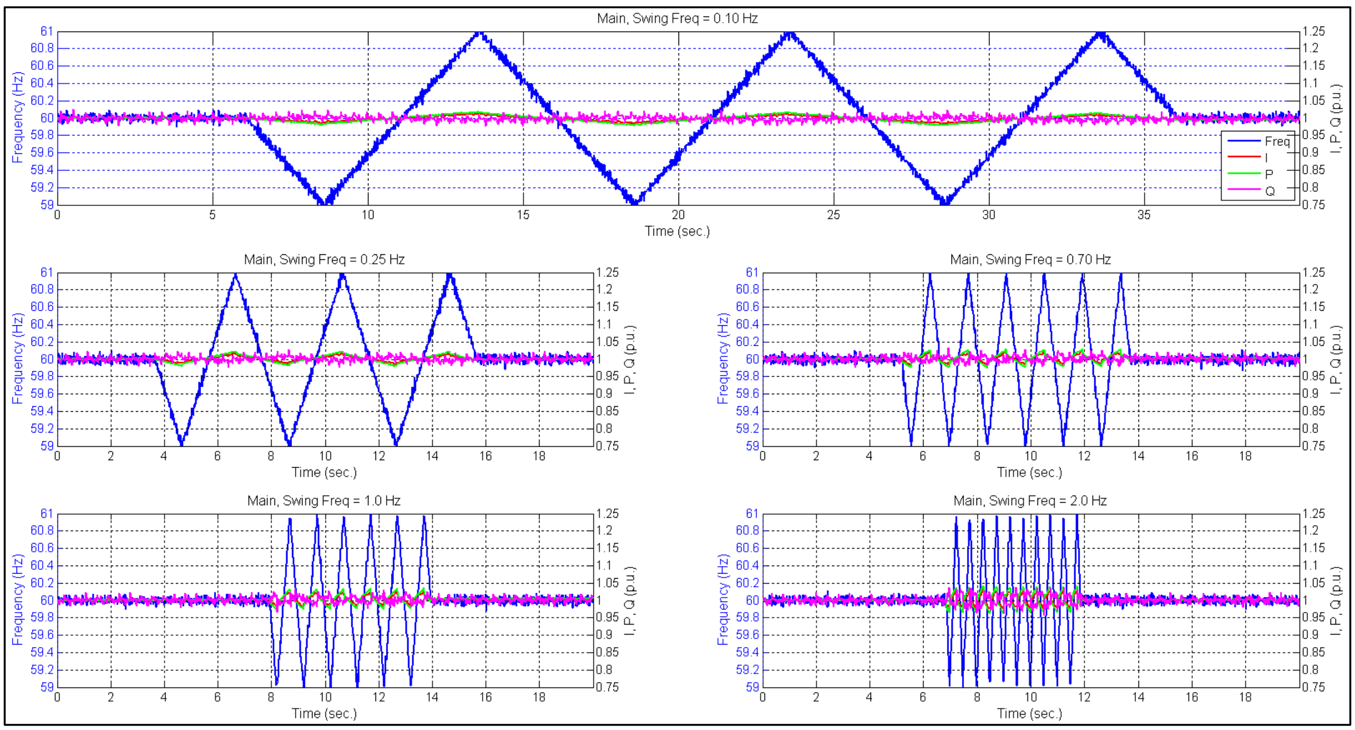

Figure 4.8.1 A/C #2 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

4.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit tripped while ramping down to 70% nominal voltage. Accordingly, the following figure shows the load performance at different voltage levels during continuous operation without tripping (down to 80% nominal voltage).

Current ramps up to approximately 20% above nominal, mitigating a large reduction in real power consumption. As a result, real power only deviates within ±2% of nominal. Reactive power is reduced significantly ramping as low as 25% below normal reactive load.

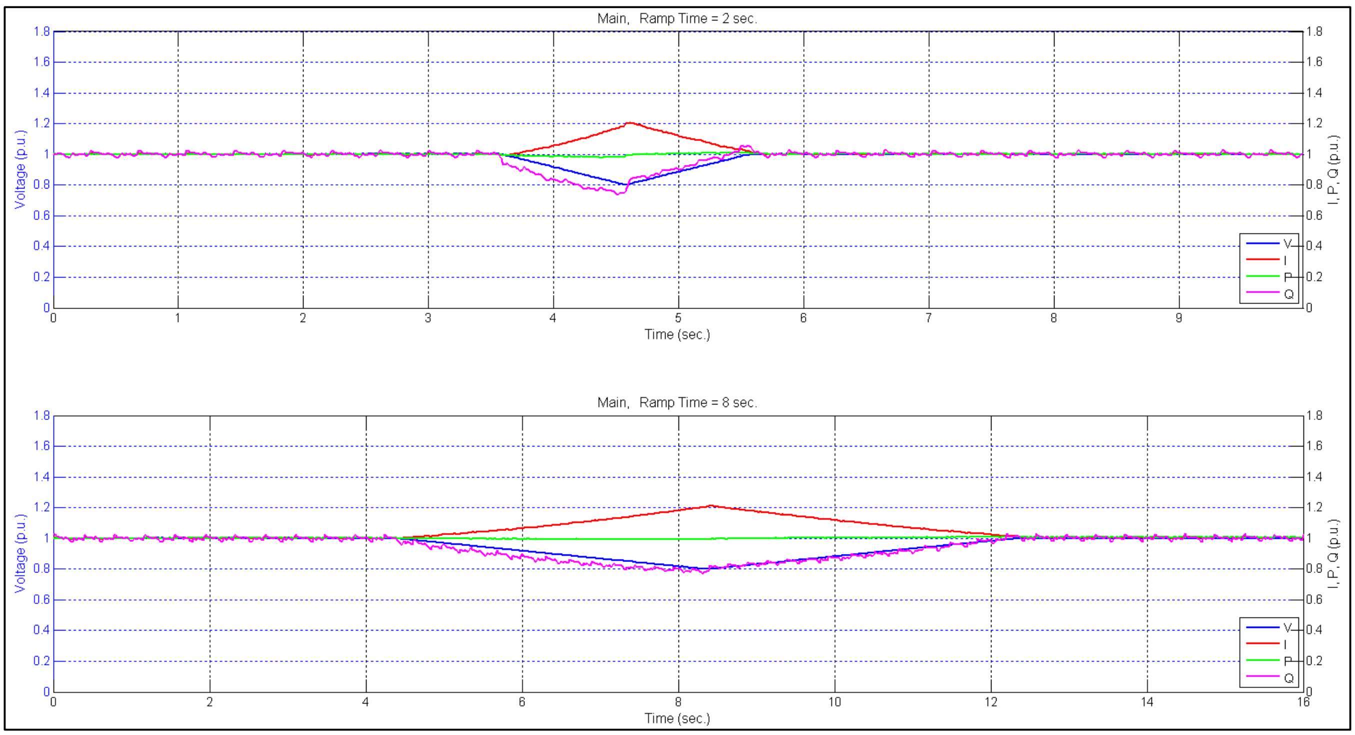

Figure 4.9.1 A/C #2 Voltage Ramp Down to 60% (2 & 8 sec.)

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 approximately 6% below nominal. Real power only deviates by +1% from steady state. Finally, reactive power increase to approximately 22% above of nominal reactive load consumption.

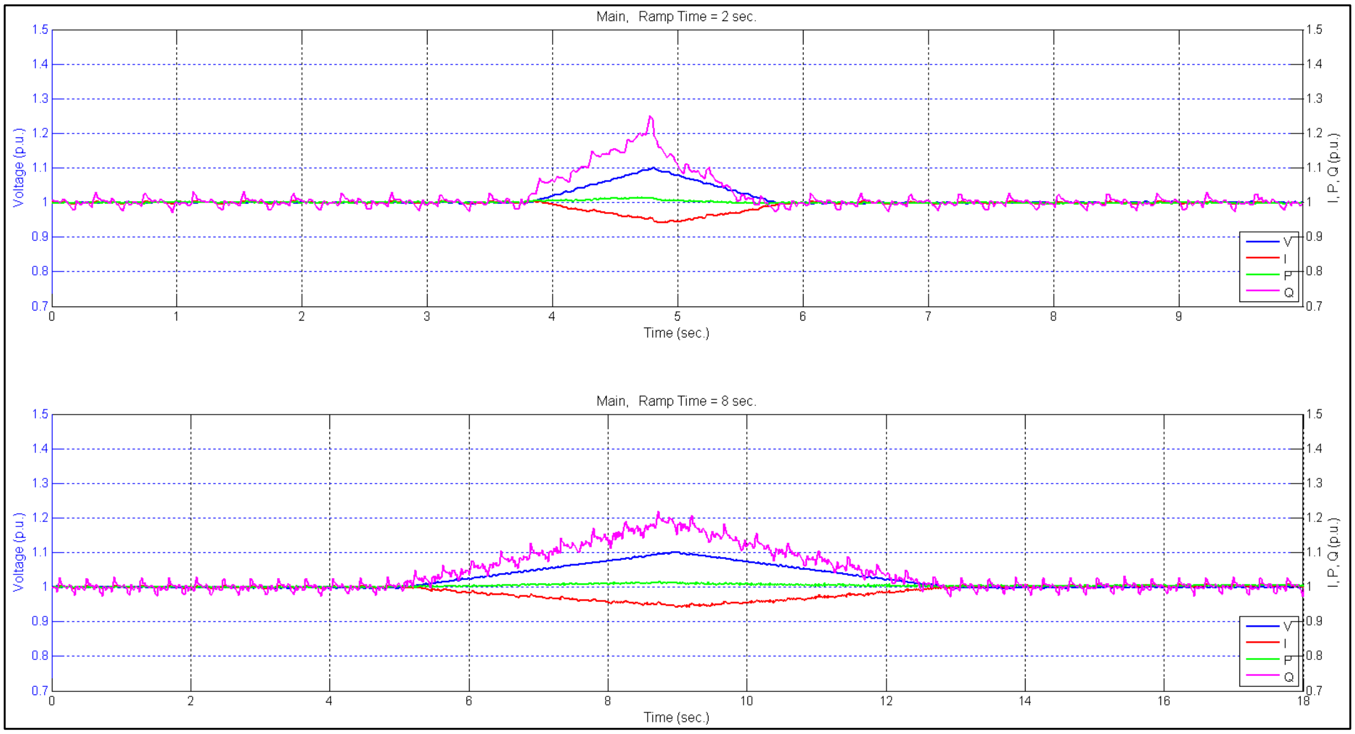

Figure 4.9.2 A/C #2 Voltage Ramp Up to 110% (in 2 & 8 sec.)

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.

Current ramps down to 9% below its nominal output. Real power consumption is reduced during the under-frequency condition dipping to nearly 17% below steady state. Reactive power ramps up to 15% above of normal consumption.

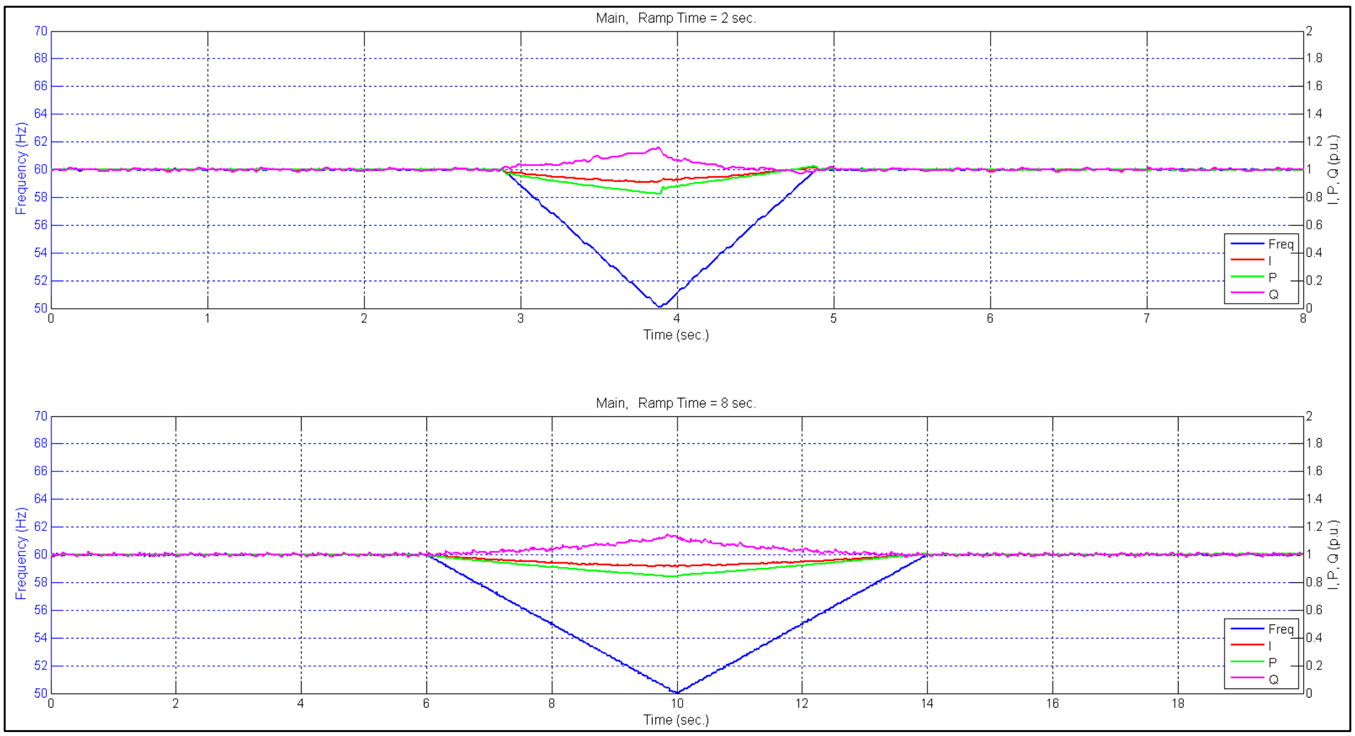

Figure 4.10.1 A/C #2 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

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.

Current is observed ramping up to approximately 17% above its normal current output. Real power consumption is actually increased ramping up to 20% above steady state. Reactive power remains relatively close its steady state value during the frequency ramp.

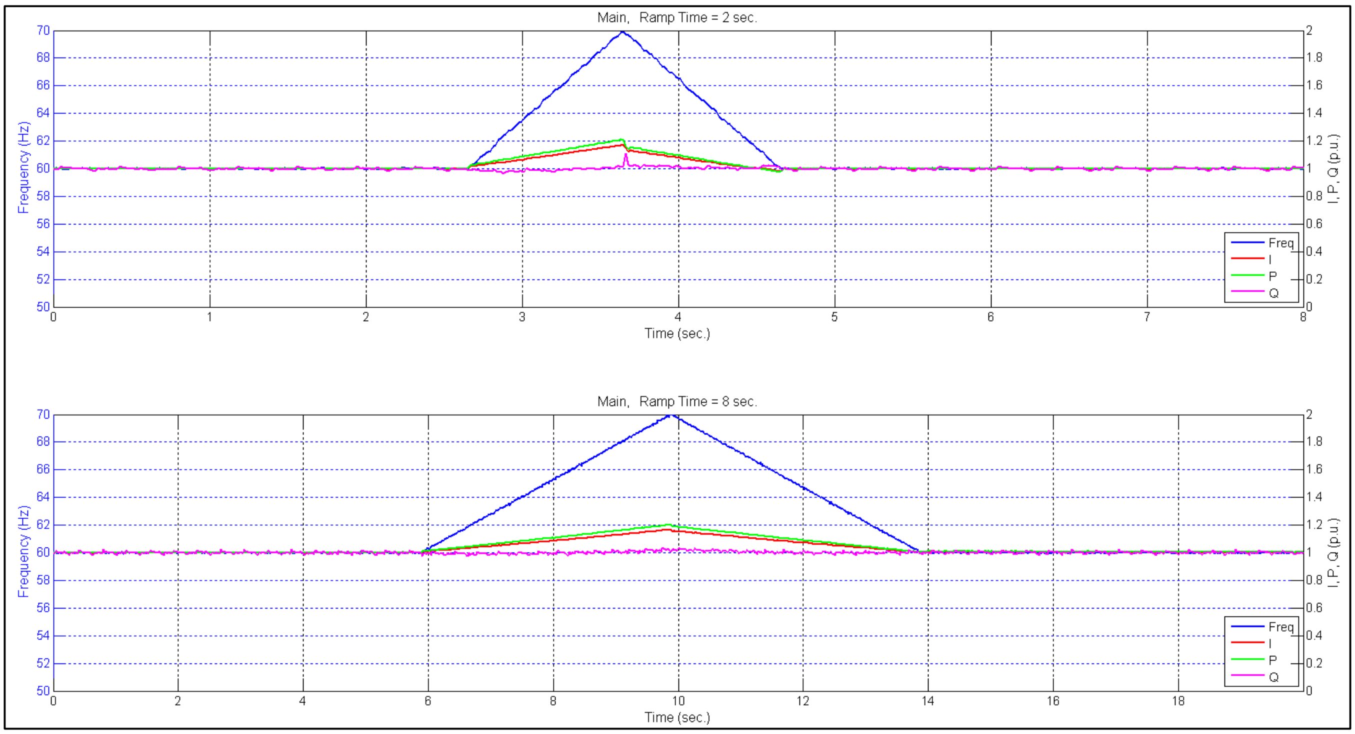

Figure 4.10.2 A/C #2 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

4.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times to calculate the harmonic contribution of A/C unit #2 to the grid. The total harmonic distortion of current was determined to be nearly 36% of the fundamental. The cause of this high harmonic contribution is the current sinusoidal waveforms or pulses of the indoor fan motor as shown in the figure below. The multiple speed drive performance the motor ultimately creates significant distortion in the total current measured at the main disconnect terminals.

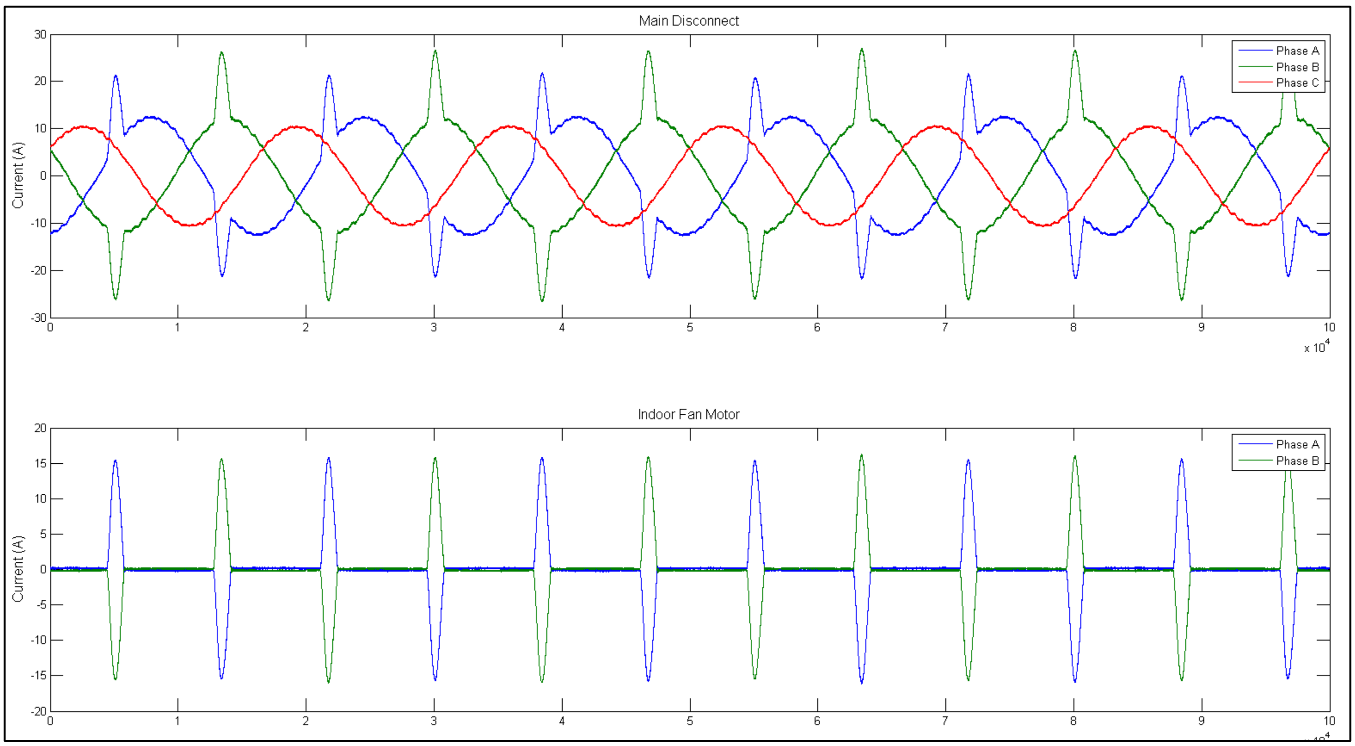

Figure 4.11.1 A/C #2 Main Disconnect and Indoor Fan Motor Current

Data Set #	THD (% of Fundamental)					
	$V_{A\ (L\text{-}N)}$	$V_{B\ (L\text{-}N)}$	$V_{C\ (L\text{-}N)}$	I_A	I_B	I_C
1	0.46	0.50	0.10	35.82	32.60	1.99
2	0.46	0.51	0.10	35.86	32.63	1.98
3	0.46	0.50	0.10	35.98	32.71	1.98

Table 4.11.1 A/C #2 Total Harmonic Distortion

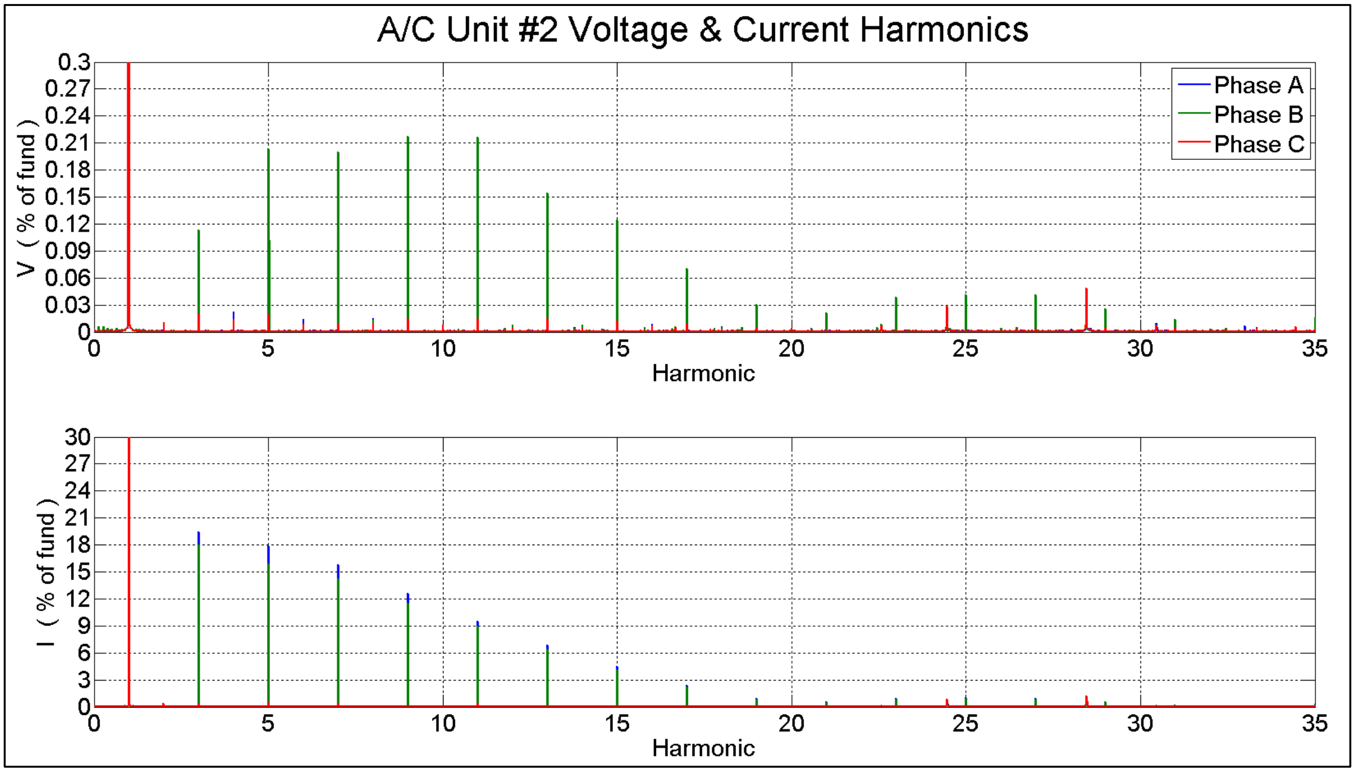

Figure 4.11.2 A/C #2 Harmonics Contribution

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. Outdoor conditions resulted in mild loading of the single compressor operating at approximately 60% of the rated load amps.

Current increases by approximately 0.84% of nominal current for every 1% decrease in nominal voltage. Real power remains nearly constant during the course of CVR, within ±1% of nominal. Reactive power is observed stepping down with the voltage and decreases by 1.4% nominal reactive power for every 1% decrease in nominal voltage.

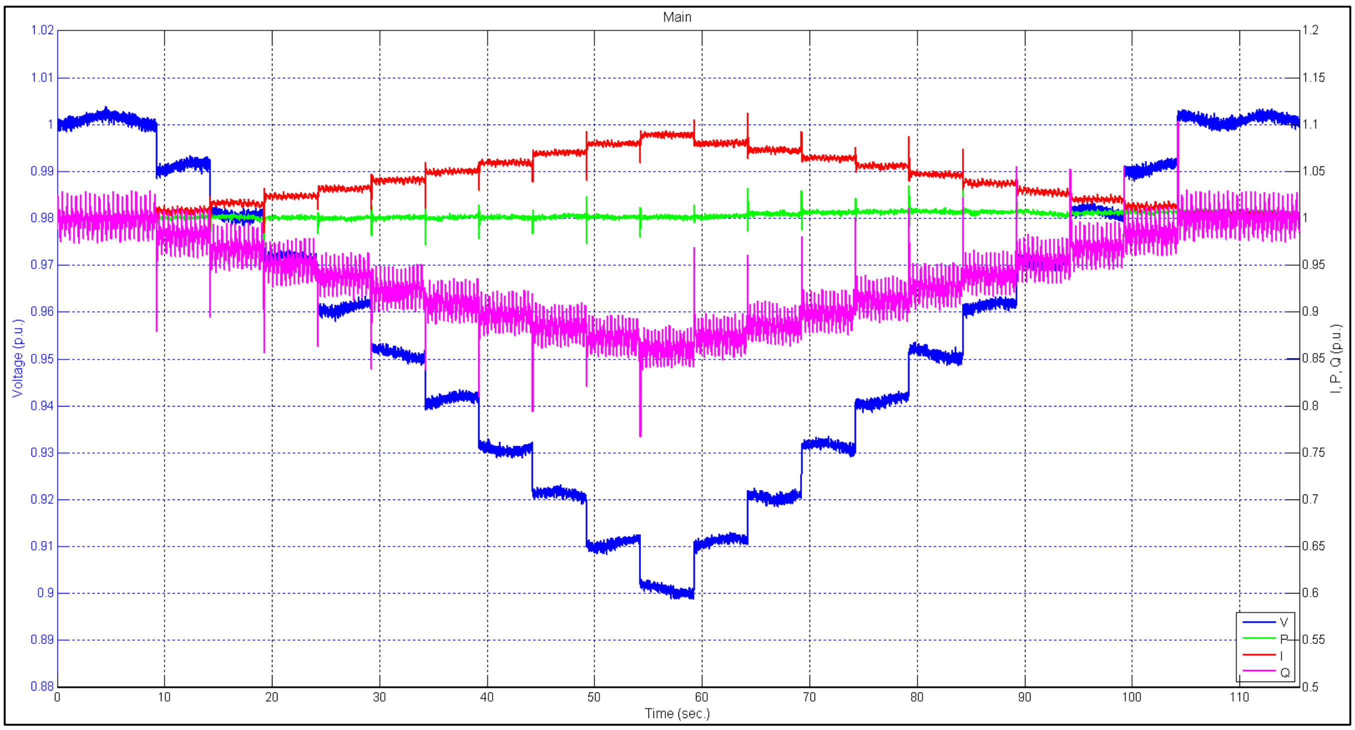

Figure 4.12.1 A/C #2 CVR Response Down to 90% Voltage

Alternatively, the service voltage at A/C #2 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 0.72% of nominal current for every 1% decrease in nominal voltage. Real power remains nearly constant during the course of CVR, within +1% of nominal. Reactive power is observed stepping up with the voltage and increases by 1.7% nominal reactive power for every 1% increase in nominal voltage.

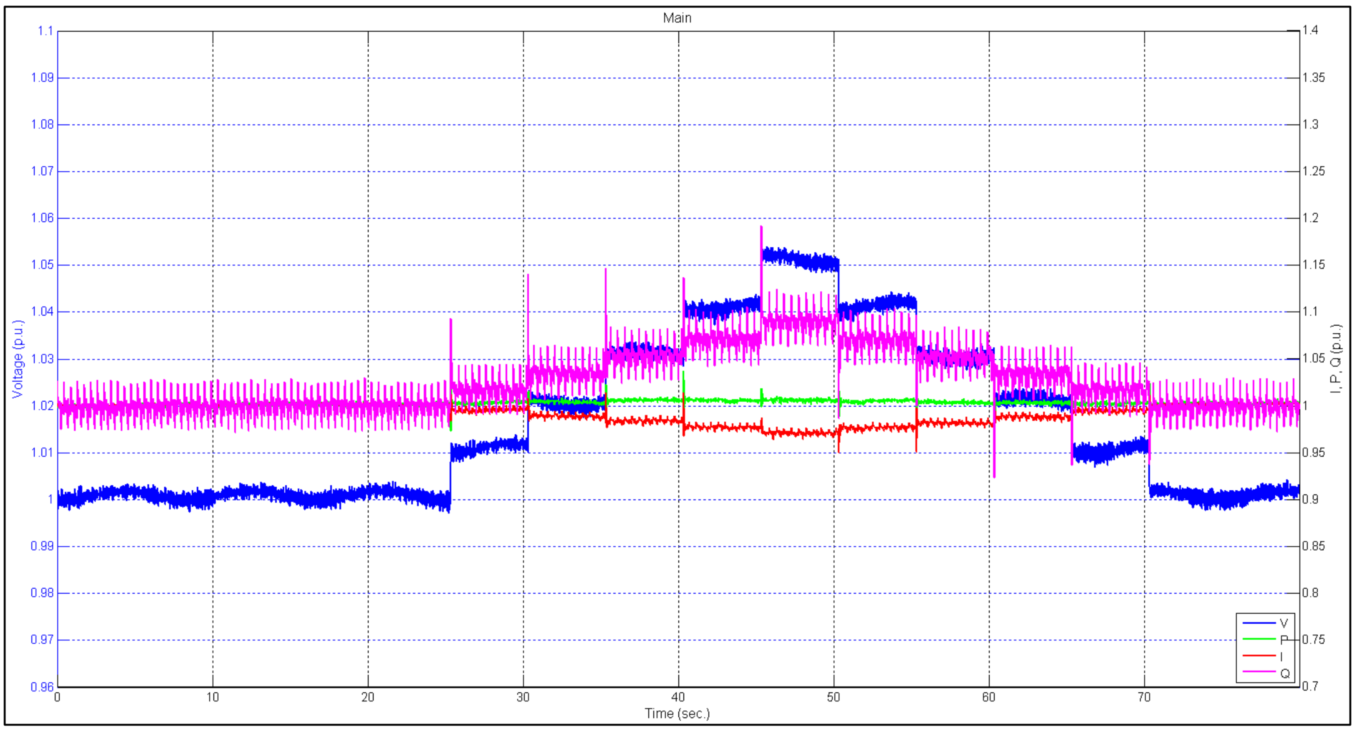

Figure 4.12.2 A/C #2 CVR Response Up to 105% Voltage

4.13 Compressor Stalling

After numerous under-voltage tests with various duration times, A/C unit #2 did not display any noticeable signs of compressor stalling. The contactors and/or controls typically dropped out and reclosing would not occur until several minutes later at which time the unit started up normally. Therefore several additional undervoltage tests were performed after making modifications to the device controls in order to induce compressor stalling behavior. Rather than using the service voltage from the main terminals of the A/C unit to serve the step-down transformer (24 V output) and power the controls, a separate power supply was used to energize these controls (contactor coils, relays, thermostat, etc.) to bypass any dropout performance.

Prior tests revealed that dropout had occurred at 60% which was used as a starting point for these additional under-voltage tests. A series of balanced under-voltage sags were performed in 1% voltage decrements with duration times of 3 seconds as shown in the following figures. It was revealed that the compressor began stalling at 48% voltage. However, the compressor does not stall immediately after the voltage dip and takes approximately 1.4 seconds to completely stall. Notice that stalling is identified by the dramatic increase in current and reactive power as well as the reduced mechanical vibration of the compressor. Lower voltage magnitudes resulted in faster stalling behavior.

The compressor restarted from its stalling condition within 6 cycles after voltage returns to nominal. It consistently restarts after each and every voltage sag performed. Voltage was also held at 48% voltage indefinitely during a separate test which caused thermal overload protection to generally occur between 55 and 60 seconds after stalling begins.

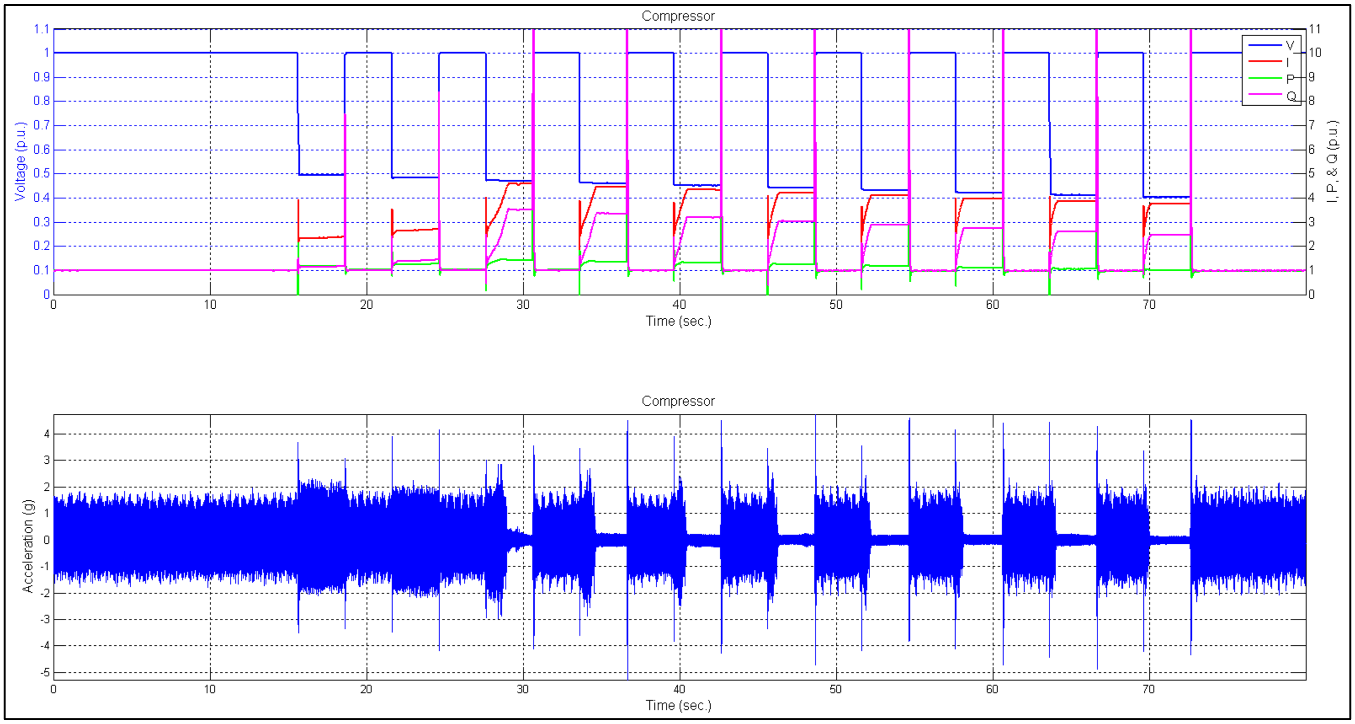

Figure 4.13.1 A/C #2 Compressor Stalling During Under-voltages (50% to 41% voltage)

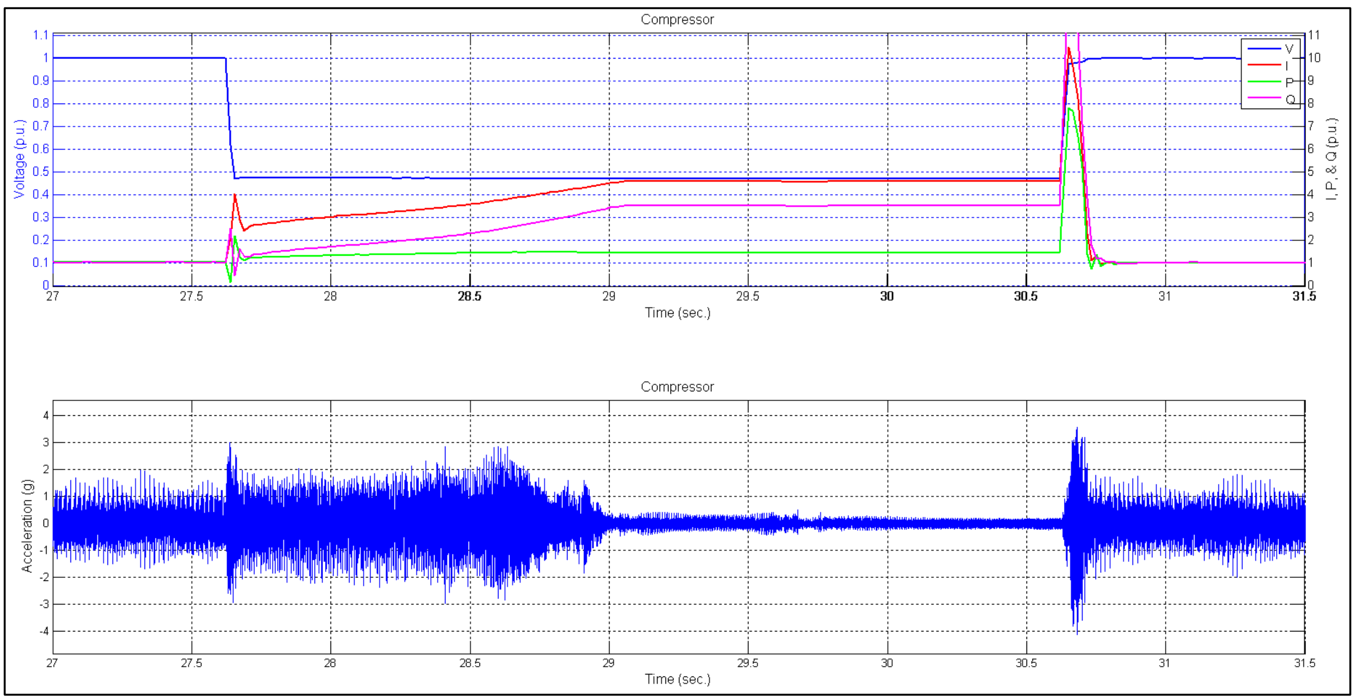

Figure 4.13.2 A/C #2 Compressor Stalling During Under-voltage (48% voltage)

Additionally, a voltage ramp test was performed to capture the compressor's current, real power, and reactive power consumption at different voltage levels as shown in the figure below. At the stalling point current, real power, and reactive power reached 4.2 pu, 1.4 pu, and 3.3 pu. At the restarting point current, real power, and reactive power increased to as large as 6.6 pu, 3.5 pu, and 7.3 pu.

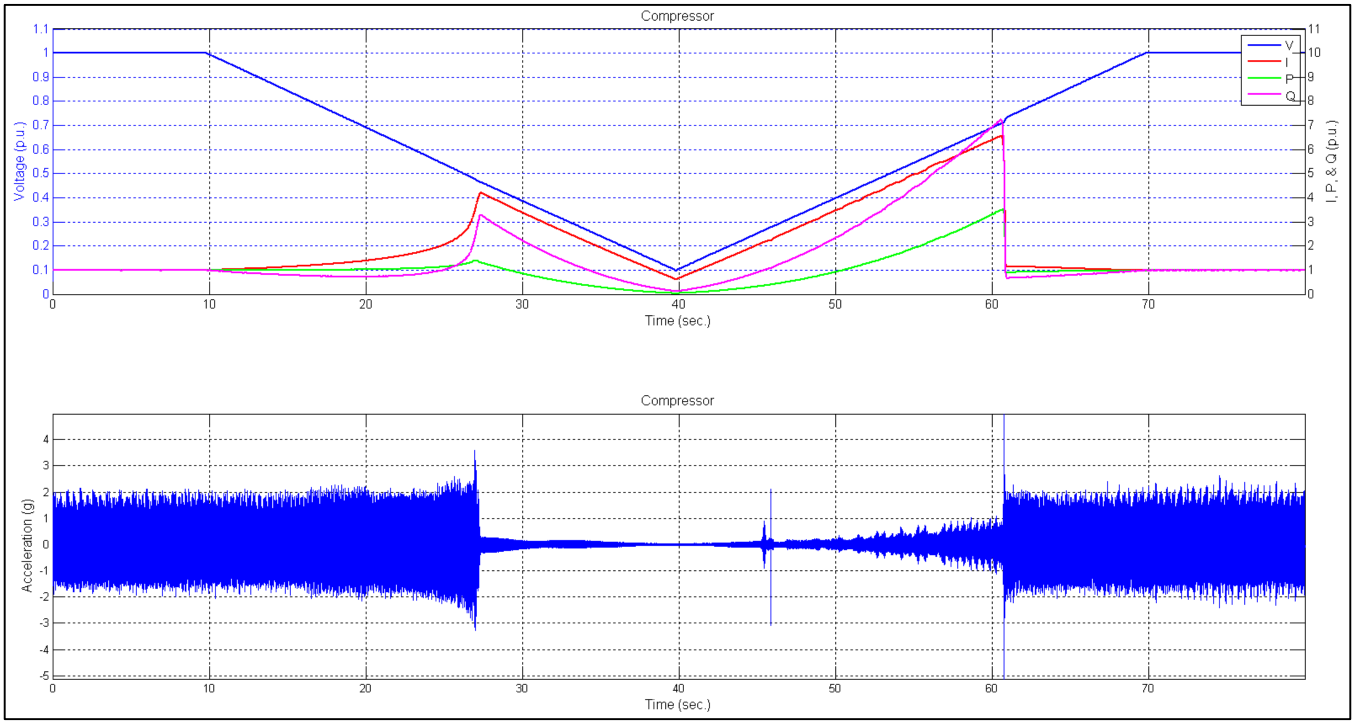

Figure 4.13.3 A/C #2 Compressor Stalling During Voltage Ramp

5.0 AIR CONDITIONER #3 TEST RESULTS

The third air conditioner tested is a 4-ton unit operated at 208 V line-to-line. The unit is comprised of a single indoor blower fan motor, outdoor fan motor, and a compressor motor. The specifications for the individual components of A/C #3 are provided in the table below.

Main System		**Compressors**	
Manufacturer	Rheem	Manufacturer	Copeland
Model	RQPLB049CK015	Model	ZP42K5E-TF5-130
Size (Tons)	4	Type	Scroll
Voltage (V)	208	Quantity	1
Refrig.	R-410A	RLA (Amps)	13.7
SEER	14	LRA (Amps)	83.1
EER	11.5	Test Press. High (PSI)	550
IEER	-	Test Press. Low (PSI)	250
Condenser Fan		**Blower Motor**	
Drive Type	Direct	Type	Direct
Quantity	1	Quantity	1
Motor HP	1/3	Motor HP	3/4
RPM	1075	RPM	1075
FLA (Amps)	2	FLA (Amps)	6
Miscellaneous Components			
Contactor(s)	Zettler, XMCO-323-EBBDOOF-203	Capacitor(s)	CSC Electronics, 325P505H37A15A4X
Transformer	Zettler, AHR40310FMW-139	Phase Balance Relay	-

Table 5.0.1 A/C #3 Specifications

5.1 Compressor Shutdown

A/C #3 was shut down during normal operation using the connected thermostat. The figure below displays the measurements taken at the main service connections as well as the behavior of the individual motors.

The compressor and outdoor fan motor shut down at the same time shortly after triggering the thermostat. The only power consumption after the compressor shuts down was from the single-phase indoor fan motor that is pulling 2 Amps (total of 400 W or 475 VA). The indoor fan motor begins ramping down to zero approximately 31 seconds after the other components.

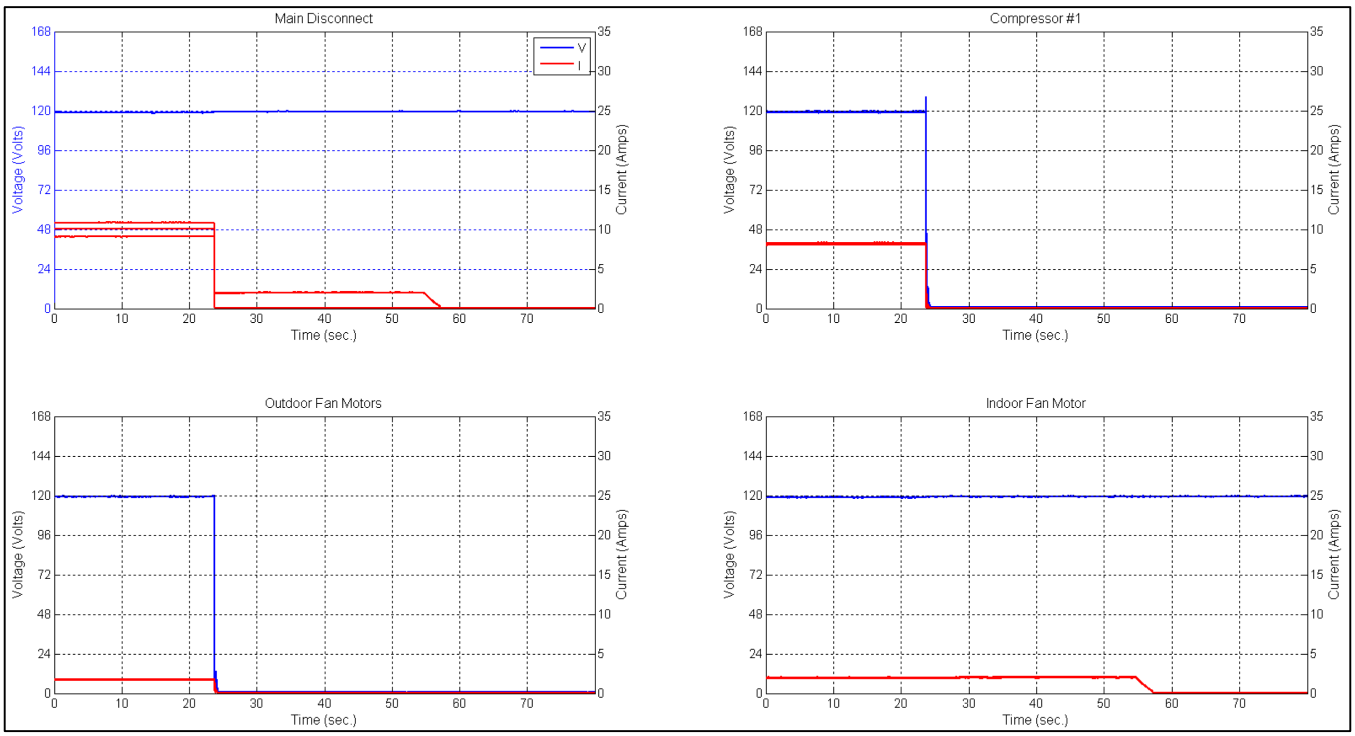

Figure 5.1.1 A/C #3 Compressor Shutdown

5.2 Inrush Current

After starting up A/C unit #3 via the programmable thermostat, the compressor and the outdoor fan motors start up at the same time followed shortly by the indoor fan motor approximately 4.6 cycles later. However the indoor fan motor ramps up without a sudden spike in current. The inrush currents observed at the main disconnect of the unit indicate a maximum value of 77.54 Amps and a duration time of 7 cycles.

Compressor Inrush: Maximum of 75.5 Amps and duration of 7 cycles

Outdoor Fan Motor Inrush: Maximum of 3.8 Amps and duration of 2.2 seconds

Indoor Fan: Ramps up to nominal within 3.3 seconds

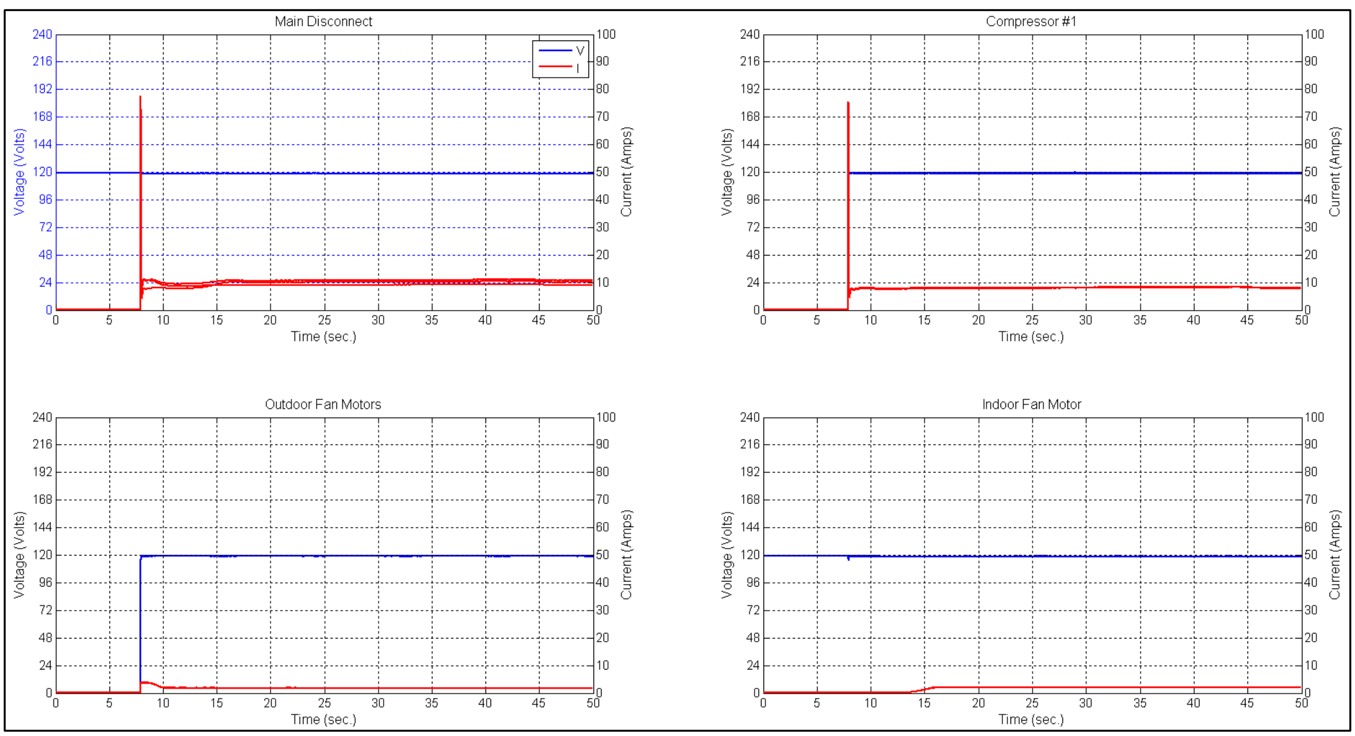

Figure 5.2.1 A/C #3 Inrush Current

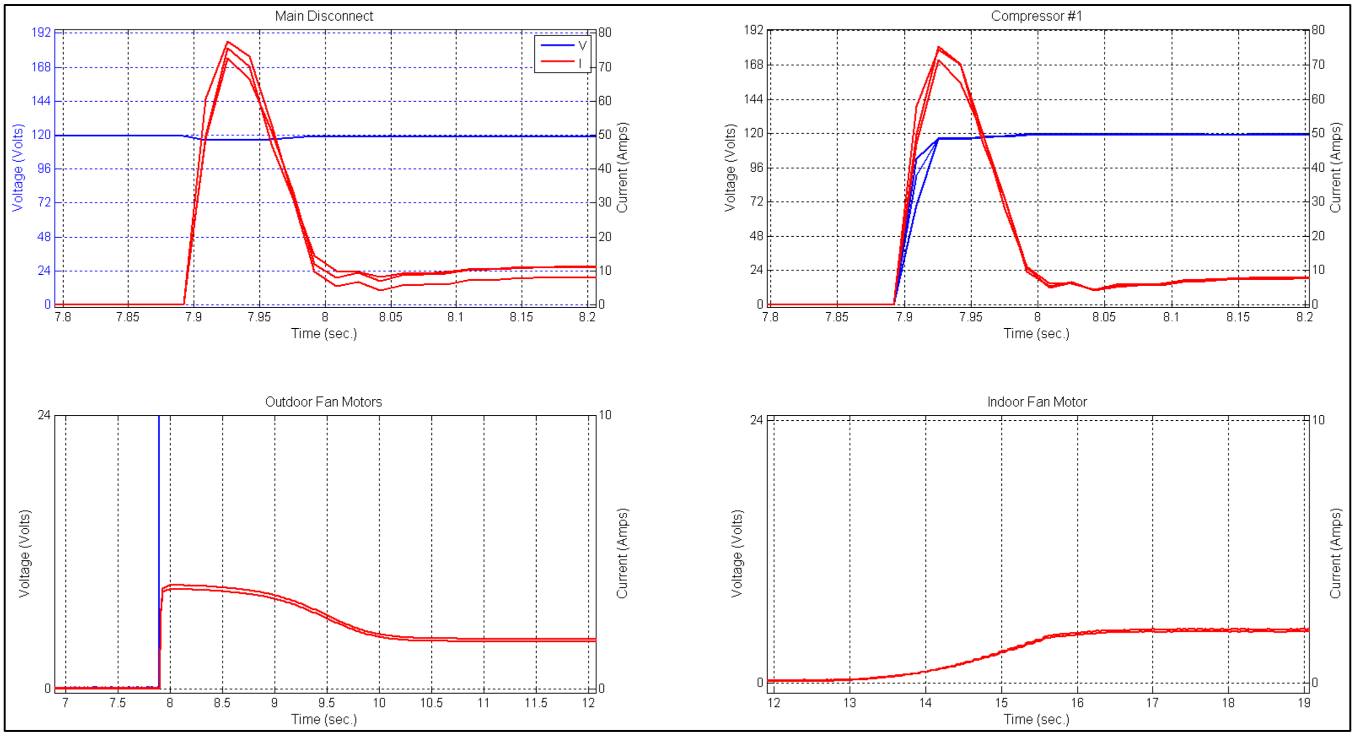

Figure 5.2.2 A/C #3 Inrush Current [Zoom In]

5.3 Balanced & Unbalanced Under-voltages

Control voltage measurements (24 V) were monitored at the thermostat output and contactor coil to help determine the root cause of compressor tripping and to make the following conclusions regarding the performance of A/C unit #3. Stalling behavior was observed only during certain unbalanced under-voltage tests while all balanced tests resulted in the contactor opening before stalling could occur. Contactor chattering was repeatedly observed during the voltage step changes during the voltage sag tests. Data captured several seconds after the disconnection of the compressor did not reveal immediate contactor reclosing during these tests, except for special tests where the contactor control wiring was re-configured. Contactors would only reclose several minutes after voltage recovered to steady state, due to a relay located at the controller or even at the thermostat.

Balanced voltage sags on all three phases in decrements of 10% revealed that the compressor would disconnect after the contactor opened at 50% nominal voltage for transients with a duration in the range of 3 to 130 cycles. Typically, the contactor would open between 2 and 3 cycles after the start of the voltage sag and would not reclose immediately after voltage recovered. Every time after the contactors opened due a balanced under-voltage sag, they would only reclose several minutes later likely due to the operations of the local controller and/or thermostat.

The only case where the contactor and compressor motor rode through balanced 0% under-voltage sags was during switching transients with a duration time of 1 cycle. “N/A” or “not applicable” as noted in the following tables represents these ride through situations where there is no trip voltage or trip time available.

The following figure visually displays one of the longer duration balanced under-voltage tests. The following table provides the details regarding the compressor contactor operation and control voltage measurements during the various tests. The trip voltage represents the magnitude where the contactor opened and where the control voltage (at the contactor coil and thermostat) disappeared along with the associated time after the start of the voltage sag.

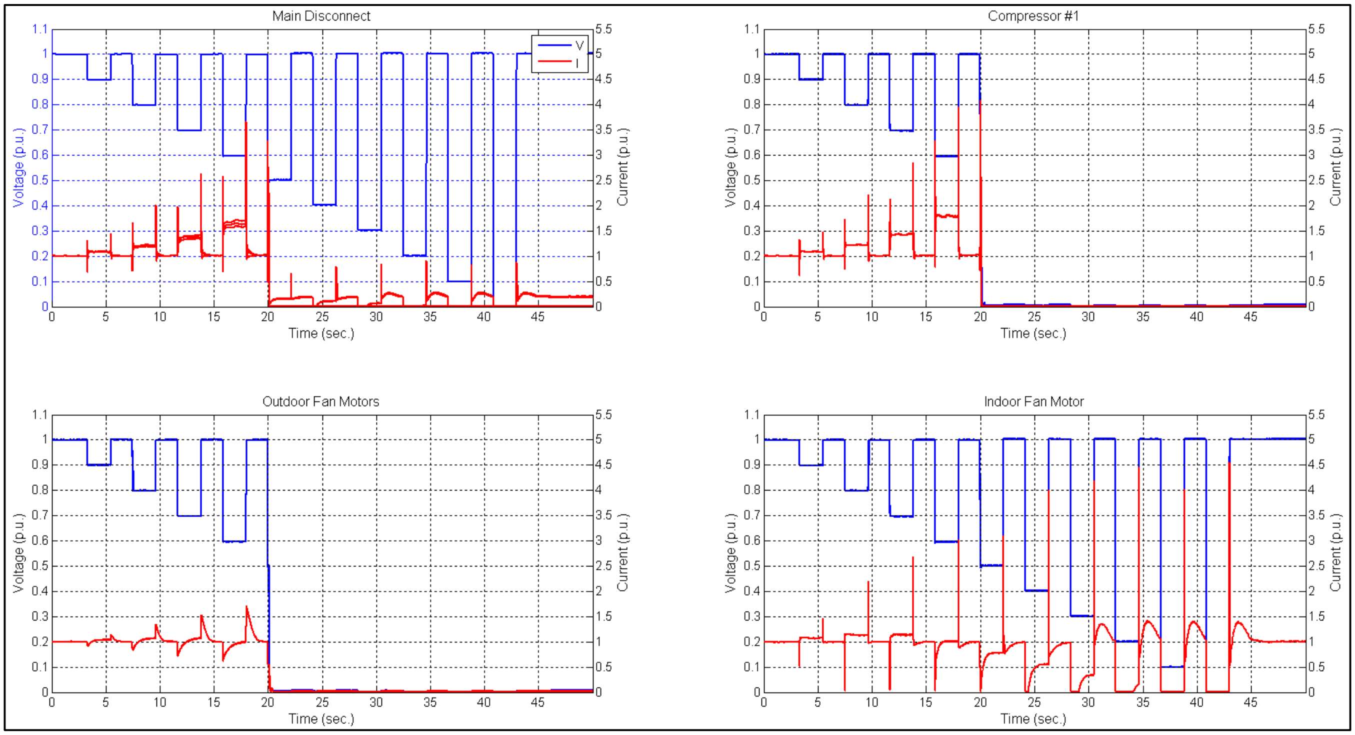

Figure 5.3.1 A/C #3 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor		Contactor Coil		Thermostat (Y)	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	50%	7	50%	6	50%	6
		50%	2	50%	8	50%	8
		50%	3	50%	6	50%	6
		50%	3	50%	6	50%	6
100%, 90%, 80%,... 0%	6	50%	3	50%	6	50%	6
		50%	3	50%	5	50%	5
		50%	2	50%	8	50%	8
		50%	3	50%	6	50%	6
100%, 90%, 80%,... 0%	3	50%	3	50%	6	50%	6
		50%	3	50%	5	50%	5
		50%	3	50%	5	50%	5
100%, 90%, 80%,... 0%	1	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A

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

In order to narrow down the voltage where the compressors are disconnected and contactor/controls dropout occurs, additional balanced under-voltage tests were performed in decrements of 1% nominal voltage where the contactor coil is energized directly by supply voltage using the step-down controls transformer. The contactor consistently opened at 58% nominal voltage typically within 38 cycles after the voltage sag started. The contactor did not reclose due to the thermostat. The following table provides the details of the 1% voltage decrements.

Under-Voltage Transient		Compressor	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
60%, 59%, 58%, …	130	58%	59
60%, 59%, 58%, …	130	58%	38
60%, 59%, 58%, …	130	58%	37

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

Unbalanced under-voltages on A/C unit #3 resulted in a greater variety of trip voltages and trip times because the controls (including the contactor coil) are energized using one of the line-to-line supply voltages, phase C to phase A. Phase C to A under-voltages are therefore similar to the results of the balanced under-voltage tests. Also, phase B under-voltage transients do not result in contactor dropout, only voltage ride-through for all voltage magnitudes.

Stalling behavior was discovered during the 130 cycle unbalanced under-voltages for $V_{\Phi A-\Phi B}$ and $V_{\Phi B-\Phi C}$. When phases A and B experience under-voltage, the compressor takes approximately 24.0 cycles to completely stall at 20% nominal voltage and approximately 12.6 cycles to stall at 10% nominal voltage. When phases B and C experience under-voltage, the compressor takes approximately 20.4 cycles to completely stall at 20% nominal voltage and approximately 13.2 cycles at 10% nominal voltage. The compressors restarts from stalling condition within 5.5 cycles after the voltage sag recovers to nominal. The following two figures display this stalling behavior.

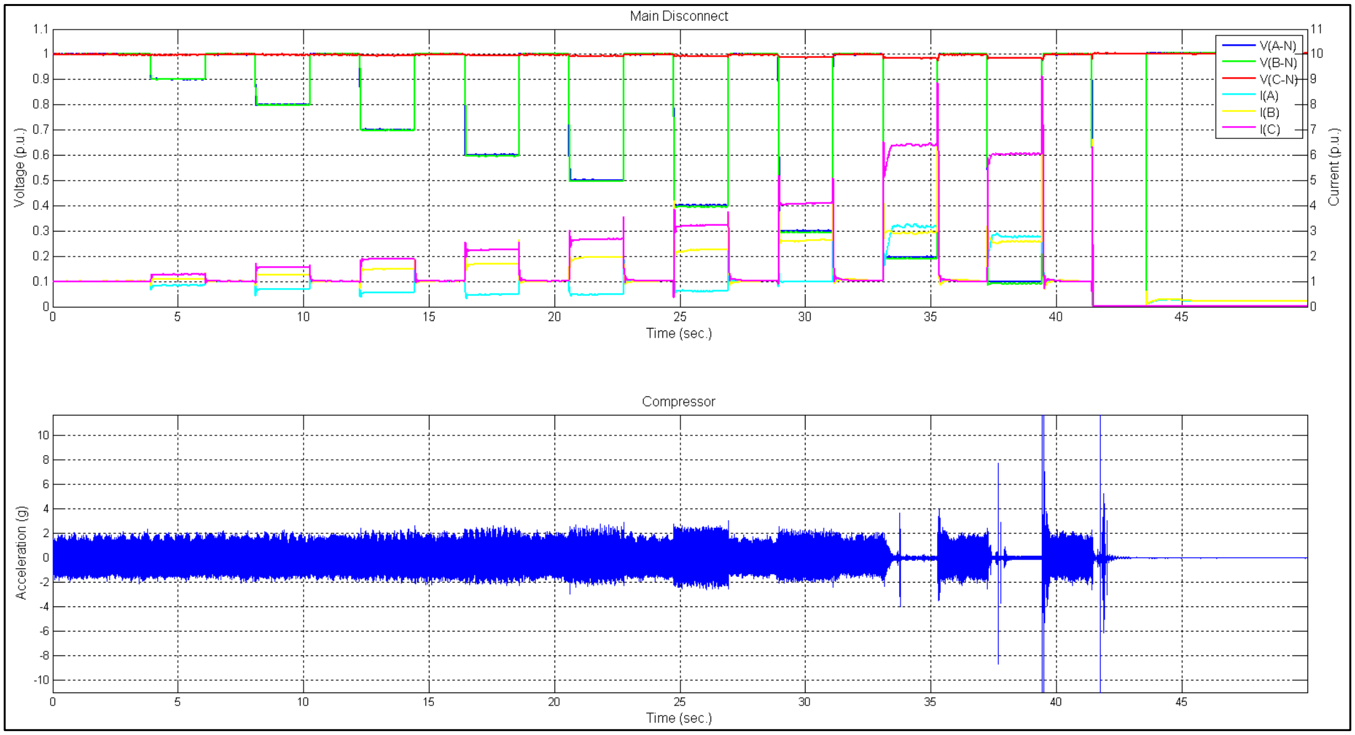

Figure 5.3.2 A/C #3 Unbalanced Under-voltage Response (Phases A & B, 130 cycles)

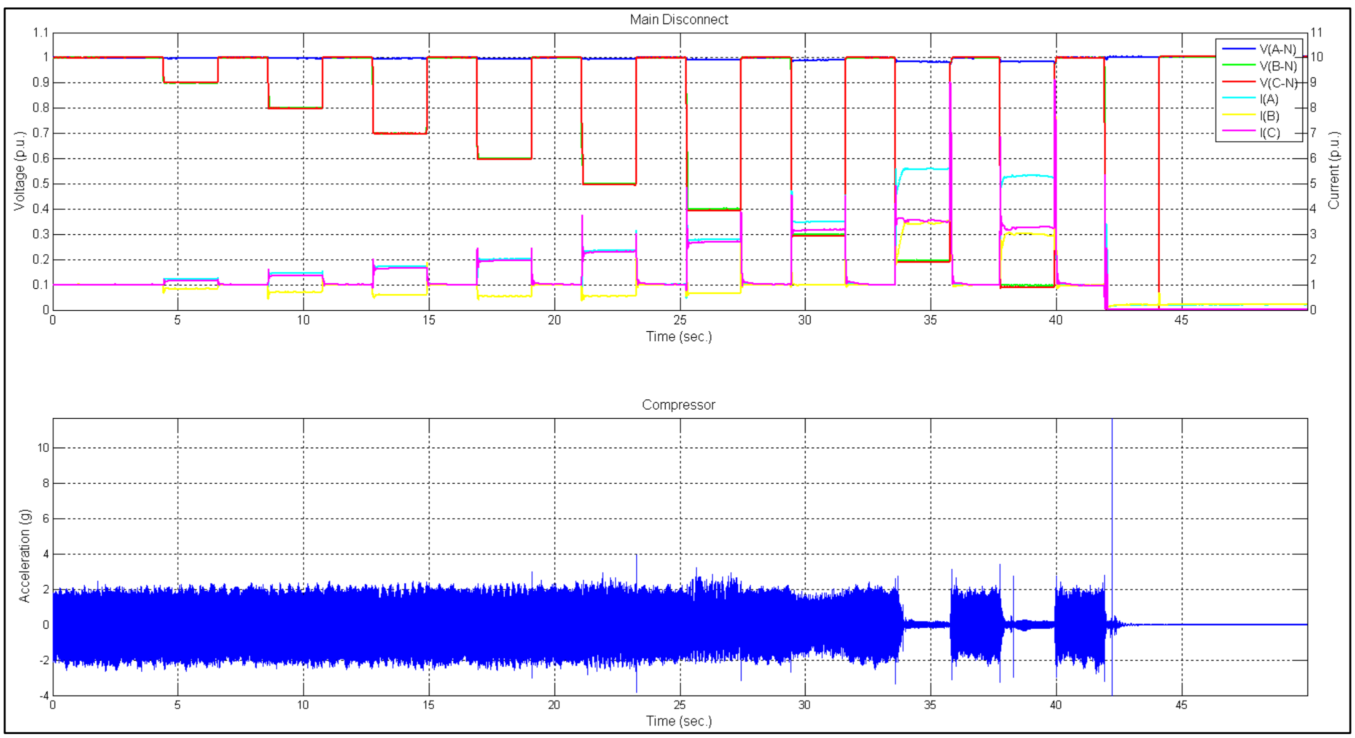

Figure 5.3.3 A/C #3 Unbalanced Under-voltage Response (Phases B & C, 130 cycles)

The following table provides more dropout/tripping details on the results of the unbalanced transients, the same as those documented for the balanced voltage sags. Notice that the 12 cycle unbalanced voltage sag tests for phase AB results in the contactor opening 17 cycles after the start of the voltage sag (5 cycles after voltage has recovered).

Under-Voltage Transient			Compressor		Contactor Coil		Thermostat (Y)	
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
A	100%, 90%, 80%,... 0%	130	10%	27	10%	27	10%	27
		20	N/A	N/A	N/A	N/A	N/A	N/A
		12	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 90%, 80%,... 0%	130	N/A	N/A	N/A	N/A	N/A	N/A
		12	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 90%, 80%,... 0%	130	10%	24	10%	21	10%	21
		20	0%	20	0%	17	0%	17
		12	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 90%, 80%,... 0%	130	0%	2	0%	9	0%	9
		12	0%	17	0%	16	0%	16
		6	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 90%, 80%,... 0%	130	0%	4	0%	6	0%	6
		12	0%	6	0%	6	0%	6
		6	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 90%, 80%,... 0%	130	50%	2	50%	6	50%	6
		6	50%	6	50%	6	50%	6
		3	50%	3	50%	6	50%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A

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

5.4 Balanced & Unbalanced Over-voltages

The A/C unit was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve to avoid damage. Multiple voltage swells were performed in 2% increments for up to 120% nominal voltage for each test. The following figure shows a sample over-voltage test and the following table specifies the tests performed that resulted in voltage ride-through.

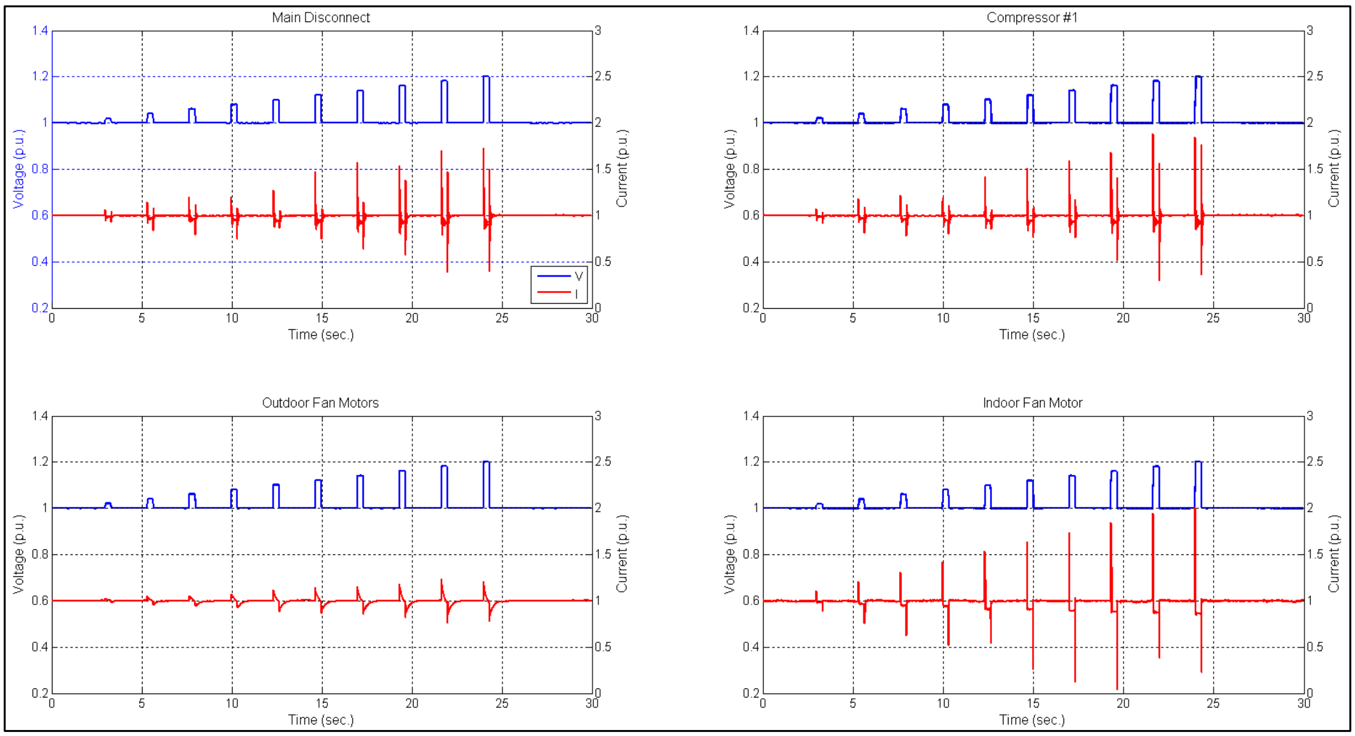

Figure 5.4.1 AC #3 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		Contactor Coil		Thermostat (Y)	
Φ	**Volt Range**	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
ABC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
A	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A

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

5.5 Voltage Oscillations

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

The currents oscillate in the opposite direction of voltage (+8%) for all swing frequencies tested. Real power remains relatively close to steady state, oscillating within +2% of the nominal power consumption. Real power also experiences larger deviations as the swing frequency or rate of oscillation increases.

Reactive power consumption experiences the largest impact (-14% to -22% deviation) oscillating in the same direction as voltage. At higher swing frequencies, deviations become larger both above and below steady state.

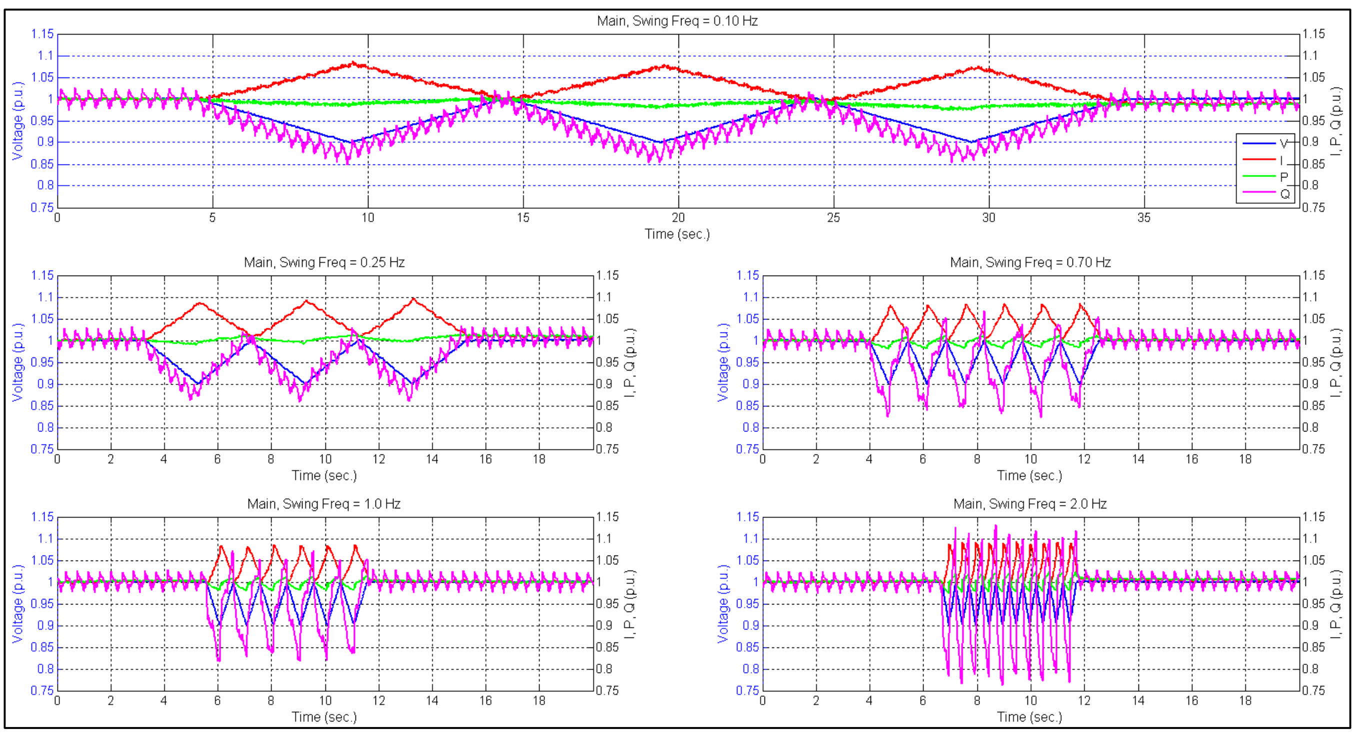

Figure 5.5.1 AC #3 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

5.6 Under-frequency Events

After subjecting A/C #3 to multiple under-frequency transients with different duration times, it is presumed that the unit does not have under-frequency protection down to 58 Hz. The device simply rides through these frequency conditions. The following figure and table identify the tests that were performed.

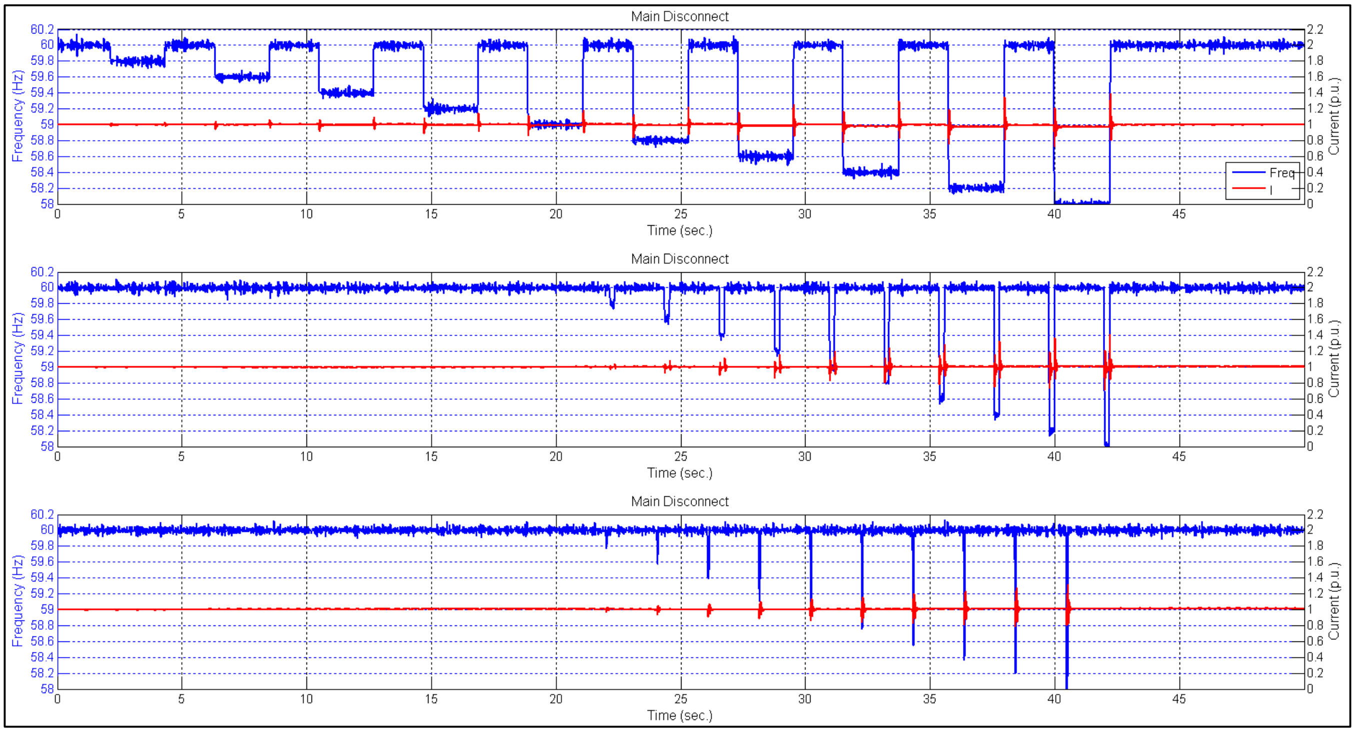

Figure 5.6.1 A/C #3 Under-frequency Response (130, 12, 3 cycles)

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

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

5.7 Over-frequency Events

Similar to the under-frequency tests, A/C #3 was subjected over-frequency transients with different duration times up to 62 Hz without triggering any protection. The unit rode through and continued operating during these frequency conditions. The following figure and table identify the over-frequency tests that were performed.

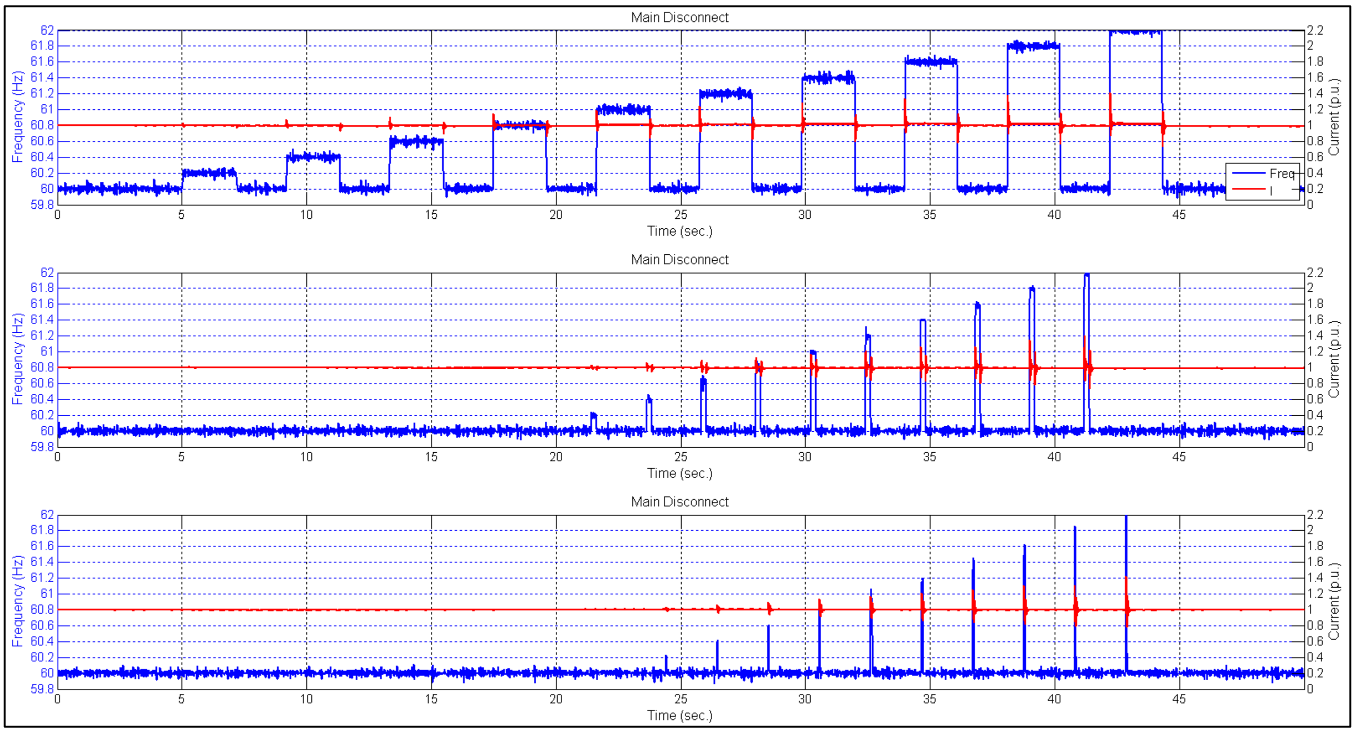

Figure 5.7.1 A/C #3 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor		Contactor Coil		Thermostat (Y)	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 60.2Hz, 60.4Hz,... 62Hz	130	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	12	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	3	N/A	N/A	N/A	N/A	N/A	N/A

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

5.8 Frequency Oscillations

The following figure shows the performance of A/C unit #3 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates.

Current, real power, and reactive power remain relatively close to steady state, only deviating within +3% of their nominal values for swing frequencies up to 1 Hz. Even at a swing frequency of 2 Hz, these values only deviate up to +4% from their nominal consumption values.

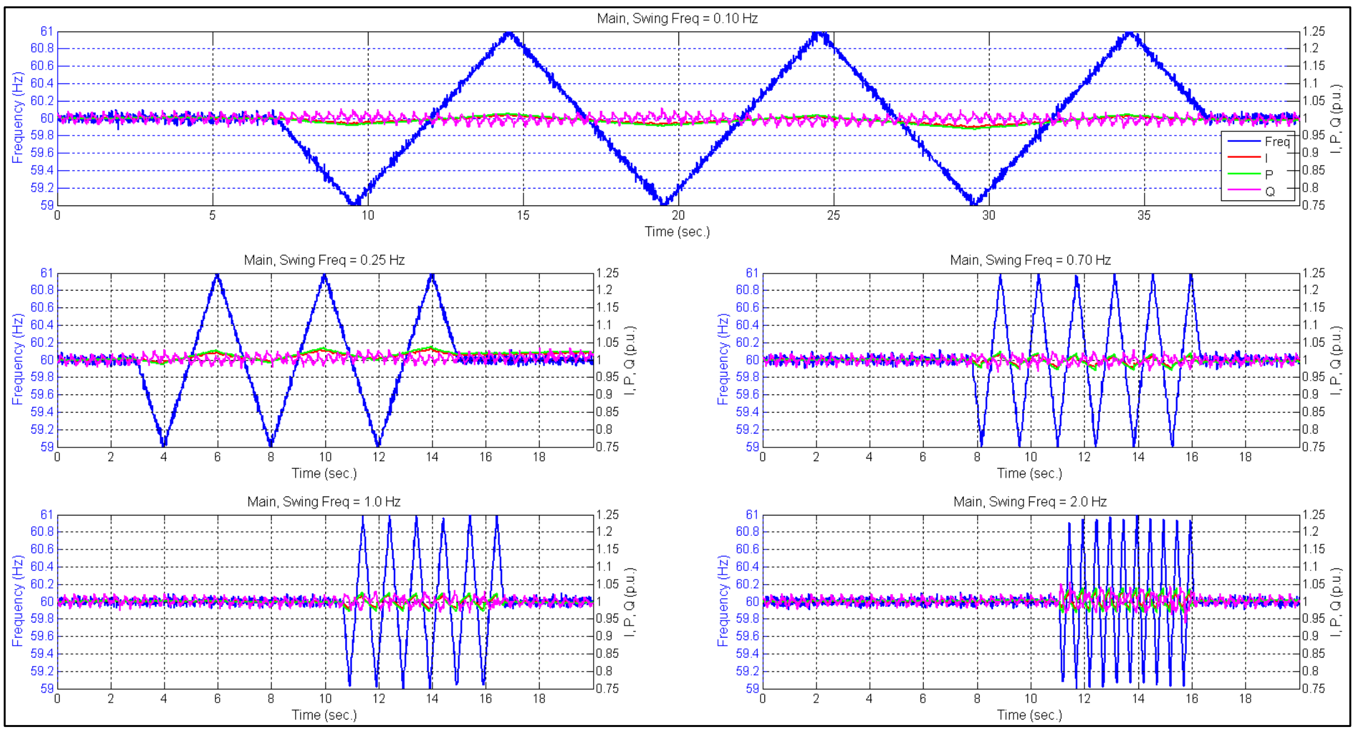

Figure 5.8.1 A/C #3 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

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 without tripping (down to 60% nominal voltage).

Current ramps up to approximately 60% above nominal, mitigating a large reduction in real power consumption. Real power deviates 8% below nominal during the faster ramp rate and 5% below nominal during the slower ramp rate. Reactive power does not linearly correlate with the voltage behavior.

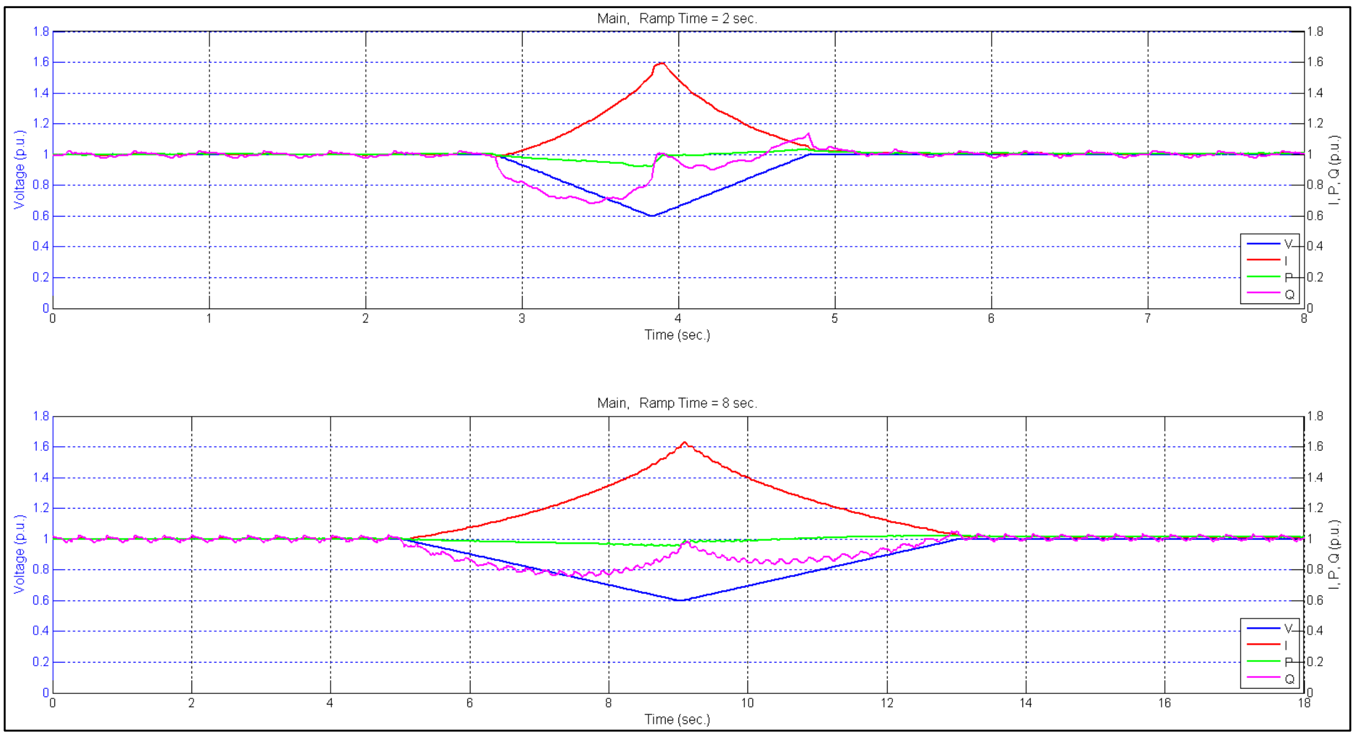

Figure 5.9.1 A/C #3 Voltage Ramp Down to 60% (2 & 8 sec.)

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 is observed ramping down to approximately 6% below nominal. Real power only deviates by ±1% from steady state. Finally, reactive power increase to approximately 20% above of nominal reactive load consumption.

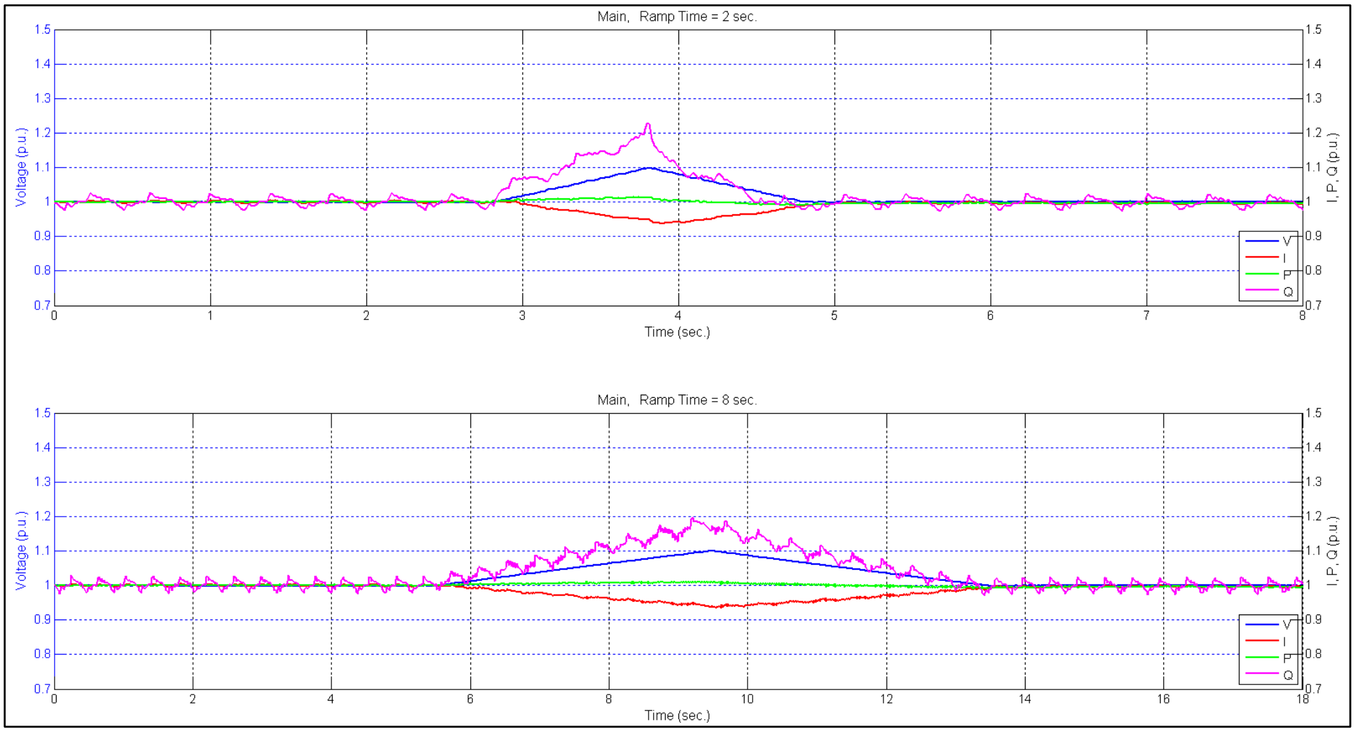

Figure 5.9.2 A/C #3 Voltage Ramp Up to 110% (in 2 & 8 sec.)

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 ramps down to 10% below its nominal output. Real power consumption is reduced during the under-frequency condition dipping to nearly 17% below steady state. Reactive power actually ramps upward to 18% above of normal consumption.

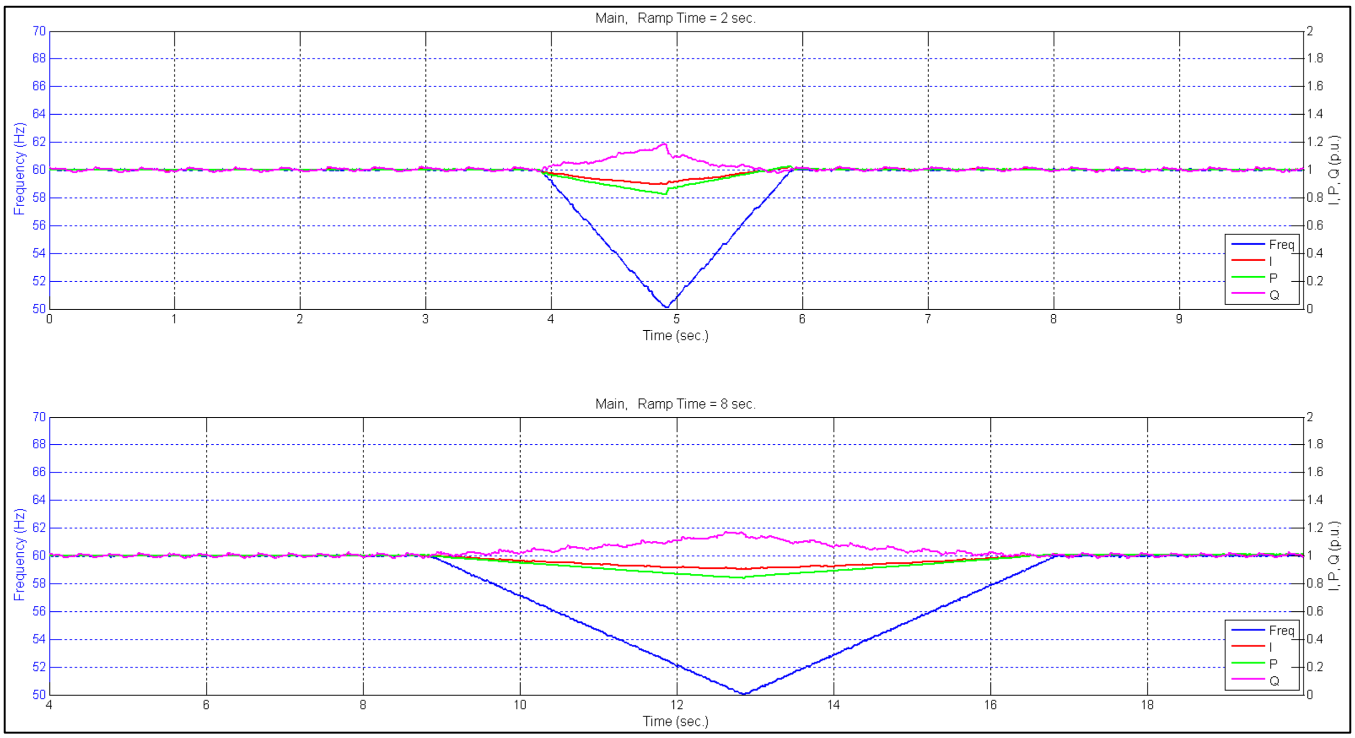

Figure 5.10.1 A/C #3 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

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. However, A/C unit #3 tripped at approximately 64 Hz and the test was redone ramping frequency up to 62 Hz as shown in the figure below.

Current, real power, and reactive power remain relatively close to their respective steady state values, within ±5%, during the frequency ramp up test.

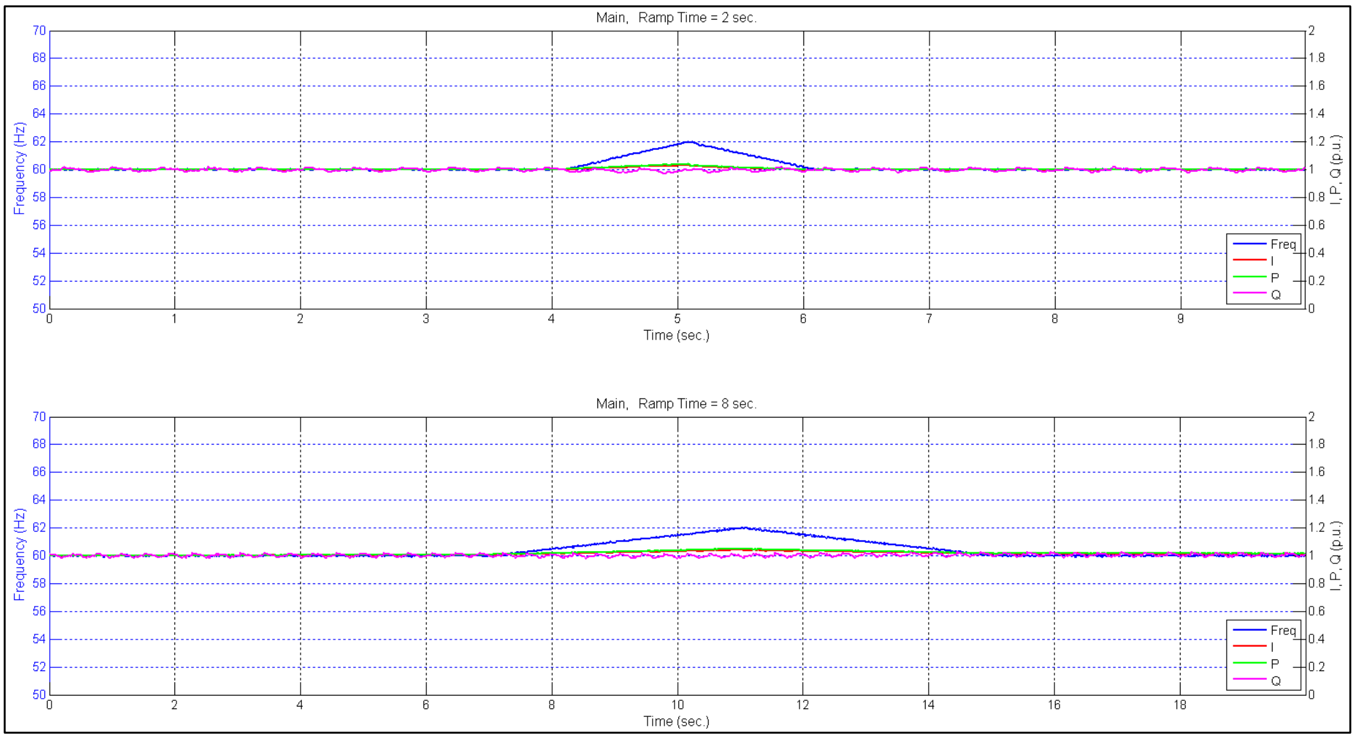

Figure 5.10.2 A/C #3 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

5.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times to calculate the harmonic contribution of A/C unit #3 to the grid. The total harmonic distortion of current was determined to be nearly 33% of the fundamental. The cause of this high harmonic contribution is the same as A/C unit #2 where the current waveforms or pulses of the indoor fan motor cause a distortion in the total current measured at the main disconnect terminals.

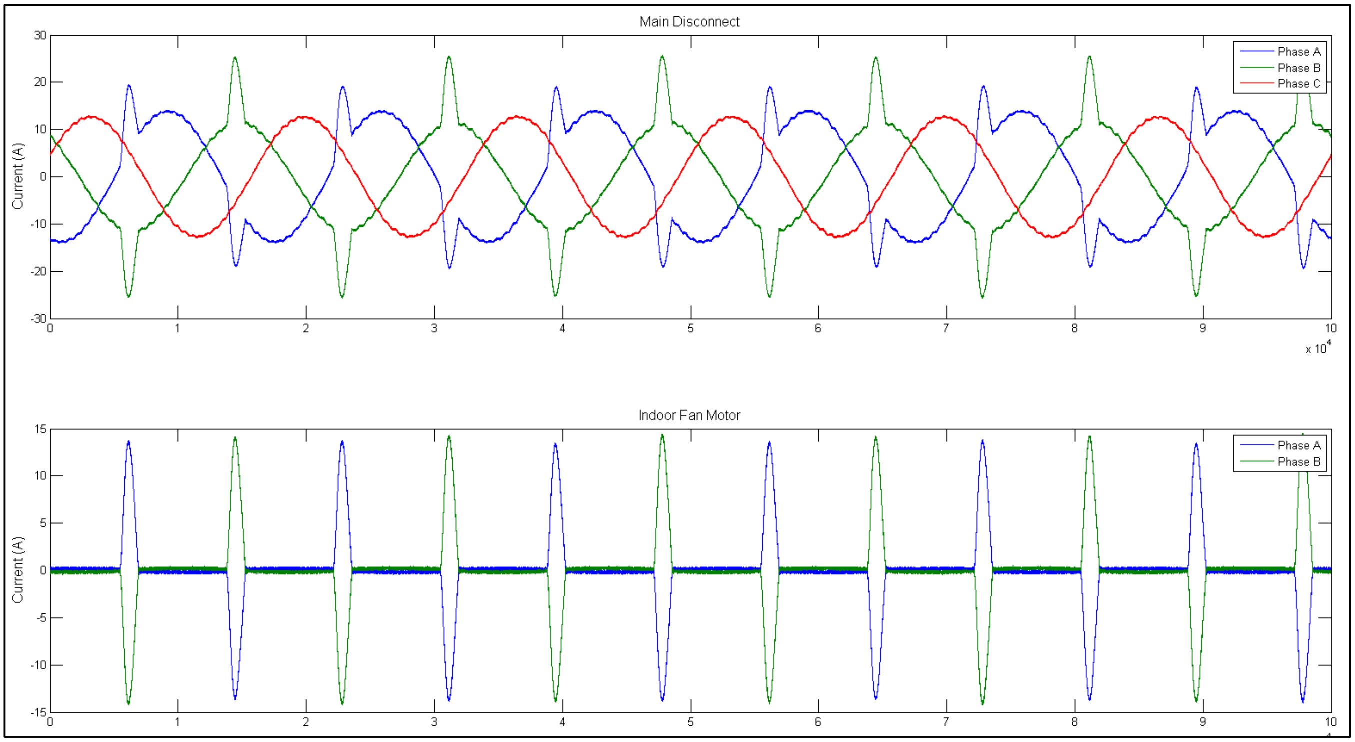

Figure 5.11.1 A/C #3 Main Disconnect and Indoor Fan Motor Current

Data Set #	THD (% of Fundamental)					
	$V_{A\,(L-N)}$	$V_{B\,(L-N)}$	$V_{C\,(L-N)}$	I_A	I_B	I_C
1	0.41	0.45	0.10	30.06	32.69	1.70
2	0.41	0.45	0.10	29.74	32.33	1.70
3	0.41	0.45	0.10	29.61	32.20	1.73

Table 5.11.1 A/C #3 Total Harmonic Distortion

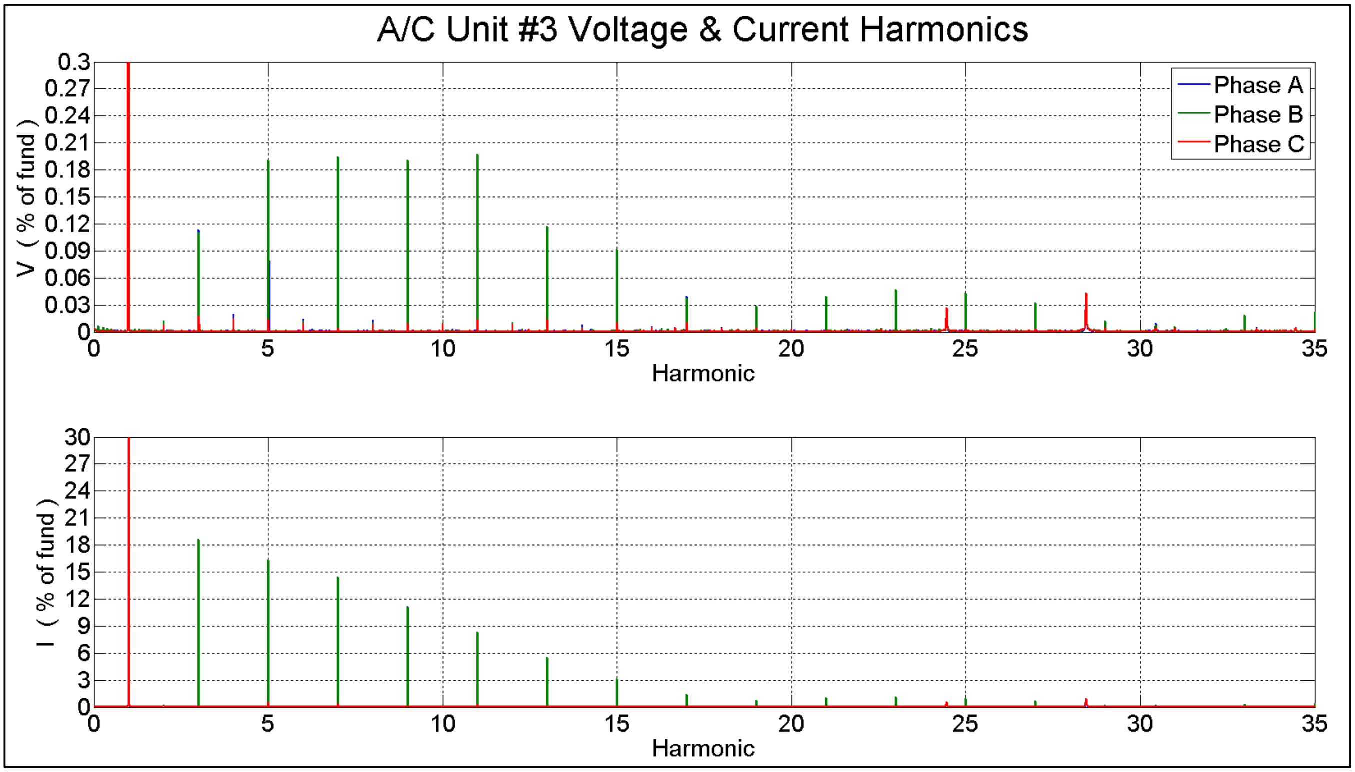

Figure 5.11.2 A/C #3 Harmonics Contribution

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. Outdoor conditions resulted in mild loading of the single compressor operating at approximately 65% of the rated load amps.

Current increases by approximately 1% of nominal current for every 1% decrease in nominal voltage. Real power remains nearly constant, within ±2% of nominal, during the CVR test. Reactive power is observed stepping down with the voltage and decreases by 1.1% nominal reactive power for every 1% decrease in nominal voltage.

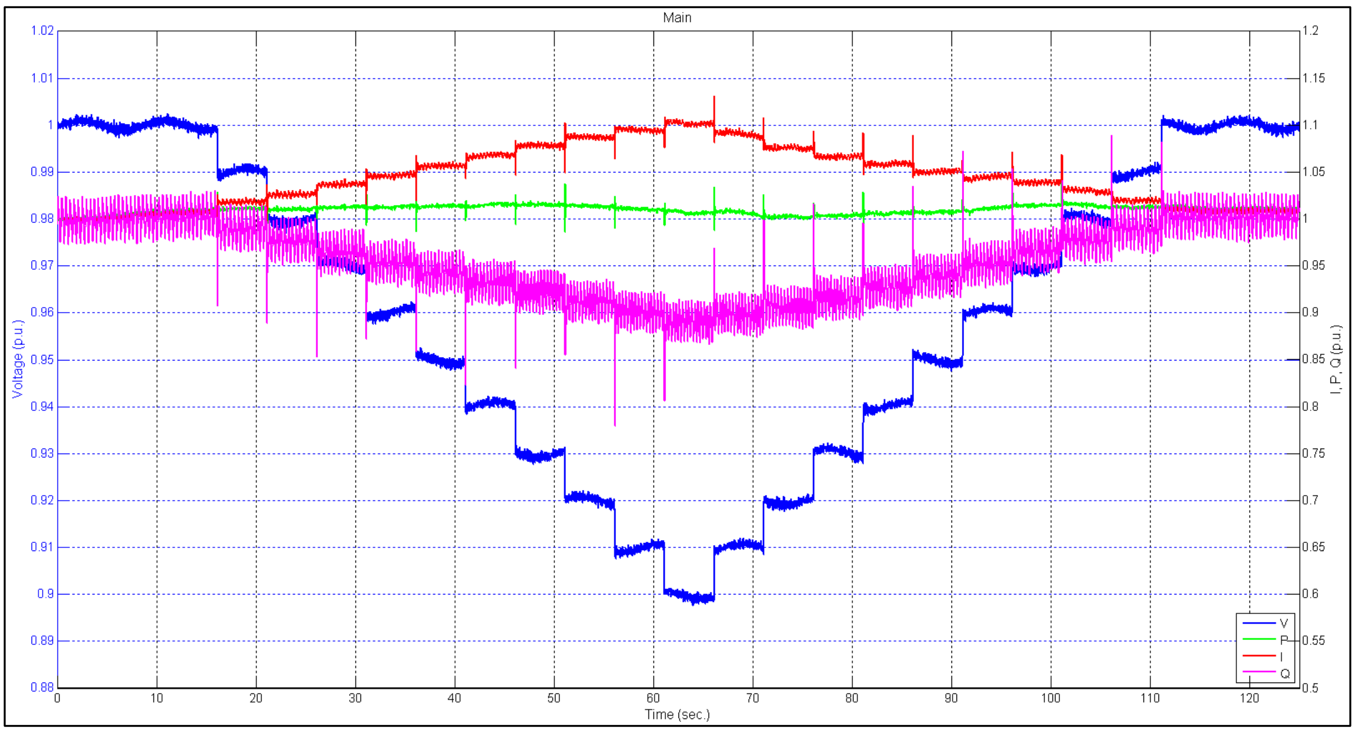

Figure 5.12.1 A/C #3 CVR Response Down to 90% Voltage

Alternatively, the service voltage at A/C #3 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 0.9% of nominal current for every 1% decrease in nominal voltage. Real power stays within +2% of steady state, but is consumed less once voltage returns to nominal. Reactive power is observed stepping up with the voltage and increases by 1.3% nominal reactive power for every 1% increase in nominal voltage.

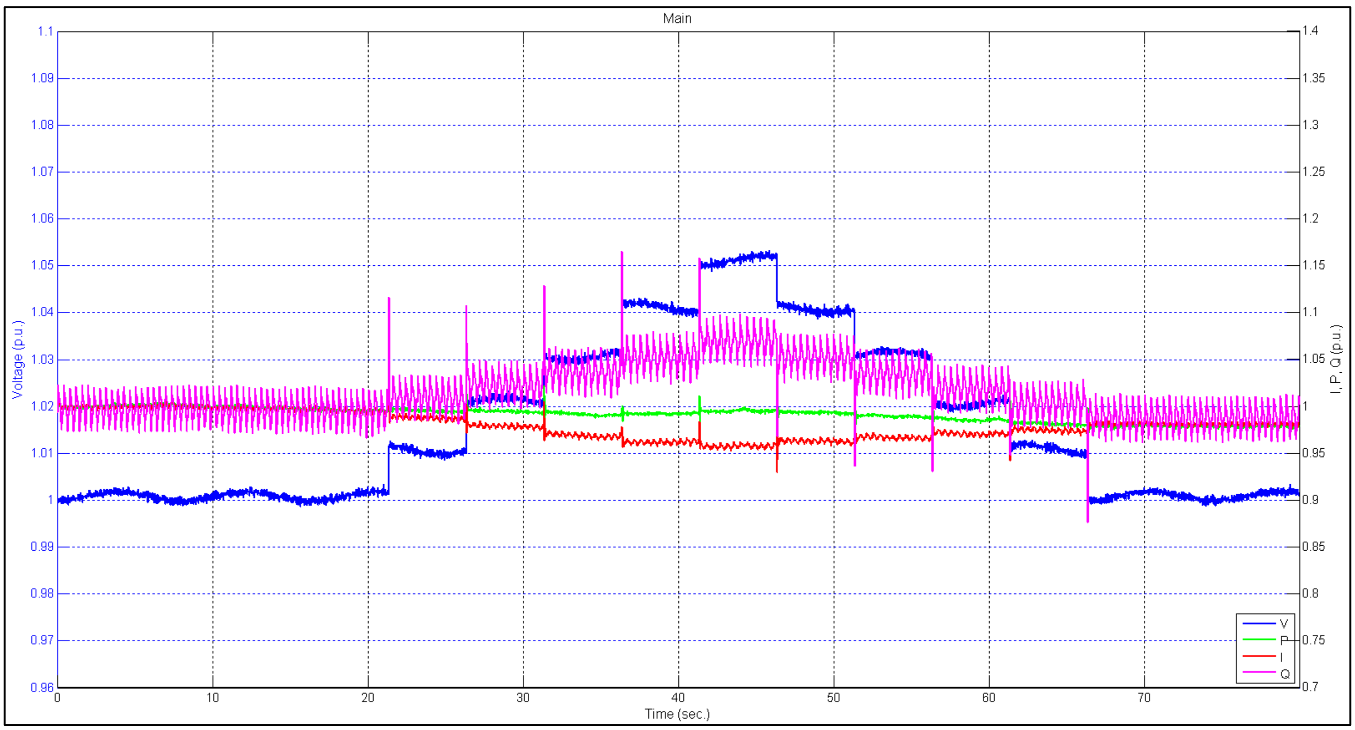

Figure 5.12.2 A/C #3 CVR Response Up to 105% Voltage

5.13 Compressor Stalling

Although A/C unit #3 displayed stalling characteristics during certain unbalanced under-voltage transients as previously mentioned, there were not any noticeable signs of compressor stalling during balanced under-voltages. The contactors and/or controls typically dropped out and reclosing would not occur until several minutes later at which time the unit started up normally. Therefore several additional undervoltage tests were performed after making modifications to the device controls in order to induce compressor stalling behavior during balanced under-voltage conditions. Rather than using the service voltage from the main terminals of the A/C unit to serve the step-down transformer (24 V output) and power the controls, a separate power supply was used to energize these controls (contactor coils, relays, thermostat, etc.) to bypass any dropout performance.

Prior tests revealed that dropout had occurred at 50% which was used as a starting point for these additional under-voltage tests. A series of under-voltage sags were performed in 1% voltage decrements with duration times of 3 seconds as shown in the following figures. It was revealed that the compressor began stalling a 49% voltage. However, the compressor does not stall immediately after the voltage dip and takes approximately 1.4 seconds to completely stall. Notice that stalling is identified by the dramatic increase in current and reactive power as well as the reduced mechanical vibration of the compressor. Lower voltage magnitudes resulted in faster stalling behavior.

The compressor restarted from its stalling condition within 5 cycles after voltage returns to nominal. It consistently restarts after each and every voltage sag performed. Voltage was also held at 49% voltage indefinitely during a separate test which caused thermal overload protection to occur nearly 102 seconds after stalling begins.

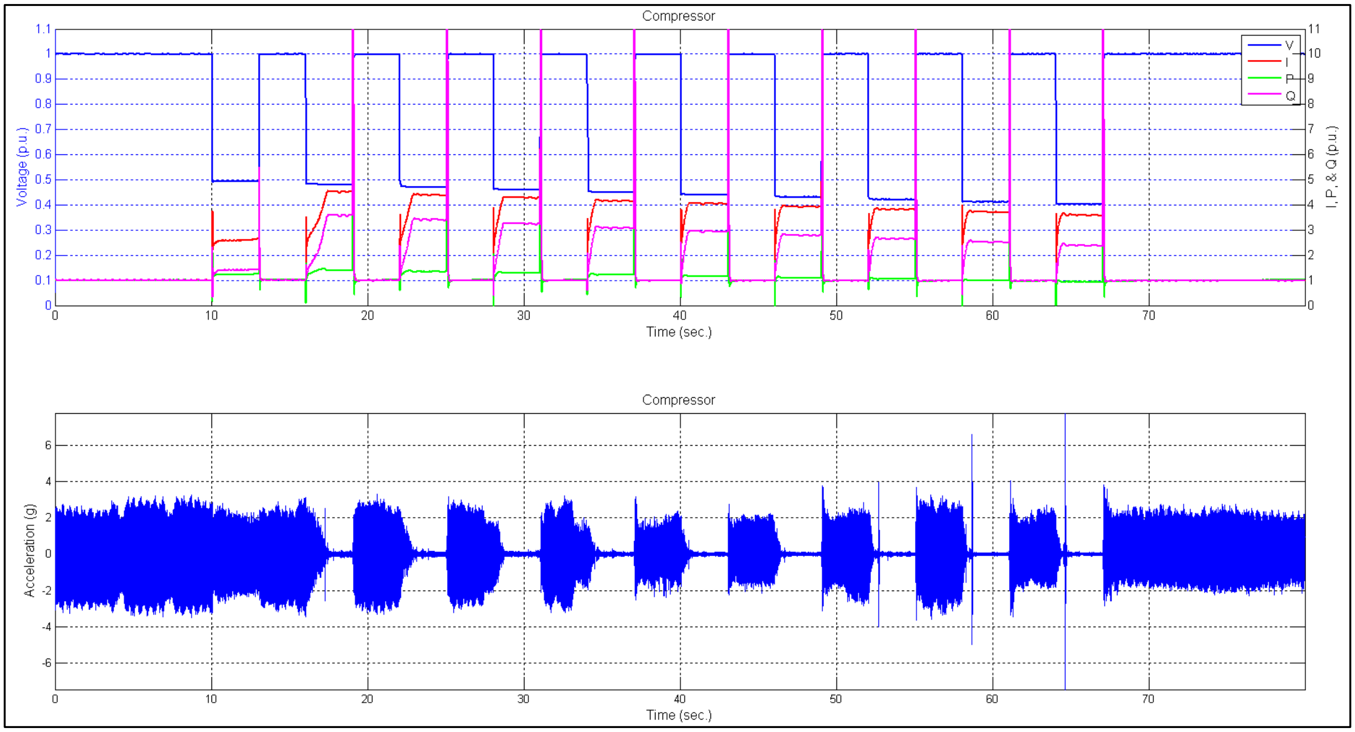

Figure 5.13.1 A/C #3 Compressor Stalling During Under-voltages (50% to 41% voltage)

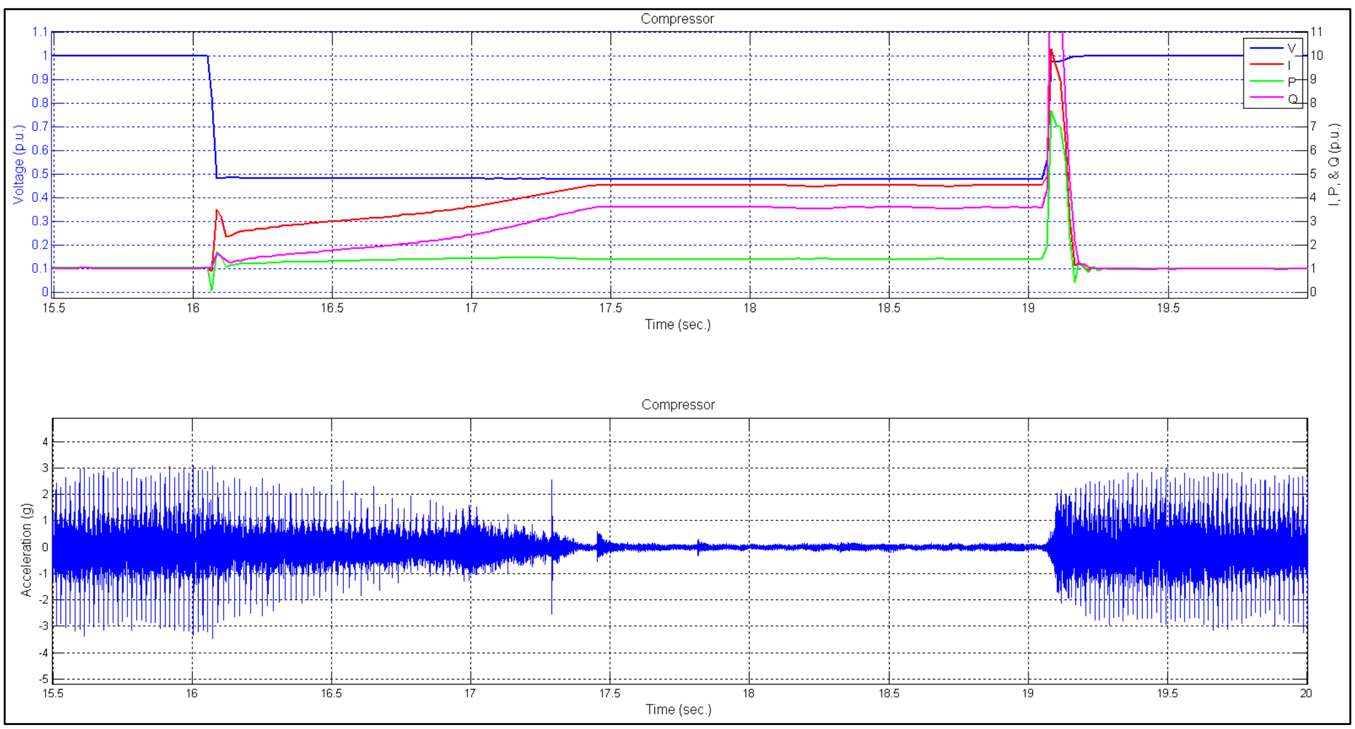

Figure 5.13.2 A/C #3 Compressor Stalling During Under-voltage (49% voltage)

Additionally, a voltage ramp test was performed to capture the compressor's current, real power, and reactive power consumption at different voltage levels as shown in the figure below. At the stalling point current, real power, and reactive power reached 4.4 pu, 1.4 pu, and 3.4 pu. At the restarting point current, real power, and reactive power increased to as large as 6.5 pu, 2.9 pu, and 6.7 pu.

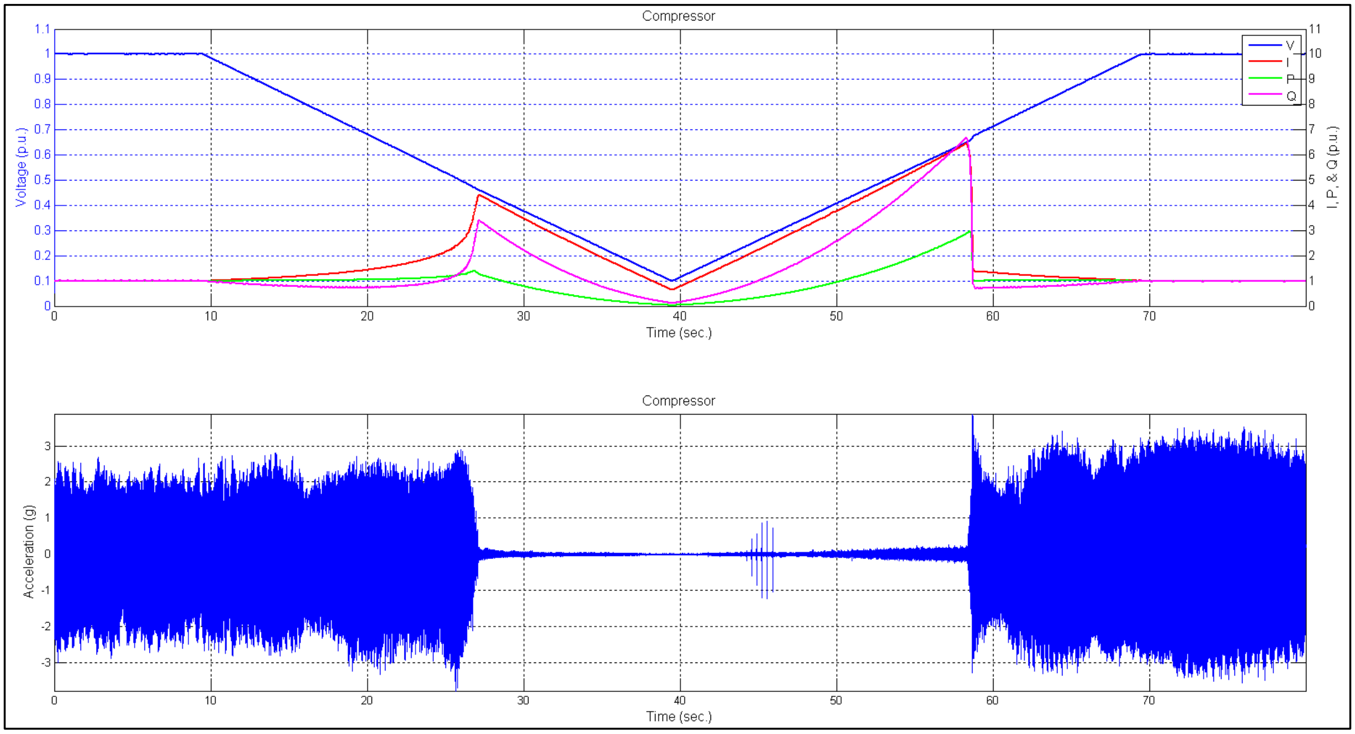

Figure 5.13.3 A/C #3 Compressor Stalling During Voltage Ramp

6.0 AIR CONDITIONER #4 TEST RESULTS

The fourth air conditioner tested is a 4-ton unit operated at 208 V line-to-line. The unit is comprised of a single indoor blower fan motor, outdoor fan motor, and a compressor motor. The specifications for the individual components of A/C #4 are provided in the table below.

Main System		**Compressors**	
Manufacturer	Lennox	Manufacturer	Copeland
Model	KHA048S4DN	Model	ZP42K5E-TF5-130
Size (Tons)	4	Type	Scroll
Voltage (V)	208	Quantity	1
Refrig.	R-410A	RLA (Amps)	13.7
SEER	13	LRA (Amps)	83.1
EER	10.7	Test Press. High (PSI)	446
IEER	-	Test Press. Low (PSI)	236
Condenser Fan		**Blower Motor**	
Drive Type	Direct	Type	Direct
Quantity	1	Quantity	1
Motor HP	1/4	Motor HP	1/2
RPM	825	RPM	Variable
FLA (Amps)	1.7	FLA (Amps)	3.9
Miscellaneous Components			
Contactor(s)	Hartland Controls, 60M1201	Capacitor(s)	Lennox, 100600-03
Transformer	Basier Electric, BE28868003	Phase Balance Relay	-

Table 6.0.1 A/C #4 Specifications

6.1 Compressor Shutdown

A/C #4 was shut down during normal operation using the connected thermostat. The figure below displays the measurements taken at the main service connections as well as the behavior of the individual motors.

The compressor, outdoor fan motor, and indoor fan motor shut down at the same time shortly after triggering the thermostat. Therefore, there was a negligible amount of power consumption from the A/C unit due to the power electronics after the various motors are no longer operating.

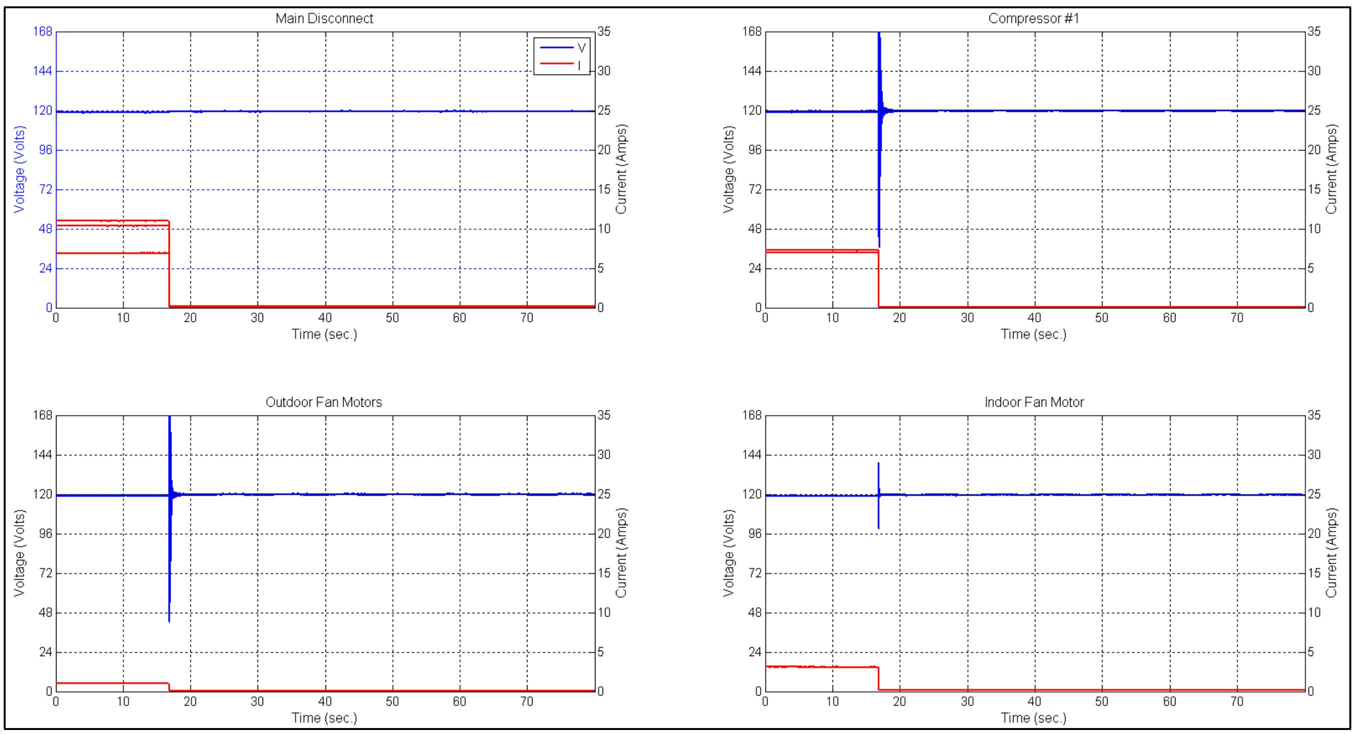

Figure 6.1.1 A/C #4 Compressor Shutdown

6.2 Inrush Current

After starting up A/C unit #4 via the programmable thermostat, the indoor fn motor starts up first followed almost immediately by the compressor and the outdoor fan motors approximately 1.8 cycles later. However the indoor fan motor ramps up without a sudden spike in current. The inrush currents observed at the main disconnect of the unit indicate a maximum value of 81.37 Amps and a duration time of 6 cycles.

Compressor Inrush: Maximum of 74.6 Amps and duration of 6 cycles

Outdoor Fan Motor Inrush: Maximum of 2.4 Amps and duration of 2.4 seconds

Indoor Fan: Maximum of 4.4 Amps and ramps down to nominal within 2.7 seconds

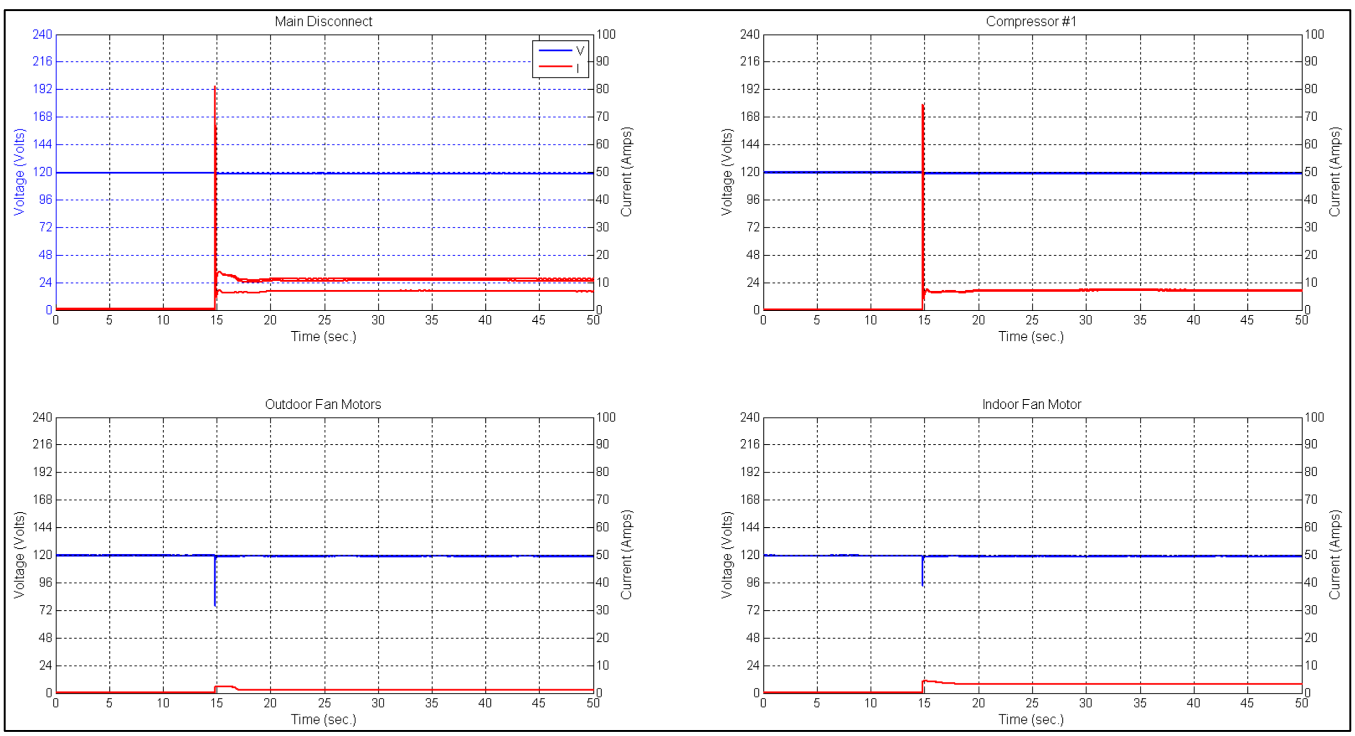

Figure 6.2.1 A/C #4 Inrush Current

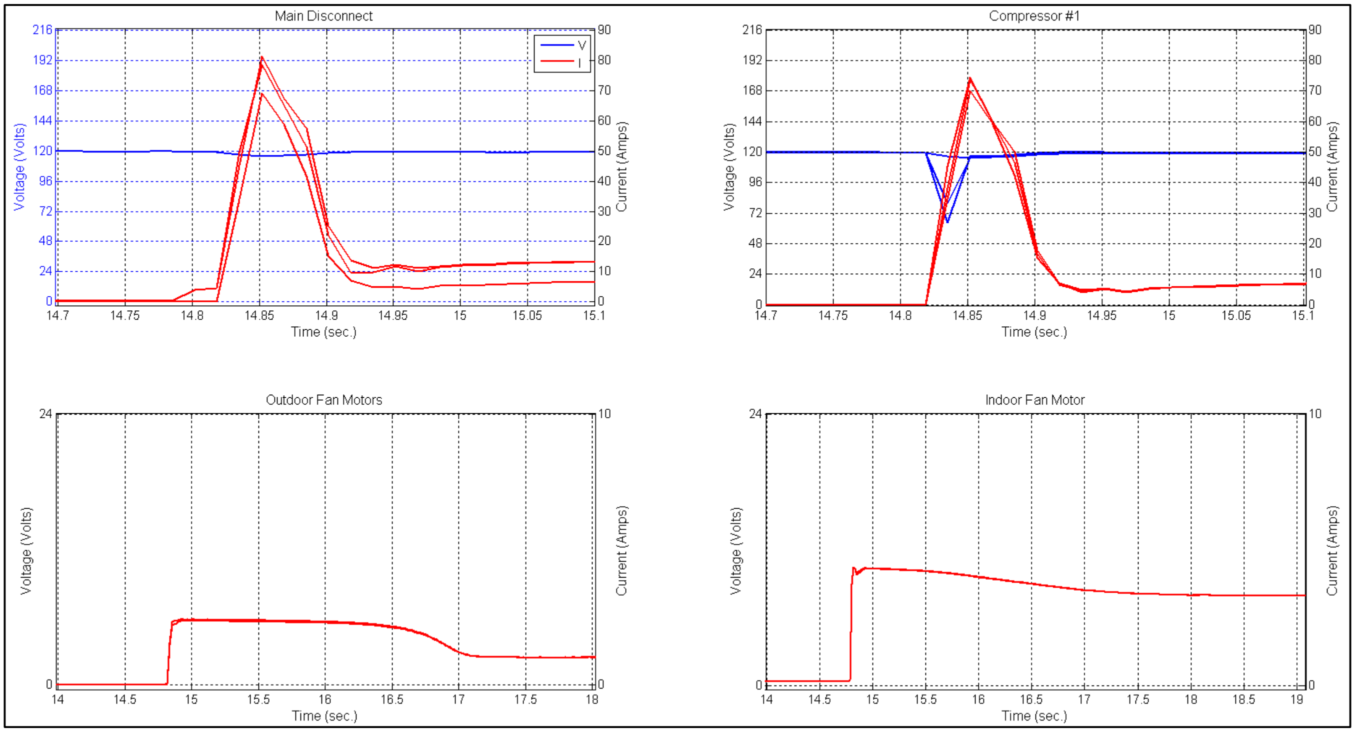

Figure 6.2.2 A/C #4 Inrush Current [Zoom In]

6.3 Balanced & Unbalanced Under-voltages

Control voltage measurements (24 V) were monitored at the thermostat output, an in-series relay output, and contactor coil to help determine the root cause of compressor tripping during A/C #4 under-voltage tests. All balanced tests resulted in the contactor opening before stalling could occur. Stalling only occurred during unbalanced voltage sags. Contactor chattering was repeatedly observed during the voltage step changes during the voltage sag tests. The contactors did not reclose immediately after the voltage recovered during testing due a thermostat or local controller relay. Contactors would only reclose several minutes as the A/C unit began startup operations.

Balanced voltage sags on all three phases in decrements of 10% revealed that the compressor would disconnect at either 60% or 50% nominal voltage for transients with a duration in the range of 3 to 130 cycles. This indicates the unit is on the edge of tripping at 60% voltage. Although there are a couple of exceptions, the contactor typically opens 2 cycles after the start of the voltage sag and did not immediately reclose upon voltage recovery.

The contactor did not dropout and the compressor rode through transients with a duration time of 1 cycle for all sags down to 0% voltage. These ride through conditions do not have associated trip voltages or trip times and are therefore noted as “N/A” or not applicable in the following tables.

The following figure visually displays one of the 130 cycle balanced under-voltage tests. The following table provides the details regarding the compressor contactor operation and control voltage measurements during the various tests. The trip voltage represents the magnitude where the contactor opened and where the control voltage (at the contactor coil, relay output, and thermostat) disappeared. The trip time is how long it took for the contactor to open or the control voltage to dissipate after the start of the voltage sag.

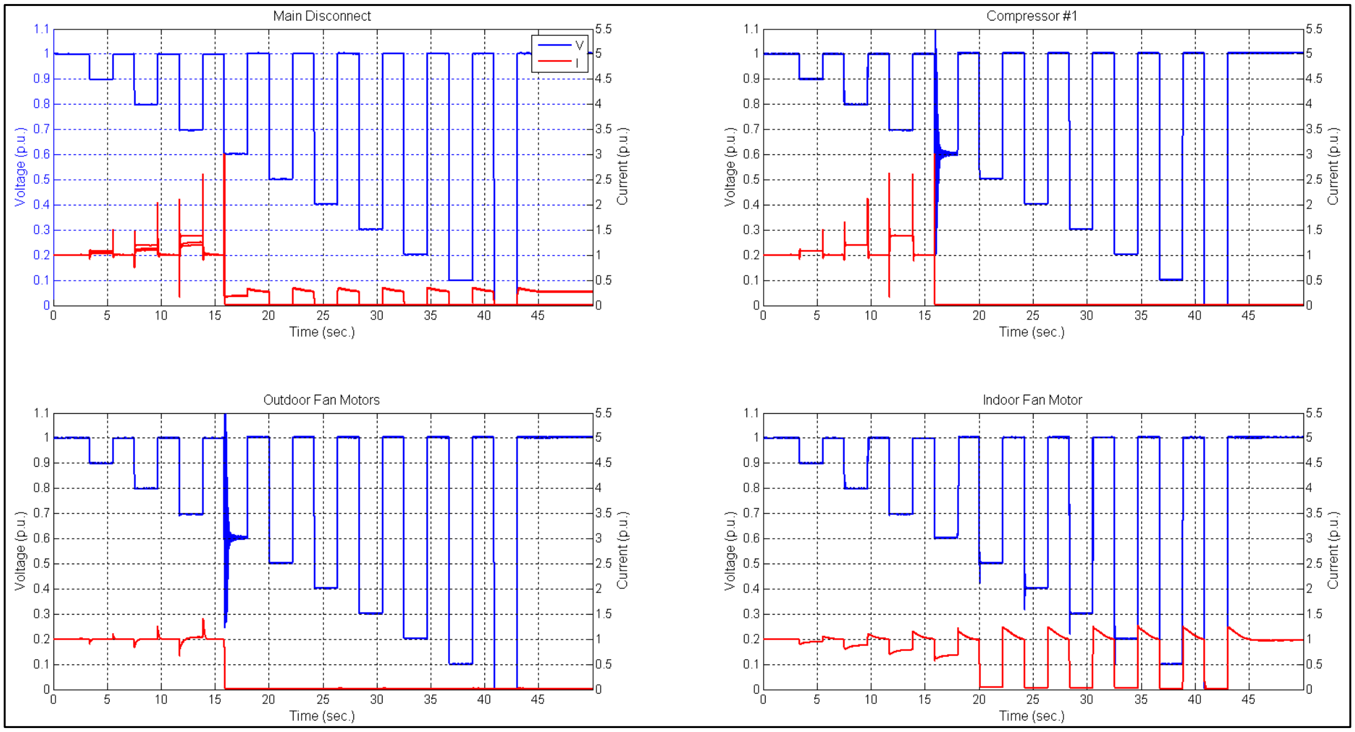

Figure 6.3.1 A/C #4 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor		Contactor Coil		Relay Output		Thermostat (Y)	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
100%, 90%, 80%,... 0%	130	50%	2	50%	3	50%	6	50%	6
		50%	2	50%	4	50%	6	50%	6
		60%	2	60%	9	60%	9	60%	9
100%, 90%, 80%,... 0%	12	60%	2	60%	9	60%	9	60%	9
		60%	2	60%	15	60%	15	60%	15
		60%	2	60%	8	60%	8	60%	8
100%, 90%, 80%,... 0%	9	50%	1	50%	2	50%	6	50%	6
		50%	1	50%	2	50%	6	50%	6
		60%	2	60%	13	60%	13	60%	13
100%, 90%, 80%,... 0%	6	50%	2	50%	2	50%	5	50%	5
		50%	2	50%	3	50%	6	50%	6
		50%	2	50%	3	50%	6	50%	6
100%, 90%, 80%,... 0%	3	50%	2	50%	3	50%	6	50%	6
		50%	2	50%	3	50%	6	50%	6
		50%	2	50%	3	50%	6	50%	6
100%, 90%, 80%,... 0%	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

In order to narrow down the voltage where the compressors are disconnected and dropout occurs for the contactor and/or controls, additional balanced under-voltage tests were performed in decrements of 1% nominal voltage. Additionally, the same test was performed where the contactor coil is energized directly by service voltage using the step-down controls transformer. The contacts opened or began intensely chattering between 60% and 58% nominal voltage and opened as quickly as 2.4 cycles after the voltage sag began. The following table provides the details of the various 1% voltage decrement tests.

Under-Voltage Transient		Compressor	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)
70%, 69%, 68%, …	130	60%	21
70%, 69%, 68%, …	130	60%	18.6
70%, 69%, 68%, …	3	58%	2.4
70%, 69%, 68%, …	130	60%	2.4
70%, 69%, 68%, …	130	58%	2.4

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

Unbalanced under-voltages on A/C unit #4 resulted in lower magnitude trip voltages and trip times because the controls (including the contactor coil) are energized using one of the line-to-line supply voltages, phase A to phase B. As a result of the controls configuration phase A to B under-voltages share results similar to those of the balanced under-voltage tests. Additionally, phase C under-voltage transients do not cause contactor dropout, only voltage ride-through for under-voltage magnitudes.

Stalling behavior was also discovered during the 130 cycle unbalanced under-voltages for $V_{\Phi B-\Phi C}$ and $V_{\Phi C-\Phi A}$. When phases B and C experience under-voltage, the compressor takes approximately 27 cycles to completely stall at 20% nominal voltage before tripping off at 10% nominal voltage. When phases C and A experience under-voltage, the compressor takes approximately 32 cycles to completely stall at 20% nominal voltage before tripping off at 10% nominal voltage. The compressors restart from stalling after voltage recovers in 4.8 cycles.

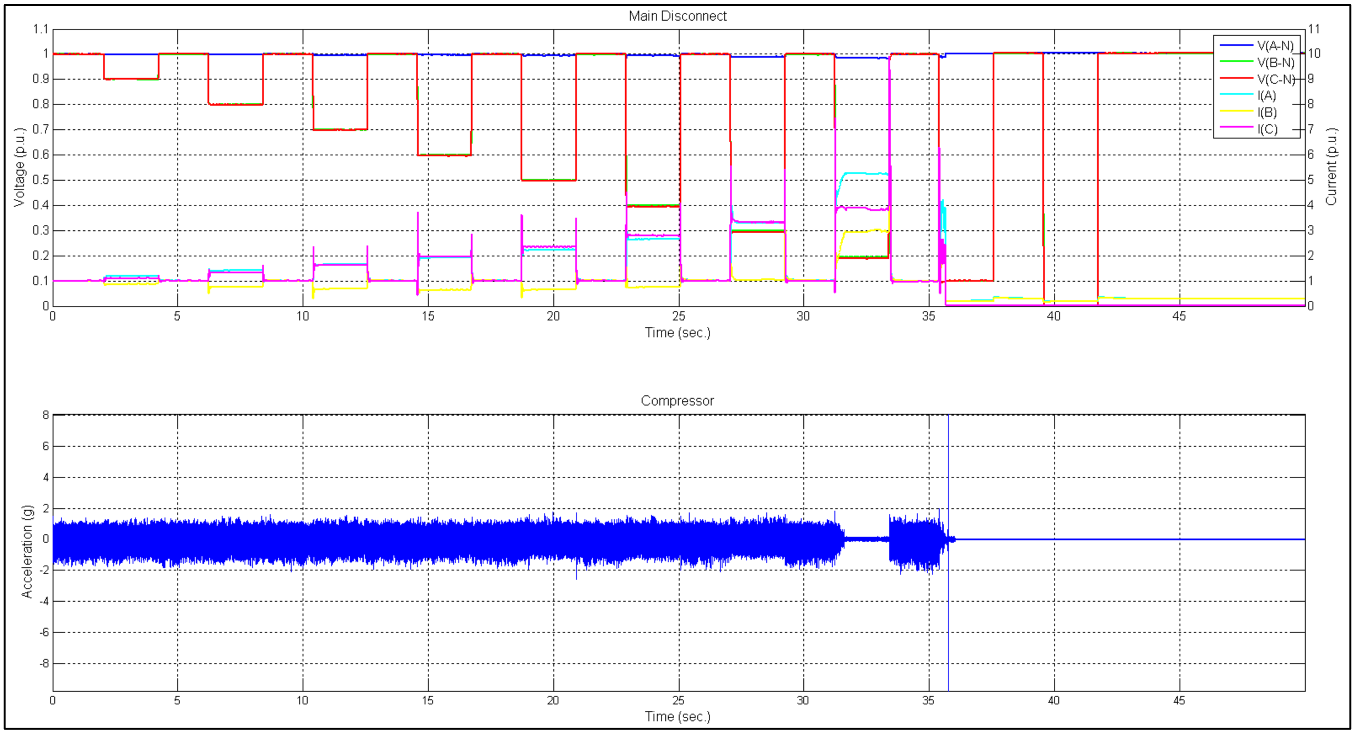

Figure 6.3.2 A/C #4 Unbalanced Under-voltage Response (Phases B & C, 130 cycles)

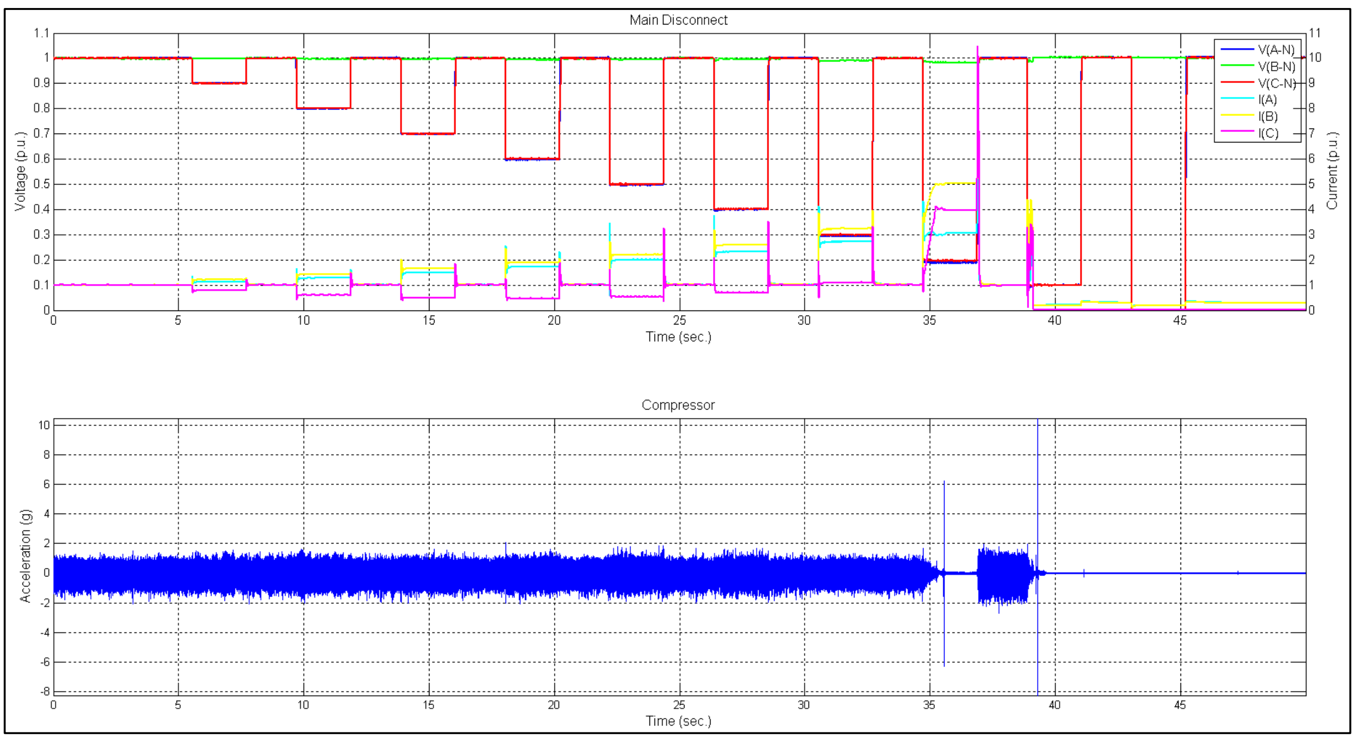

Figure 6.3.3 A/C #4 Unbalanced Under-voltage Response (Phases C & A, 130 cycles)

The remaining under-voltage configurations trip when their line-to-neutral voltages reach 10% to 0% line-to-neutral voltage which correlates with the controls (supplied by $V_{ΦA-ΦB}$) tripping at 61% to 58% line-to-line nominal voltage.

Under-Voltage Transient			Compressor		Contactor Coil		Relay Output		Thermostat (Y)	
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
A	100%, 90%, 80%,... 0%	130	10%	1	10%	15	10%	15	10%	15
		12	0%	2	0%	6	0%	6	0%	6
		9	0%	3	0%	10	0%	10	0%	10
		6	0%	2	0%	6	0%	6	0%	6
		3	0%	1	0%	6	0%	6	0%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 90%, 80%,... 0%	130	10%	2	10%	17	10%	17	10%	17
		12	0%	2	0%	9	0%	9	0%	9
		9	0%	2	0%	6	0%	6	0%	6
		6	0%	2	0%	9	0%	9	0%	9
		3	0%	1	0%	8	0%	8	0%	8
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 90%, 80%,... 0%	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 90%, 80%,... 0%	130	50%	2	50%	3	50%	10	50%	10
		12	50%	2	50%	3	50%	8	50%	8
		6	50%	1	50%	3	50%	6	50%	6
		3	50%	2	50%	4	50%	6	50%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 90%, 80%,... 0%	130	10%	3	10%	9	10%	9	10%	9
		12	0%	14	0%	16	0%	16	0%	16
		9	0%	2	0%	6	0%	6	0%	6
		6	0%	2	0%	7	0%	7	0%	7
		3	0%	2	0%	9	0%	9	0%	9
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 90%, 80%,... 0%	130	10%	3	10%	16	10%	16	10%	16
		12	0%	2	0%	6	0%	6	0%	6
		6	10%	2	10%	7	10%	7	10%	7
		3	0%	2	0%	6	0%	6	0%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

6.4 Balanced & Unbalanced Over-voltages

The A/C unit was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve to avoid damage. Multiple voltage swells were performed in 2% increments for up to 120% nominal voltage for each test. The following figure shows the balanced over-voltage test and the following table specifies the tests performed that resulted in voltage ride-through.

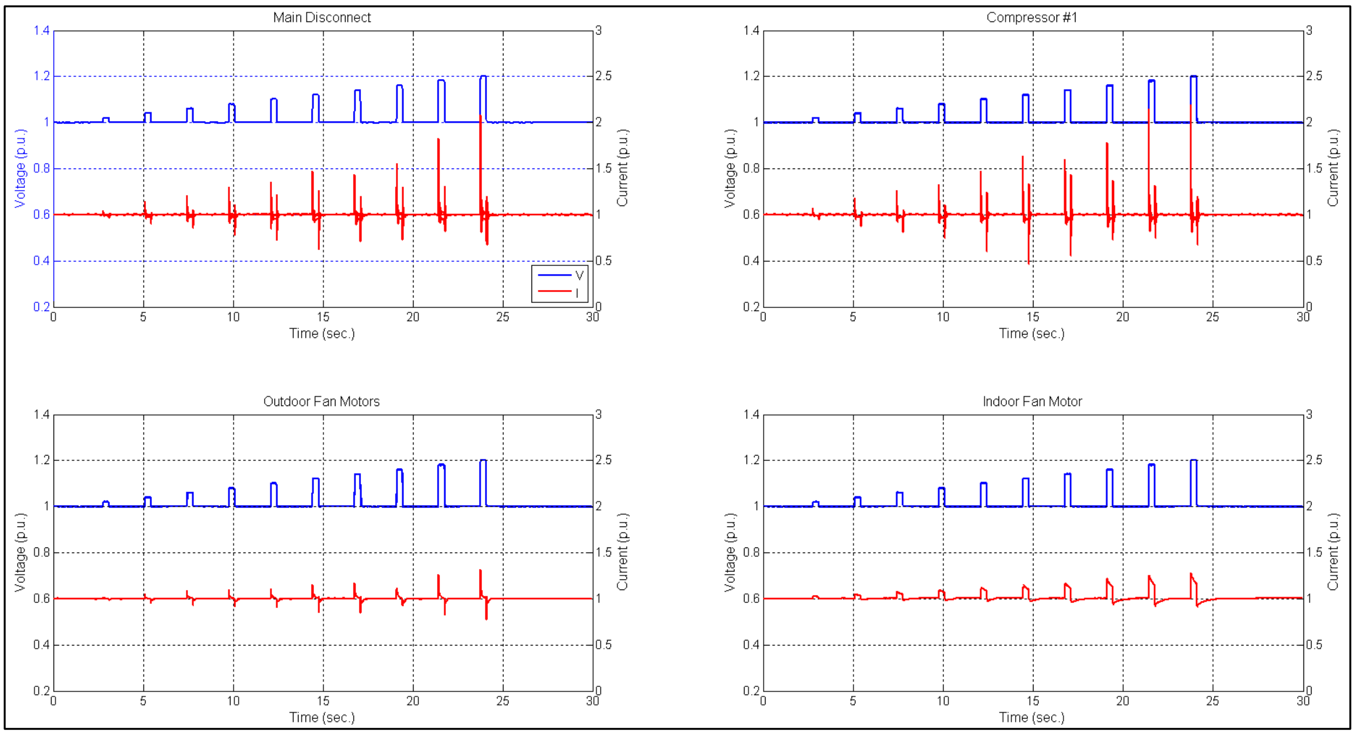

Figure 6.4.1 AC #4 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		Contactor Coil		Relay Output		Thermostat (Y)	
Φ	**Volt Range**	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
ABC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

6.5 Voltage Oscillations

The following figure shows the performance of A/C unit #4 at the main disconnect 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 +6%) for all swing frequencies tested. Conversely real power oscillates with the voltage within -5% of the nominal power consumption. Reactive power consumption experiences the largest oscillations (-15% to -23% deviation) in the same direction as voltage. At higher swing frequencies, deviations become larger both above and below steady state.

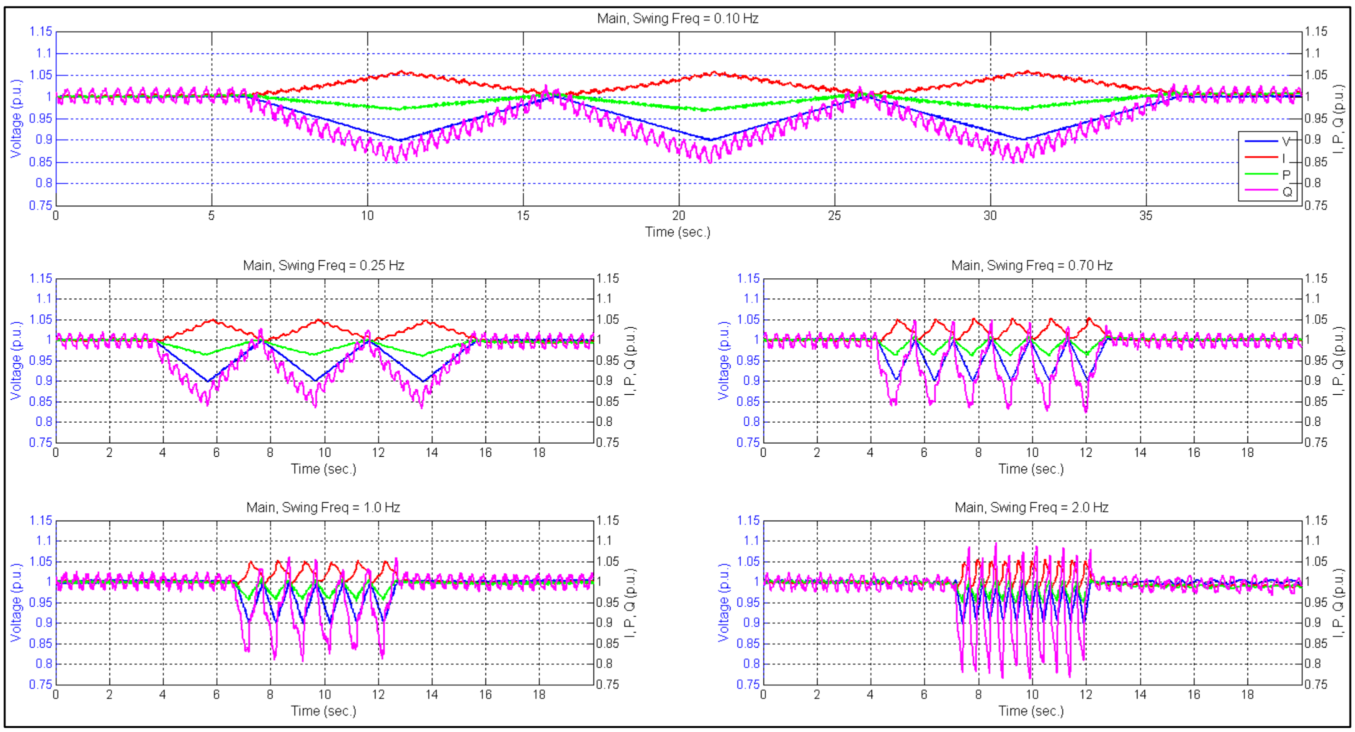

Figure 6.5.1 AC #4 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

6.6 Under-frequency Events

After subjecting A/C #4 to multiple under-frequency transients with different duration times, the device does not appear to have under-frequency protection down to 58 Hz. The unit simply rides through these frequency conditions. The following figure and table identify the tests that were performed.

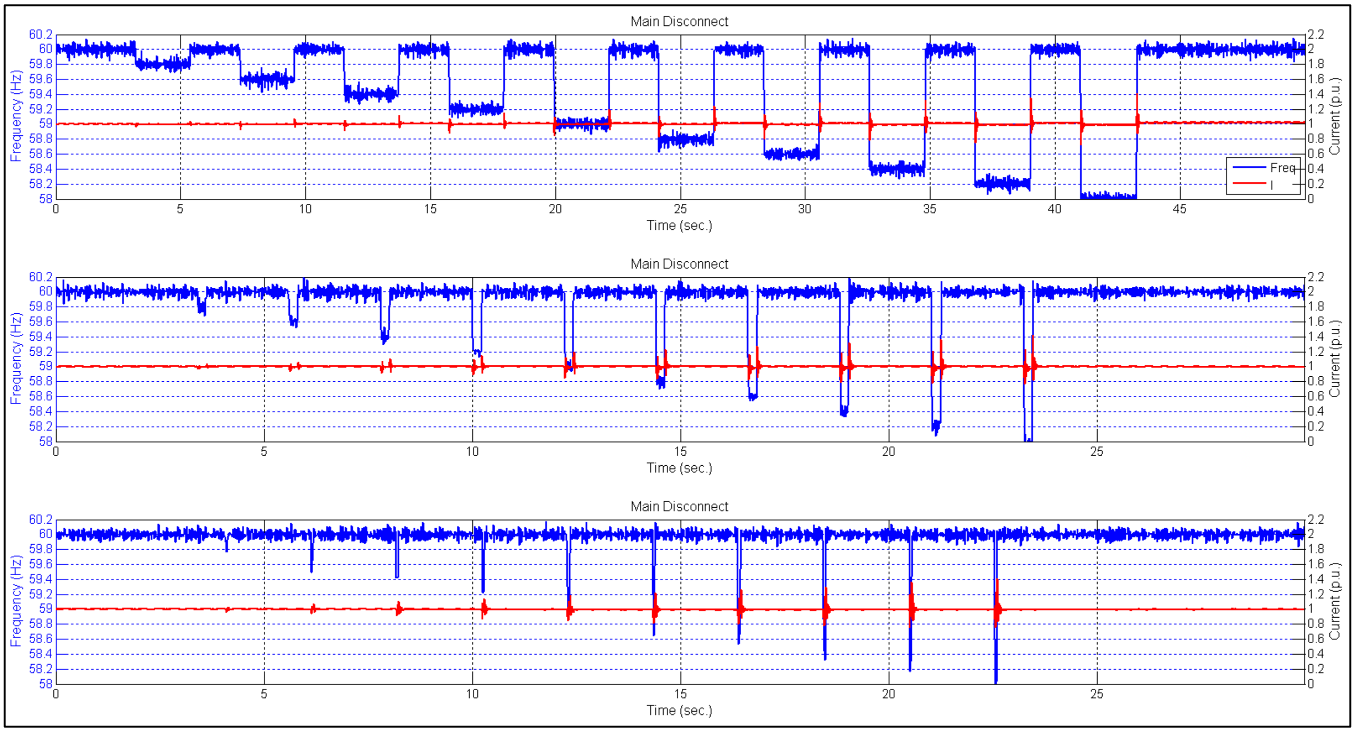

Figure 6.6.1 A/C #4 Under-frequency Response (130, 12, 3 cycles)

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

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

6.7 Over-frequency Events

Similar to the under-frequency tests, A/C #4 was subjected over-frequency transients with different duration times up to 62 Hz. The unit did not trigger any over-frequency protection and continued operating as normal. The following figure and table identify the over-frequency tests that were performed.

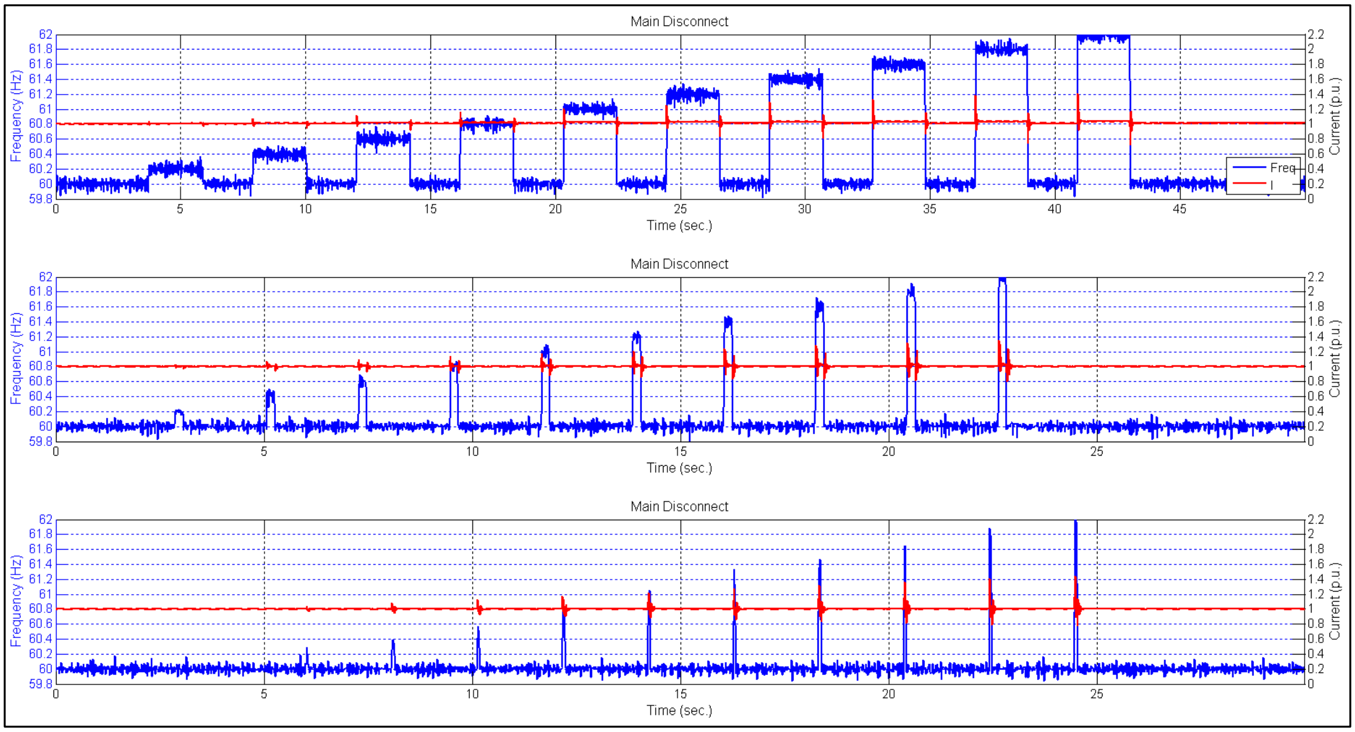

Figure 6.7.1 A/C #4 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor		Contactor Coil		Relay Output		Thermostat (Y)	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 60.2Hz, 60.4Hz,... 62Hz	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

6.8 Frequency Oscillations

The following figure shows the performance of A/C unit #4 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates.

Current, real power, and reactive power remain within +3% of their nominal values for swing frequencies up to 0.70 Hz. Faster oscillation rates, such as swing frequencies of 1 and 2 Hz, reveal deviation up to +4% from their nominal consumption values.

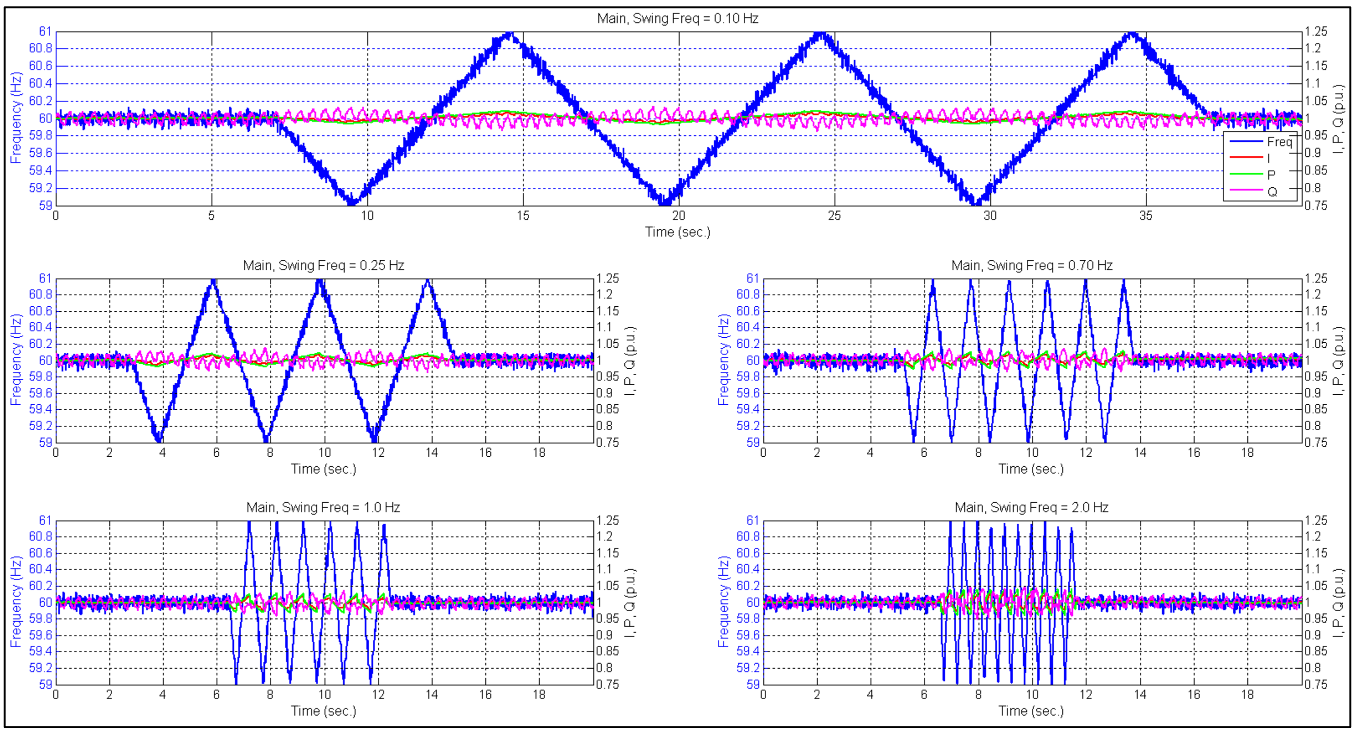

Figure 6.8.1 A/C #4 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

6.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit was found to trip when ramping down to 50% nominal voltage. Therefore the following figure shows the load performance at different voltage levels during voltage ramping down to 60% of nominal.

Current ramps up opposite of voltage to approximately 45% above nominal. Real power consumption reduces by 10% to 13% below nominal during the voltage ramps at different ramp rates. Reactive power deviates the greatest by 32% to 39% below its nominal value.

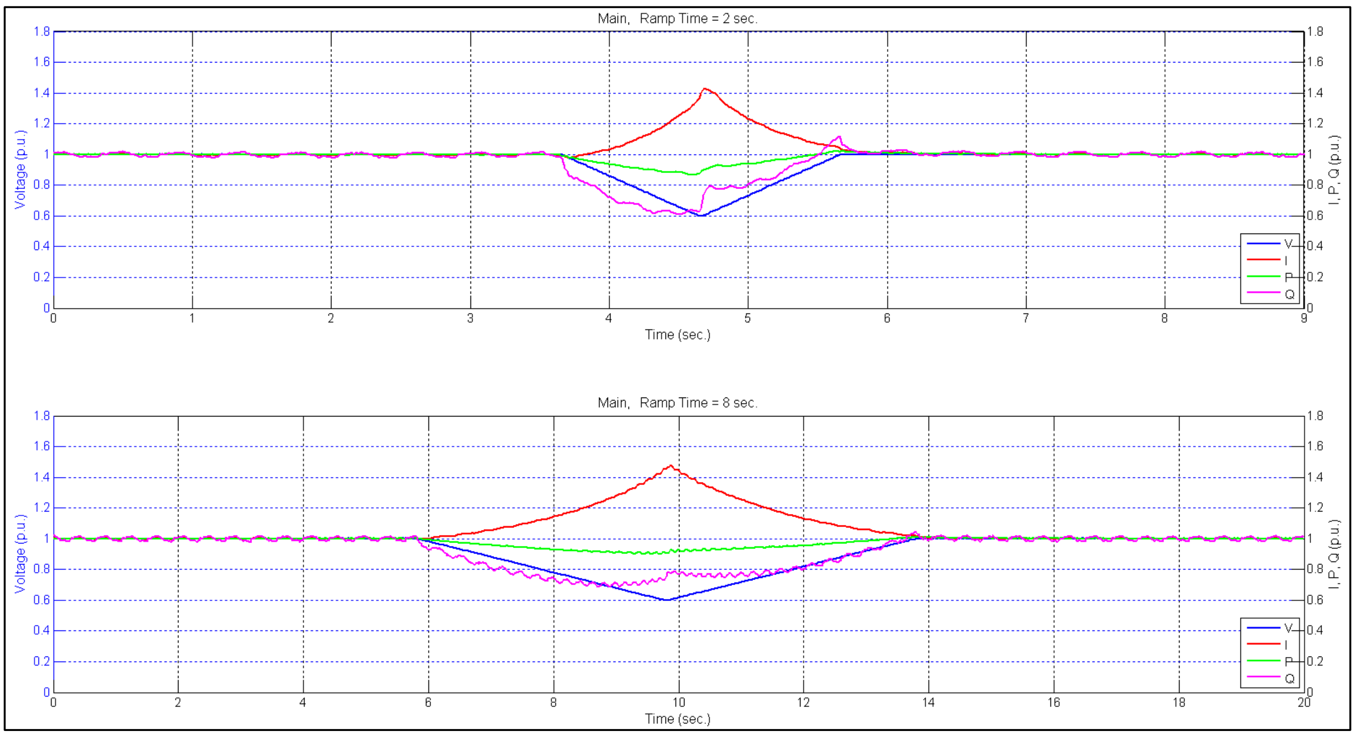

Figure 6.9.1 A/C #4 Voltage Ramp Down to 60% (2 & 8 sec.)

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

Current is slightly reduced by approximately 3% below nominal. Real power gradually ramps up to a maximum of 4% above steady state. Reactive power increase to approximately 21% above of nominal reactive load consumption.

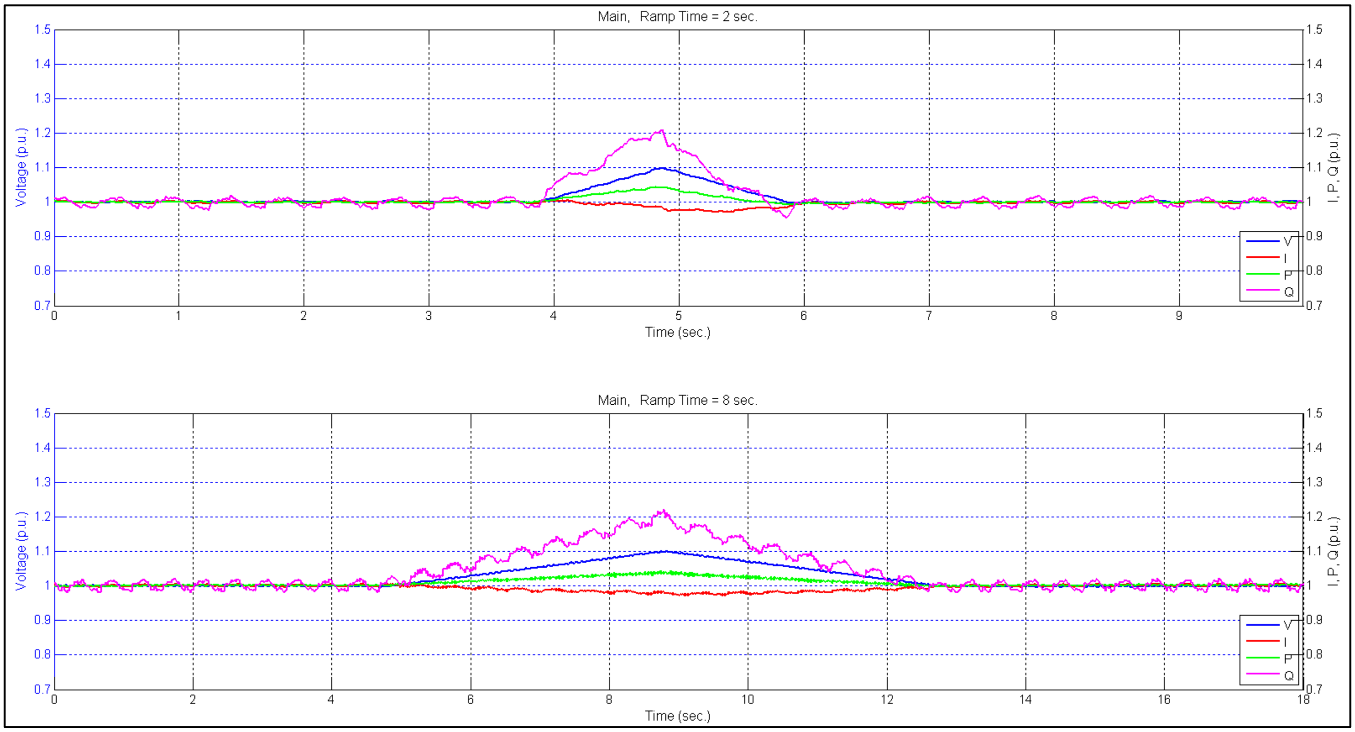

Figure 6.9.2 A/C #4 Voltage Ramp Up to 110% (in 2 & 8 sec.)

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 magnitude is reduced to 8% below its nominal output during the under-frequency condition. Real power consumption slowly ramps down to approximately 19% below steady state. In contrast, reactive power actually ramps up to a maximum of 32% above of its normal consumption.

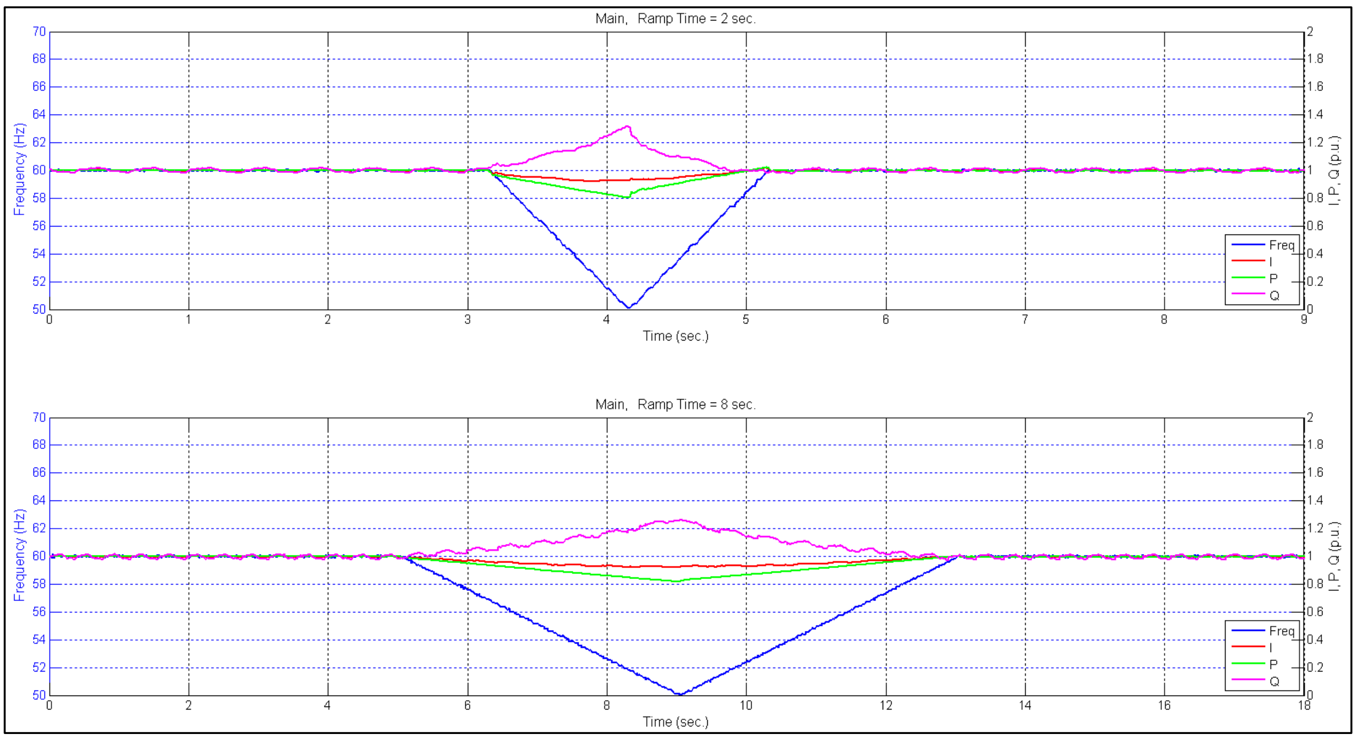

Figure 6.10.1 A/C #4 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

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 and real power are observed ramping up with frequency until peaking at 17% and 21% above their respective nominal values. Reactive power consumption is slowly reduced by nearly 7% below steady state during the frequency ramp.

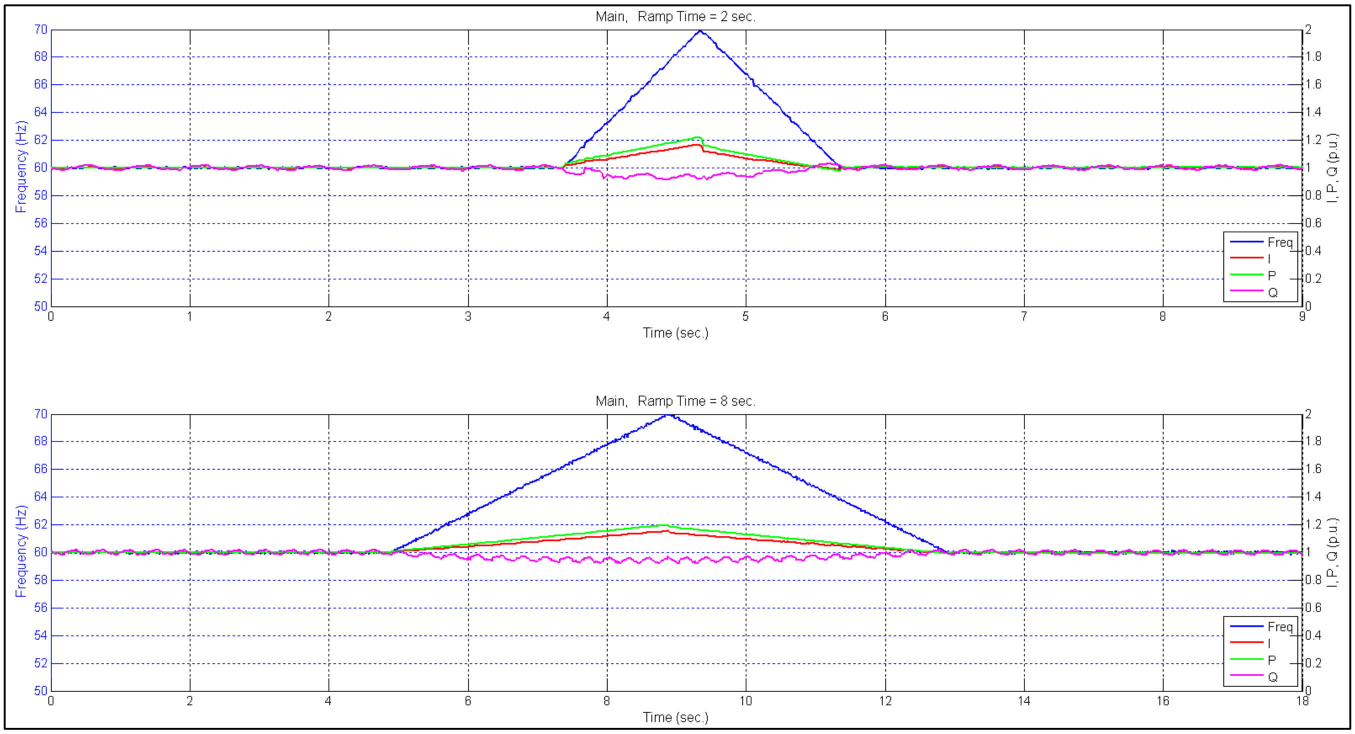

Figure 6.10.2 A/C #4 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

6.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times to calculate the harmonic contribution of A/C unit #4 to the grid. The total harmonic distortion of current on all phases was determined to be less 2% of the fundamental. The following table gives the total harmonic distortion for each phase ad the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)					
	$V_{A\ (L-N)}$	$V_{B\ (L-N)}$	$V_{C\ (L-N)}$	I_A	I_B	I_C
1	0.18	0.20	0.16	1.54	1.37	1.92
2	0.18	0.20	0.16	1.54	1.36	1.91
3	0.18	0.20	0.16	1.54	1.36	1.91

Table 6.11.1 A/C #4 Total Harmonic Distortion

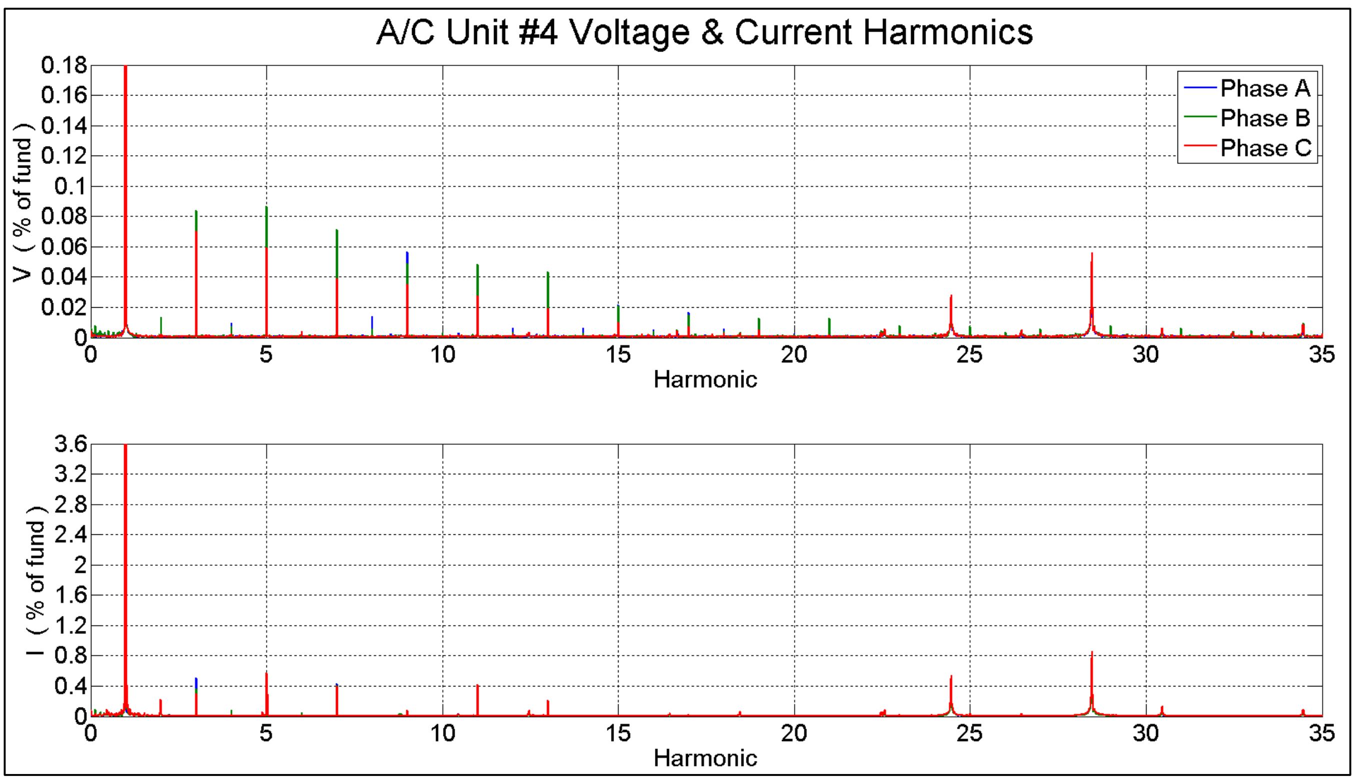

Figure 6.11.1 A/C #4 Harmonics Contribution

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. Outdoor conditions resulted in mild loading of the single compressor operating at approximately 60% of the rated load amps.

Current increases by approximately 0.37% of nominal current for every 1% decrease in nominal voltage. Real power is observed reducing at an average of 0.46% nominal for every 1% drop in voltage. Reactive power also steps down with the voltage, decreasing by 1.45% nominal reactive power for every 1% decrease in nominal voltage.

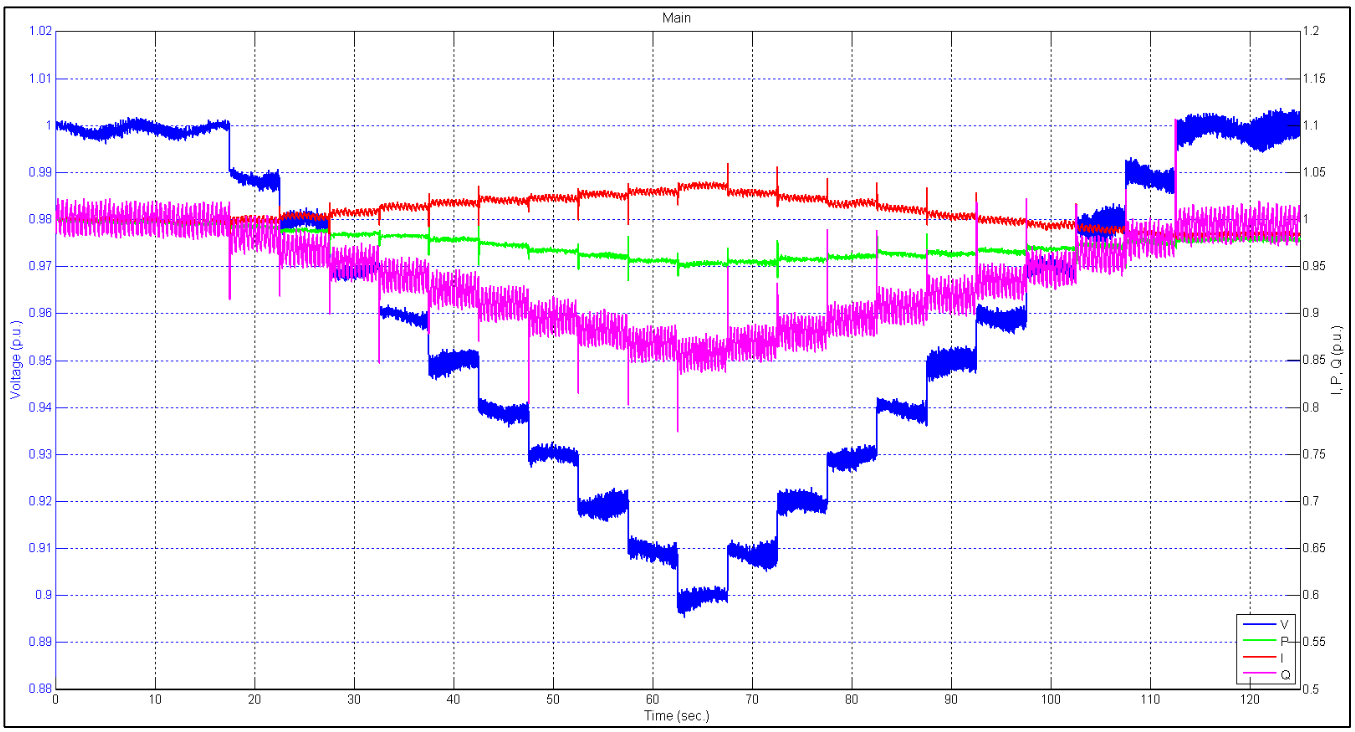

Figure 6.12.1 A/C #4 CVR Response Down to 90% Voltage

Alternatively, the service voltage at A/C #4 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 remains relatively close to steady state by not falling below 2% of nominal over the course the entire CVR test. Real power similarly stays near steady state conditions, only increasing consumption by as much as 2% consumption. Reactive power is observed stepping up with the voltage and increases by 1.8% nominal reactive power for every 1% increase in nominal voltage.

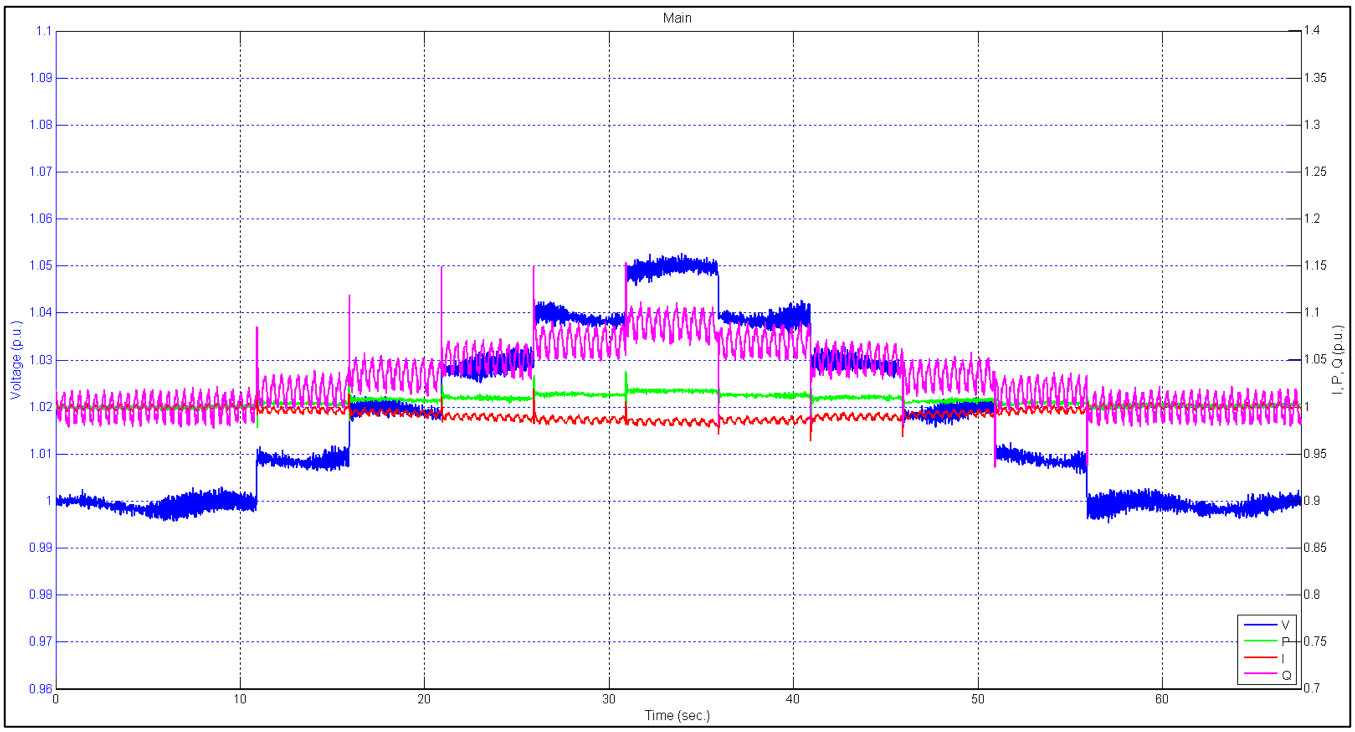

Figure 6.12.2 A/C #4 CVR Response Up to 105% Voltage

6.13 Compressor Stalling

While A/C unit #4 did reveal stalling behavior when two of its phases experienced under-voltages, compressor stalling did not occur during balanced under-voltage conditions. The compressor would shut down due to the contactor opening before reaching a voltage magnitude that could potentially cause stalling. Additionally, the unit would restart normally after the contactor reclosed several minutes later. Therefore several additional undervoltage tests were performed after making modifications to the device controls in order to induce compressor stalling behavior during balanced under-voltage conditions. Rather than using the service voltage from the main terminals of the A/C unit to serve the step-down transformer (24 V output) and power the controls, a separate power supply was used to energize these controls (contactor coils, relays, thermostat, etc.) to bypass any dropout behavior.

Prior tests revealed that dropout had occurred at 50% which was used as a starting point for these additional under-voltage tests. A series of balanced under-voltage sags were performed in 1% voltage decrements with duration times of 3 seconds as shown in the following figures. The compressor began stalling during the 49% voltage dip but did not stall immediately. The A/C unit takes approximately 1.2 seconds to fully stall and enter locked rotor condition. Notice that stalling was identified by the dramatic increase in current and reactive power as well as the reduced mechanical vibration of the compressor. Lower voltage magnitudes resulted in faster stalling behavior as witnessed when stalling occurs within 22.2 cycles at 41% nominal voltage.

The compressor consistently restarts from stalling after voltage recovers following each voltage sag. This restarting behavior typically occurs within 5 cycles after voltage returns to nominal. Voltage was also held at 49% voltage indefinitely which caused thermal overload protection to occur nearly 54 seconds after stalling began.

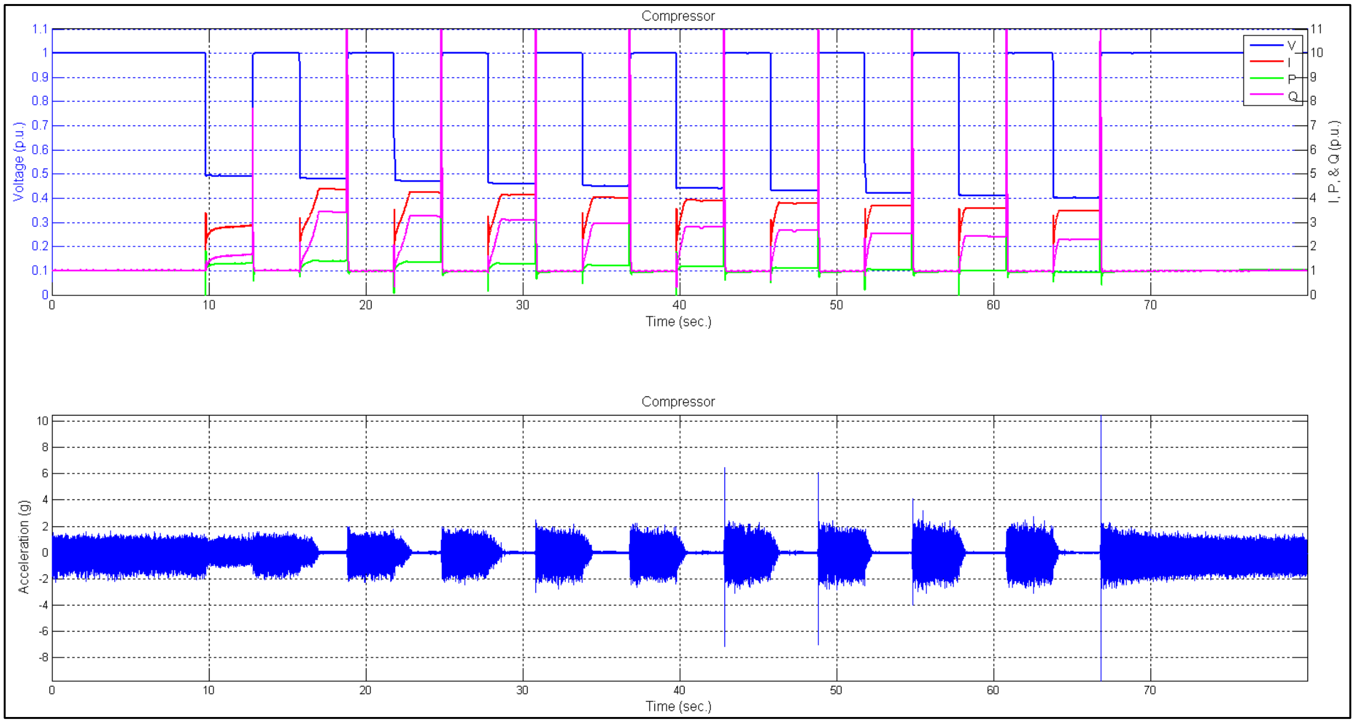

Figure 6.13.1 A/C #4 Compressor Stalling During Under-voltages (50% to 41% voltage)

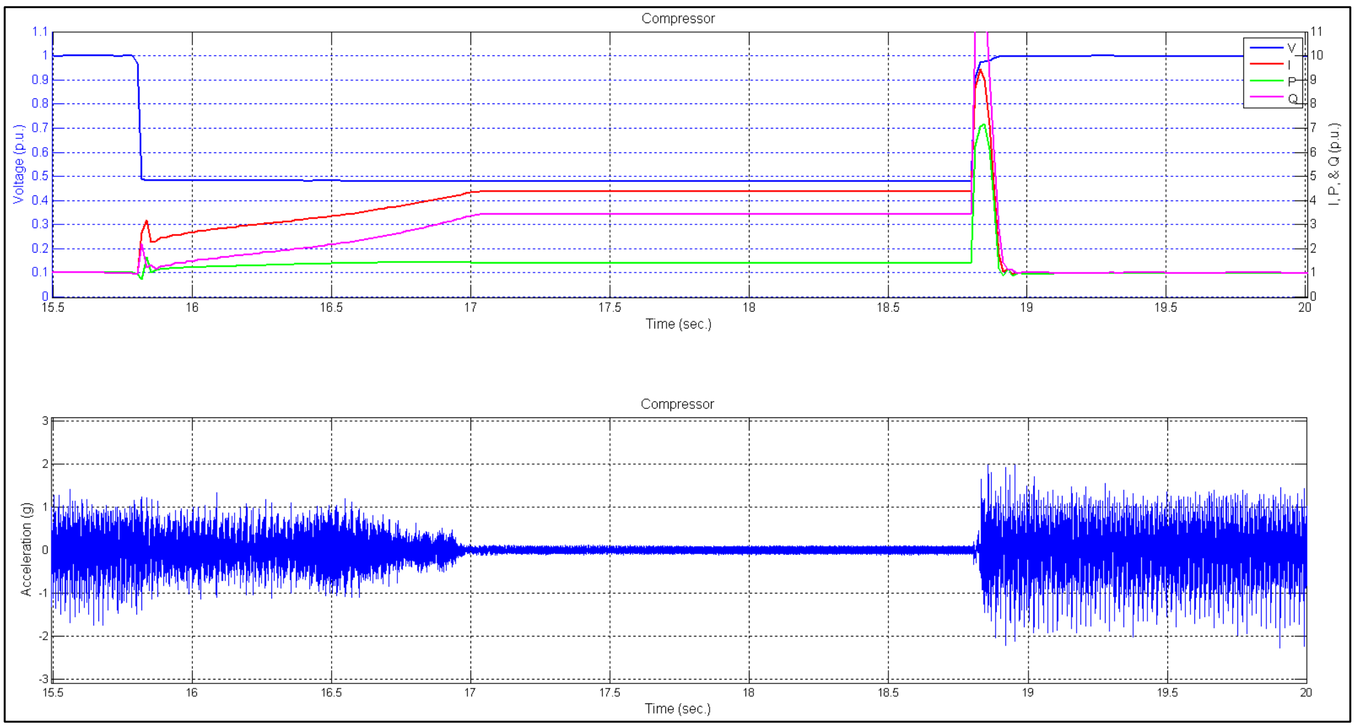

Figure 6.13.2 A/C #4 Compressor Stalling During Under-voltage (49% voltage)

Additionally, a voltage ramp test was performed to capture the compressor's current, real power, and reactive power consumption at different voltage levels as shown in the figure below. At the stalling point current, real power, and reactive power reached 4.2 pu, 1.4 pu, and 3.2 pu. At the restarting point current, real power, and reactive power increased to as large as 6.3 pu, 3.1 pu, and 6.6 pu.

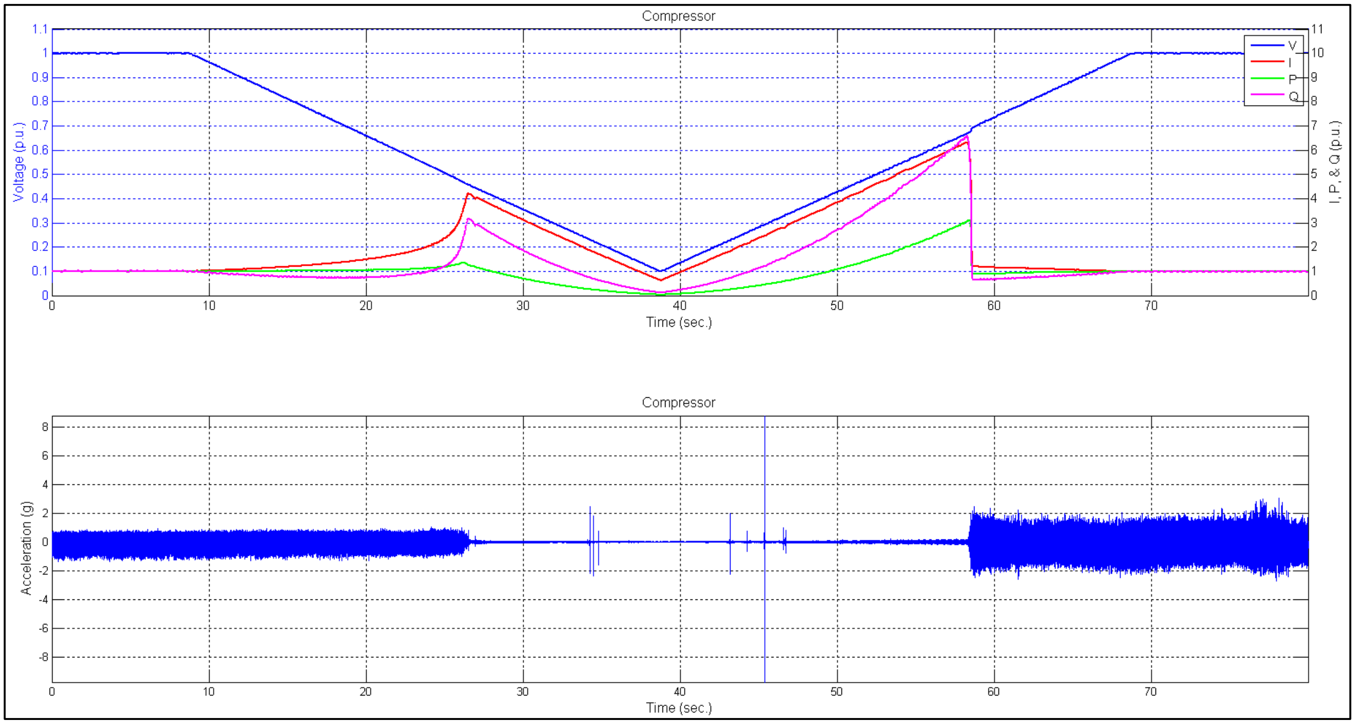

Figure 6.13.3   A/C #4 Compressor Stalling During Voltage Ramp

7.0 AIR CONDITIONER #5 TEST RESULTS

The fifth air conditioner tested is a 4-ton unit operated at 208 V line-to-line. The unit is comprised of a single indoor blower fan motor, outdoor fan motor, and a compressor motor. The specifications for the individual components of A/C #5 are provided in the table below.

Main System		**Compressors**	
Manufacturer	Goodman	Manufacturer	Copeland
Model	CPH0480153DAXX	Model	ZP39K5E-TF5-130
Size (Tons)	4	Type	Scroll
Voltage (V)	208	Quantity	1
Refrig.	R-410A	RLA (Amps)	13.1
SEER	13	LRA (Amps)	83
EER	11.3	Test Press. High (PSI)	446
IEER	-	Test Press. Low (PSI)	236
Condenser Fan		**Blower Motor**	
Drive Type	Direct	Type	Direct
Quantity	1	Quantity	1
Motor HP	1/2	Motor HP	1/2
RPM	1090	RPM	1000
FLA (Amps)	1.4	FLA (Amps)	2.9
Miscellaneous Components			
Contactor(s)	Siemens, 42AF35AJAOI	Capacitor(s)	CBB, CQC02002002590
Transformer	Tyco Electronics, B141643	Phase Balance Relay	-

Table 7.0.1 A/C #5 Specifications

7.1 Compressor Shutdown

A/C #5 was shut down during normal operation using the connected thermostat. The figure below displays the measurements taken at the main service connections as well as the behavior of the individual motors.

The compressor and outdoor fan motor shut down at the same time shortly after triggering the thermostat. The only power consumption after the compressor shuts down was from the single-phase indoor fan motor that is pulling 1.5 Amps (total of 300 W or 350 VA). The indoor fan motor shuts down approximately 65 seconds after the other components.

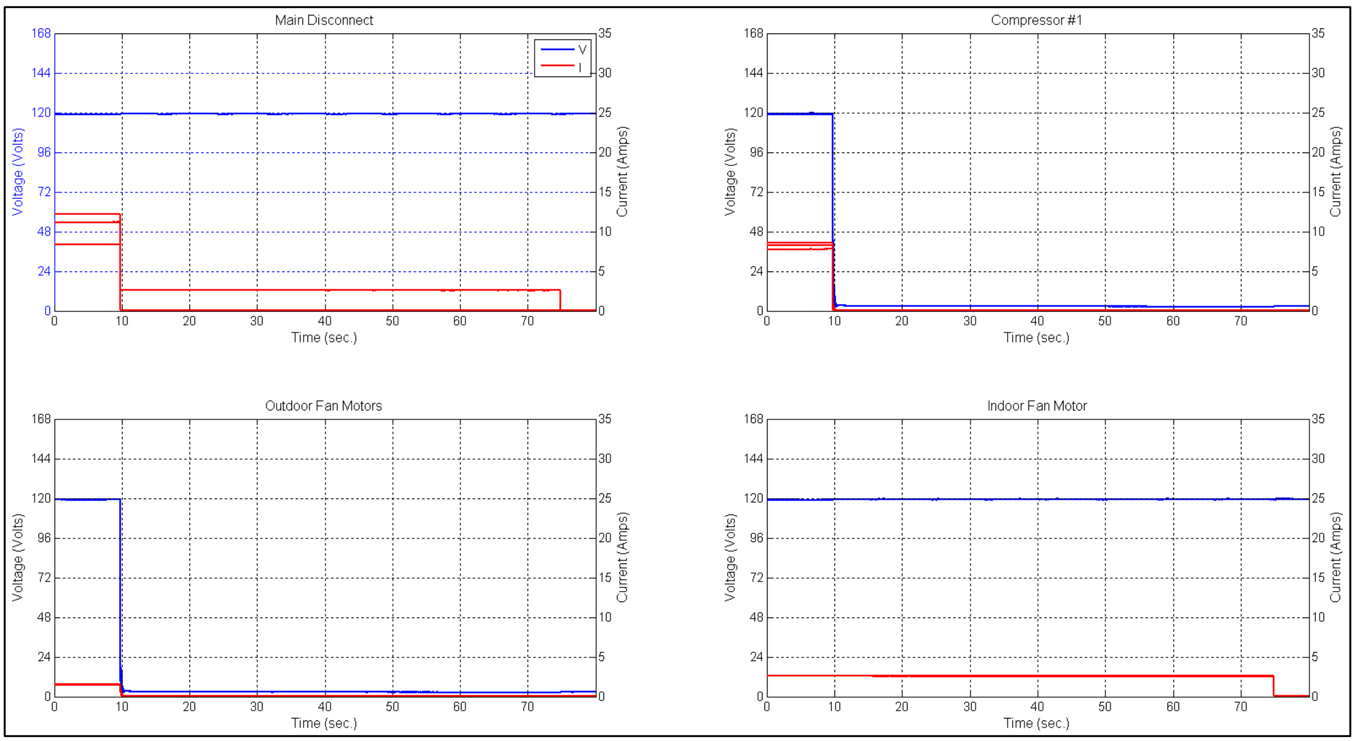

Figure 7.1.1 A/C #5 Compressor Shutdown

7.2 Inrush Current

After starting up A/C unit #5 via the programmable thermostat, the compressor and the outdoor fan motors start up at the same time followed by the indoor fan motor approximately 7 seconds later. The inrush currents observed at the main disconnect of the unit indicate a maximum value of 74.69 Amps and a duration time of 6 cycles.

Compressor Inrush: Maximum of 74.3 Amps and duration of 6 cycles

Outdoor Fan Motor Inrush: Maximum of 2.6 Amps and duration of 5 seconds

Indoor Fan: Maximum of 3.4 Amps and ramps down to nominal within 1.8 seconds

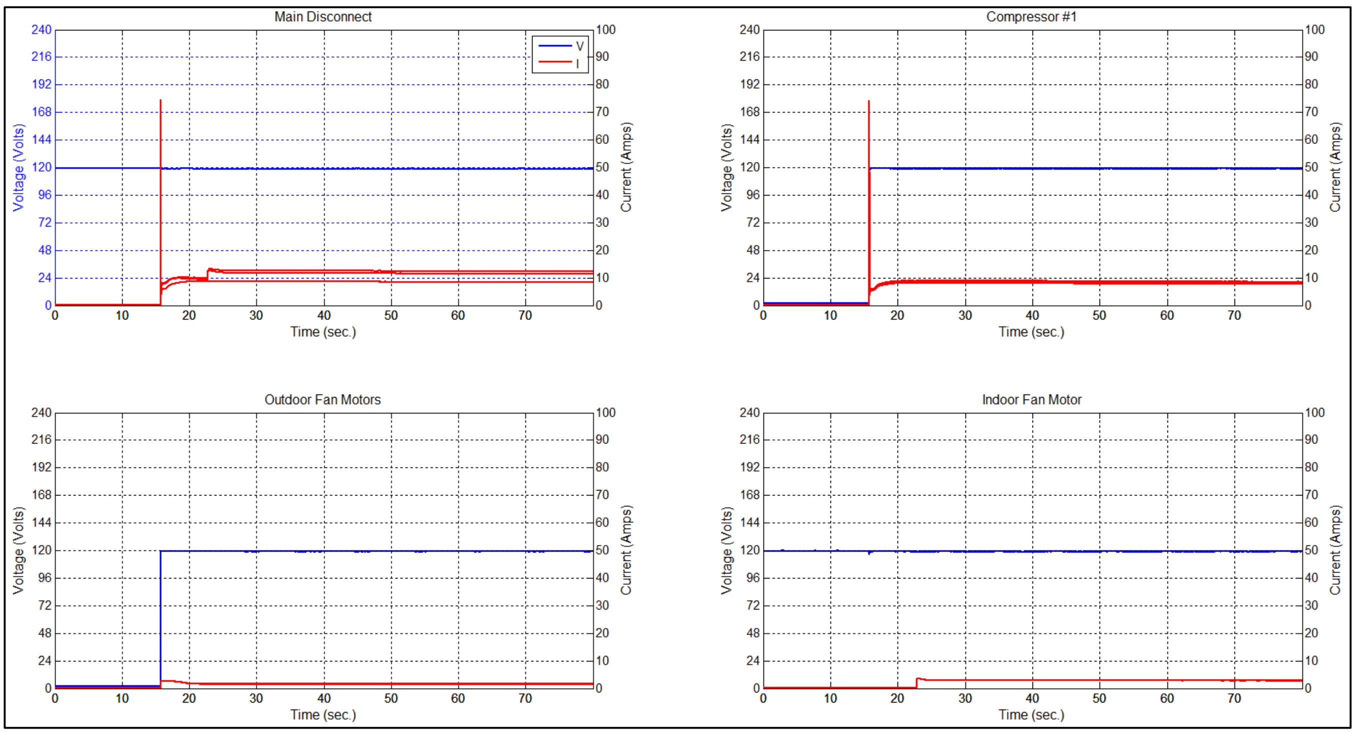

Figure 7.2.1 A/C #5 Inrush Current

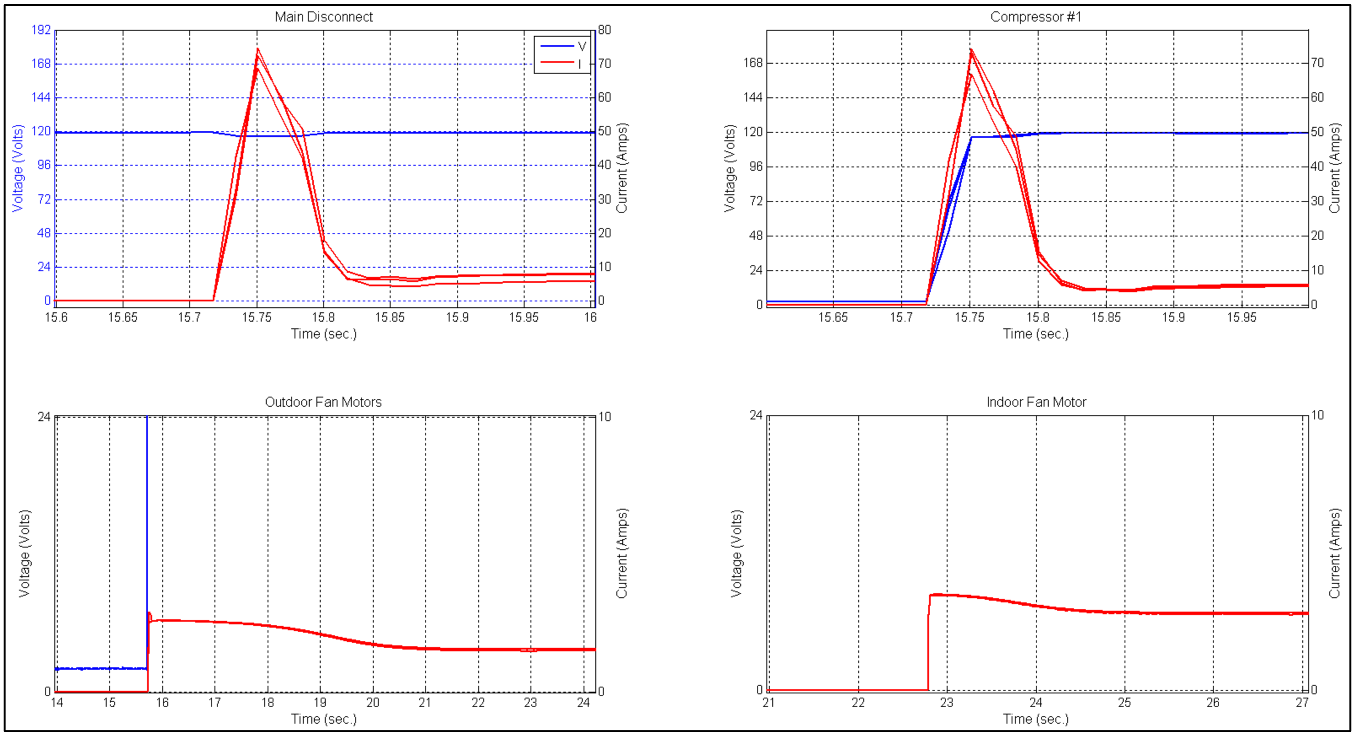

Figure 7.2.2 A/C #5 Inrush Current [Zoom In]

7.3 Balanced & Unbalanced Under-voltages

Control voltage measurements (24 V) were monitored at the thermostat output and contactor coil to help determine the cause of compressor tripping during A/C #5 under-voltage tests and provide the following results. Stalling behavior was only observed during certain two-phase unbalanced under-voltage tests. On the other hand, all balanced under-voltages resulted in the contactor opening before stalling could occur. Contactor chattering was repeatedly observed during the voltage step changes during the voltage sag tests. Data captured several seconds after the disconnection of the compressor did not reveal immediate contactor reclosing during these tests, except for special tests where the contactor control wiring was re-configured. Contactors only reclosed when he A/C unit restarted several minutes after voltage recovered to steady state. This is due to a relay located at the controller or even at the thermostat.

Balanced voltage sags on all three phases in decrements of 10% revealed that the compressor would disconnect after the contactor opened at 50% nominal voltage for transients with a duration in the range of 3 to 130 cycles. The contactor would open between 2 and 7 cycles after the start of the voltage sag and would not reclose immediately after voltage recovered.

The contactor did not dropout for switching transients with a duration time of 1 cycle. “N/A” or “not applicable” represents these cases where no trip voltage or trip time available in the following tables. Therefore the compressor would ride through all of these very quick sags, down to 0% voltage.

The following figure visually displays one of the longer duration balanced under-voltage tests. The following table provides the details regarding the compressor contactor operation and control voltage measurements during the various tests. The trip voltage represents the magnitude where the contactor opened and where the control voltage (at the contactor coil and thermostat) disappeared. The associated trip times after the start of the voltage sag are included as well.

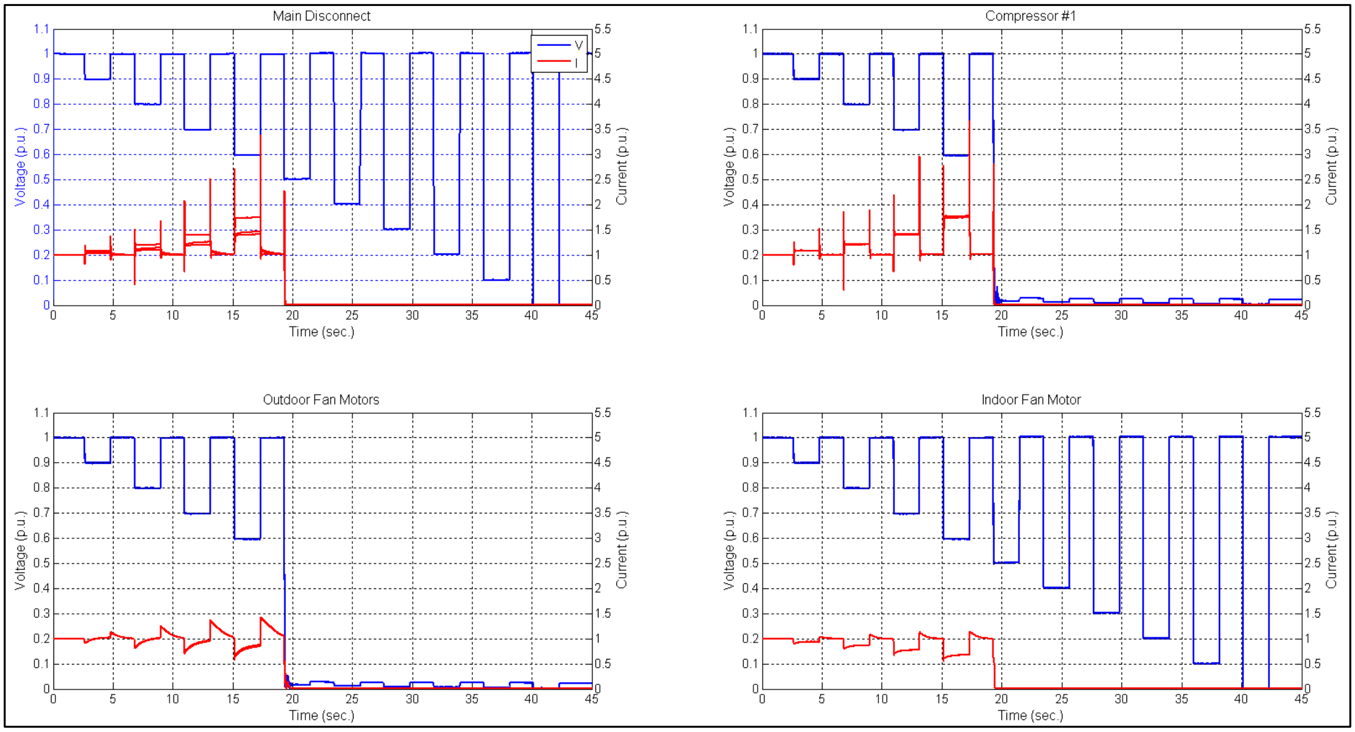

Figure 7.3.1 A/C #5 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		Compressor		Contactor Coil		Thermostat (Y)	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
100%, 90%, 80%,... 0%	130	50%	2	50%	6	50%	6
		50%	3	50%	7	50%	7
		50%	3	50%	6	50%	6
100%, 90%, 80%,... 0%	60	50%	3	50%	7	50%	7
		50%	7	50%	7	50%	7
		50%	4	50%	8	50%	8
100%, 90%, 80%,... 0%	9	50%	6	50%	6	50%	6
		50%	2	50%	8	50%	8
		50%	4	50%	7	50%	7
100%, 90%, 80%,... 0%	6	50%	5	50%	7	50%	7
		50%	2	50%	6	50%	6
		50%	3	50%	6	50%	6
100%, 90%, 80%,... 0%	3	50%	2	50%	7	50%	7
		50%	2	50%	6	50%	6
		50%	2	50%	6	50%	6
100%, 90%, 80%,... 0%	1	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A

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

In order to narrow down the voltage where the contactor is opened, additional balanced under-voltage tests were performed in decrements of 1% nominal voltage. The contactors consistently opened at 59% nominal voltage within 22.2 cycles after the start of the voltage sag. The contactor did not immediately reclose due the local controller and/or thermostat. The following table provides these details for multiple 1% voltage decrement tests.

Under-Voltage Transient		Compressor	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)
60%, 59%, 58%, …	130	59%	22.2
60%, 59%, 58%, …	130	59%	20.4
60%, 59%, 58%, …	130	59%	21

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

Many of the unbalanced under-voltages on A/C unit #5 resulted in lower magnitude trip voltages because the controls (including the contactor coil) are energized using one of the line-to-line supply voltages, phase A to phase B. Therefore phase A to B under-voltages resulted in trip voltages and trip times similar to those observed during balanced under-voltages. Also as a result of the controls configuration, phase C under-voltage transients do not cause contactor dropout and the compressor rides through all of the tested voltage sags.

Stalling behavior was discovered during the 130 cycle unbalanced under-voltages for $V_{\Phi B\text{-}\Phi C}$ and $V_{\Phi C\text{-}\Phi A}$. When phases B and C experience under-voltage, the compressor takes approximately 24.0 cycles to completely stall at 30% nominal voltage and approximately 10.8 cycles to stall at 10% nominal voltage. When phases C and A experience under-voltage, the compressor takes approximately 24.6 cycles to completely stall at 30% nominal voltage and approximately 13.8 cycles at 20% nominal voltage. The compressors restarts from stalling condition within 5 cycles after the voltage sag recovers to nominal. The following two figures display this stalling behavior.

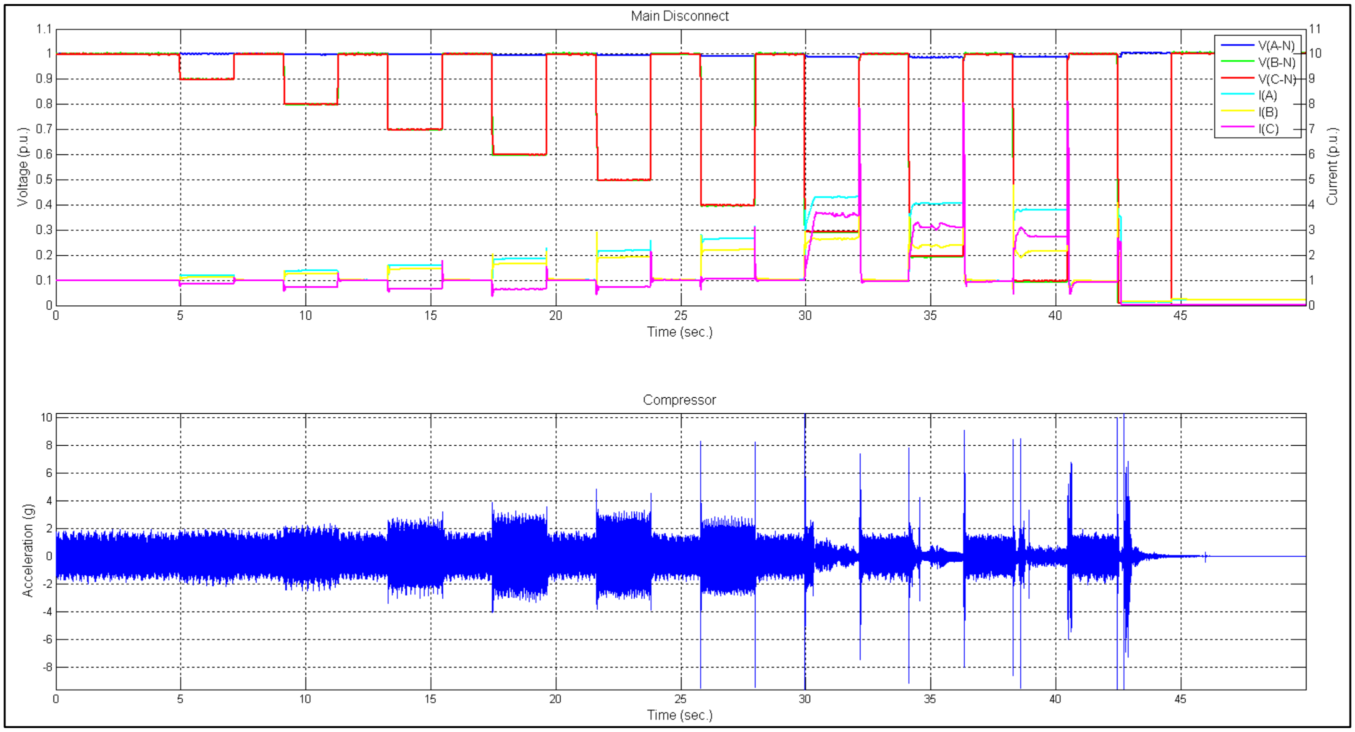

Figure 7.3.2 A/C #5 Unbalanced Under-voltage Response (Phases B & C, 130 cycles)

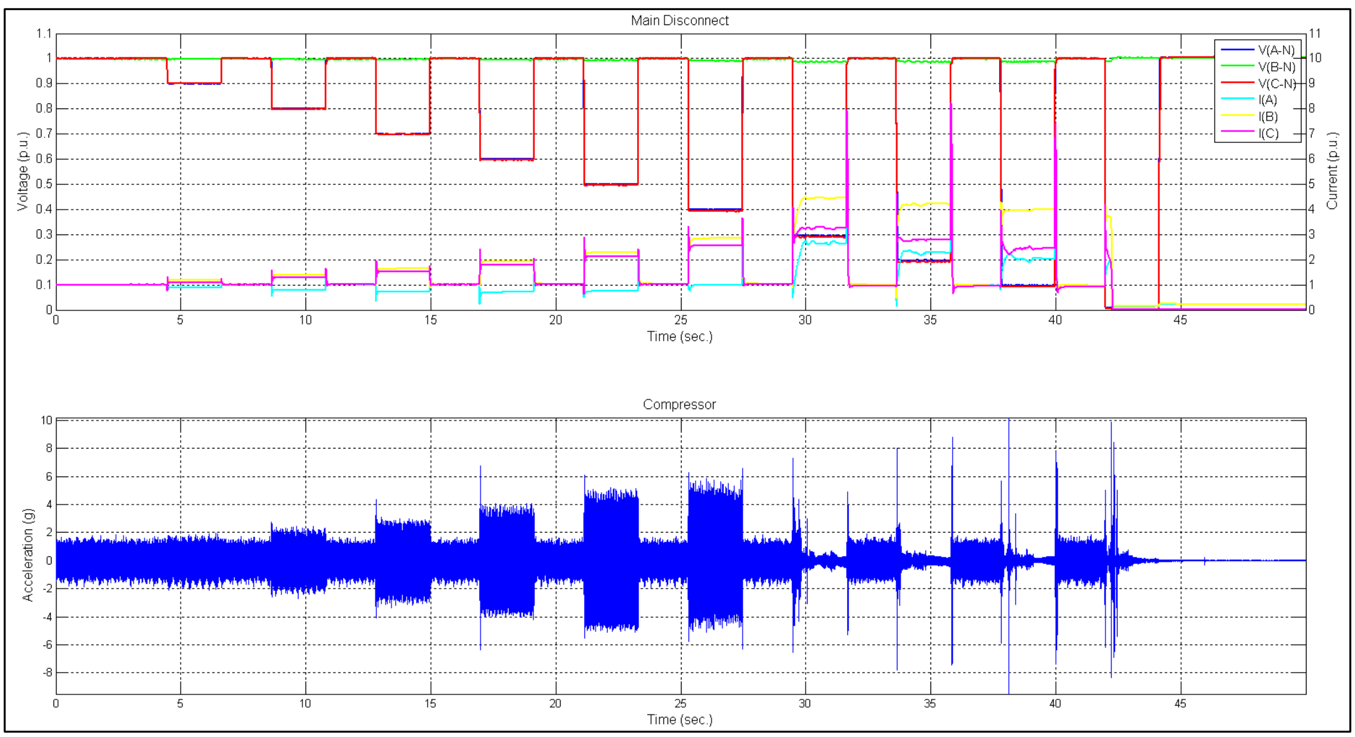

Figure 7.3.3 A/C #5 Unbalanced Under-voltage Response (Phases C & A, 130 cycles)

Under-Voltage Transient			Compressor		Contactor Coil		Thermostat (Y)	
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
A	100%, 90%, 80%,... 0%	130	0%	20	0%	20	0%	20
		12	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 90%, 80%,... 0%	130	0%	16	0%	15	0%	15
		12	0%	7	0%	7	0%	7
		9	0%	7	0%	7	0%	7
		6	0%	7	0%	7	0%	7
		3	0%	9	0%	9	0%	9
		1	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 90%, 80%,... 0%	130	N/A	N/A	N/A	N/A	N/A	N/A
		12	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 90%, 80%,... 0%	130	50%	3	50%	8	50%	8
		12	50%	2	50%	6	50%	6
		9	50%	4	50%	6	50%	6
		6	50%	3	50%	7	50%	7
		3	50%	6	50%	6	50%	6
		1	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 90%, 80%,... 0%	130	0%	9	0%	9	0%	9
		12	0%	7	0%	7	0%	7
		9	0%	8	0%	8	0%	8
		6	0%	6	0%	6	0%	6
		3	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 90%, 80%,... 0%	130	0%	15	0%	15	0%	15
		12	0%	16	0%	16	0%	16
		9	0%	10	0%	10	0%	10
		6	0%	6	0%	7	0%	7
		3	0%	10	0%	10	0%	10
		1	N/A	N/A	N/A	N/A	N/A	N/A

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

7.4 Balanced & Unbalanced Over-voltages

The A/C unit was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve to avoid damage. Multiple voltage swells were performed in 2% increments for up to 120% nominal voltage for each test. The following figure shows the balanced over-voltage test and the following table specifies the tests performed that resulted in voltage ride-through.

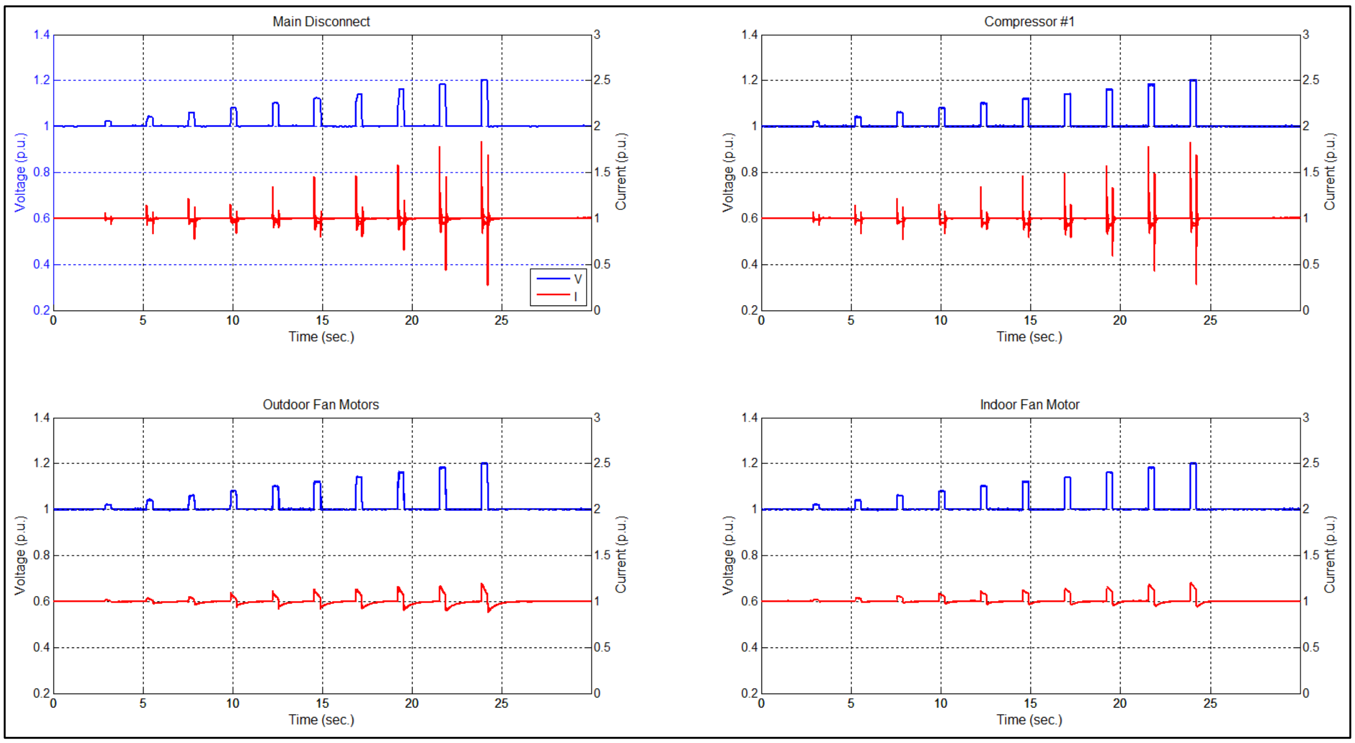

Figure 7.4.1 AC #5 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor		Contactor Coil		Thermostat (Y)	
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
ABC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
A	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 102%, 104%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A

Table 6.4.2 A/C #5 Balanced & Unbalanced Over-voltage Results

7.5 Voltage Oscillations

The following figure shows the performance of A/C unit #5 at the main disconnect 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 5% and 7% above steady state) for all swing frequencies tested. Real power oscillates in the same direction as voltage down to 4% below nominal consumption. Reactive power consumption experiences the largest oscillations (-13% to -19% deviation) in the same direction as voltage. At higher swing frequencies, reactive power deviations become larger both above and below steady state.

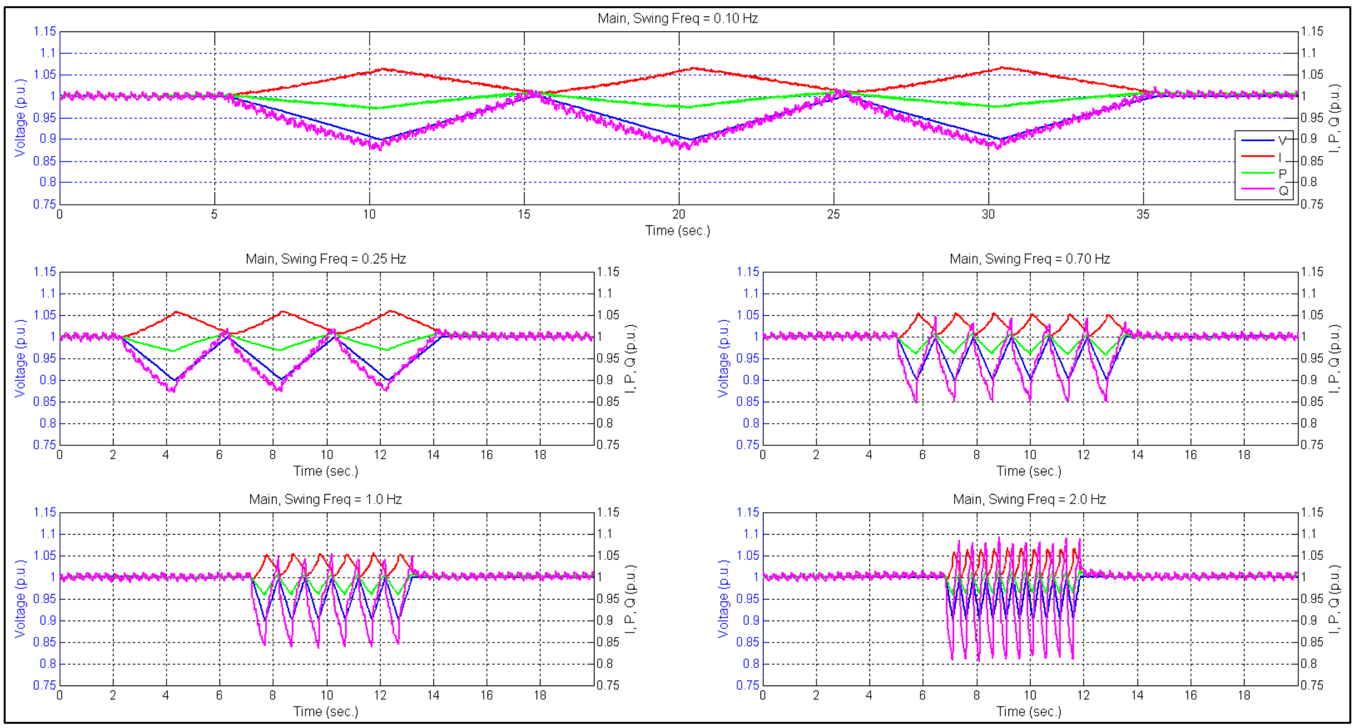

Figure 7.5.1 AC #5 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

7.6 Under-frequency Events

After subjecting A/C #5 to multiple under-frequency transients with different duration times, the device does not appear to have under-frequency protection down to 58 Hz. The unit simply rides through these frequency conditions. The following figure and table identify the tests that were performed.

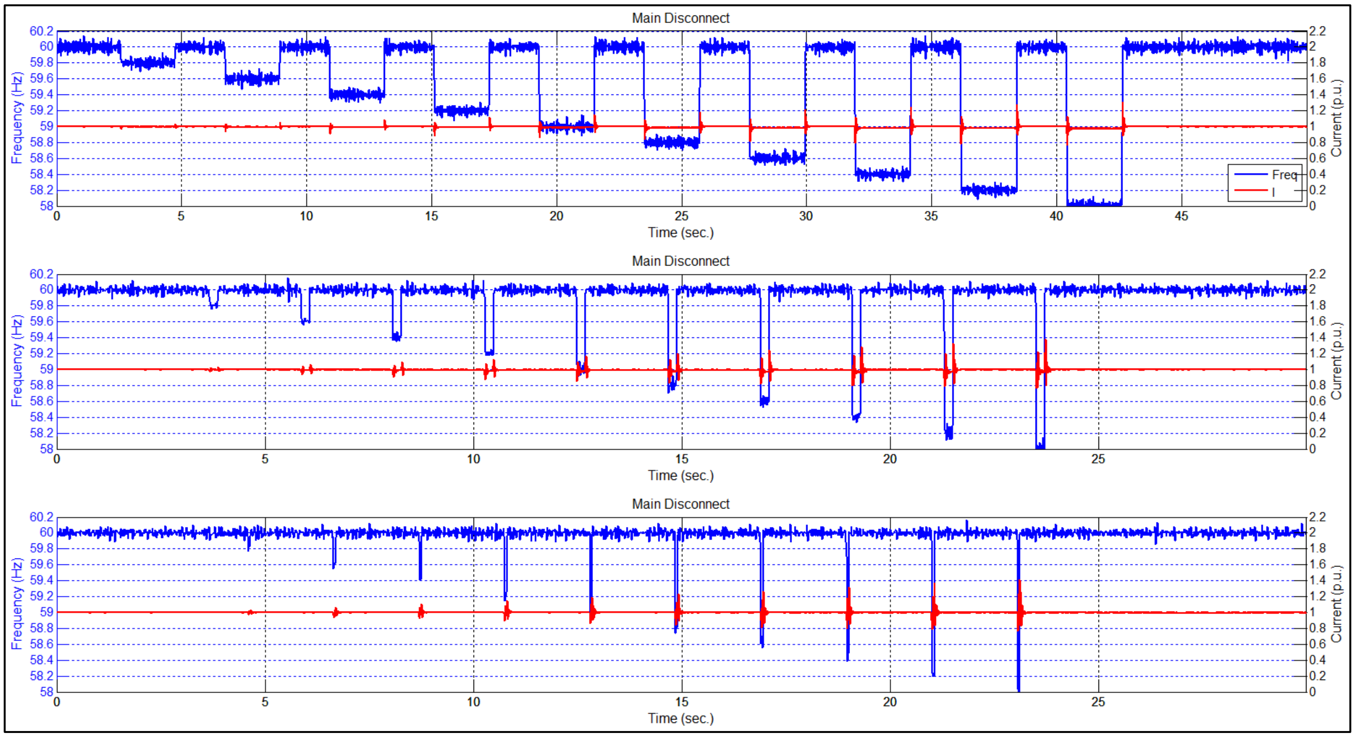

Figure 7.6.1 A/C #5 Under-frequency Response (130, 12, 3 cycles)

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

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

7.7 Over-frequency Events

Similar to the under-frequency tests, A/C #5 was subjected over-frequency transients with different duration times up to 62 Hz. The unit did not trigger any over-frequency protection and continued operating as normal. The following figure and table identify the over-frequency tests that were performed.

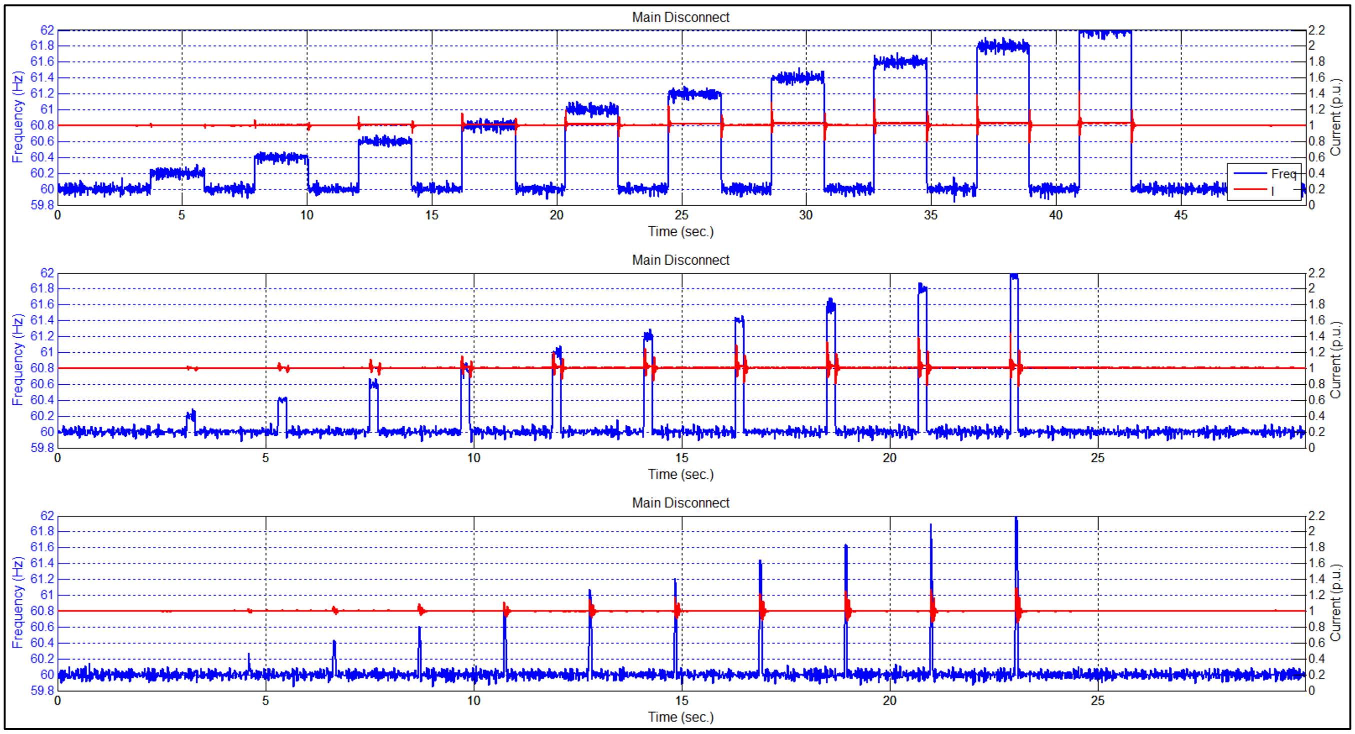

Figure 7.7.1 A/C #5 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor		Contactor Coil		Thermostat (Y)	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 60.2Hz, 60.4Hz,... 62Hz	130	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	12	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz, 60.4Hz,... 62Hz	3	N/A	N/A	N/A	N/A	N/A	N/A

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

7.8 Frequency Oscillations

The following figure shows the performance of A/C unit #5 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates.

Current and real power slightly oscillate with the frequency, but still remain within +3% of their nominal consumption values. Reactive power oscillates slightly in the opposite direction of frequency but also remains close to its steady state value, within +4% of nominal.

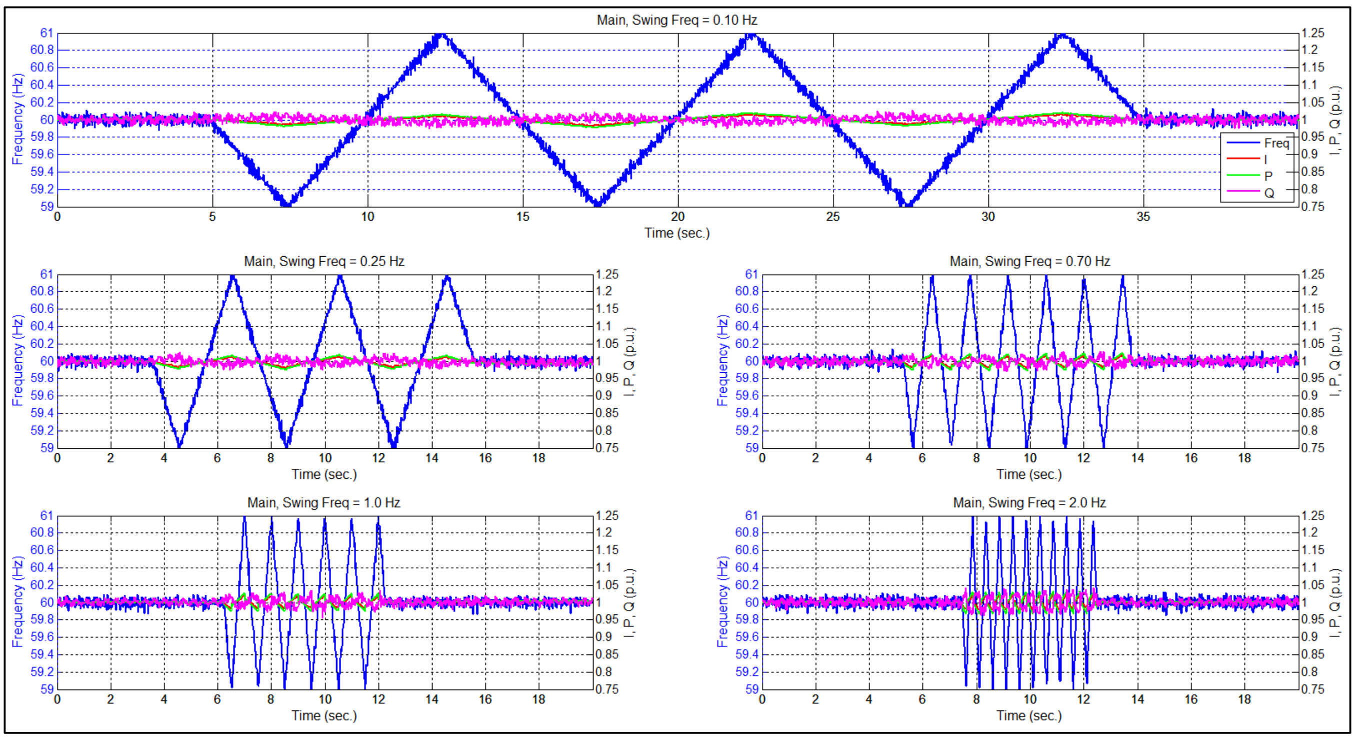

Figure 7.8.1 A/C #5 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

7.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit was found to trip when ramping down to 50% nominal voltage. Therefore the following figure shows the load performance at different voltage levels during voltage ramping down to 60% of nominal.

Current ramps up opposite of voltage to approximately 60% above nominal. Real power consumption droops during the voltage ramp, reducing by 7% to 9% below nominal at different ramp rates. The reactive power load initially ramps down until voltage reaches 75% at which point the reactive power begins increasing. Reactive power consumption is reduced by as much as 25% below its nominal value.

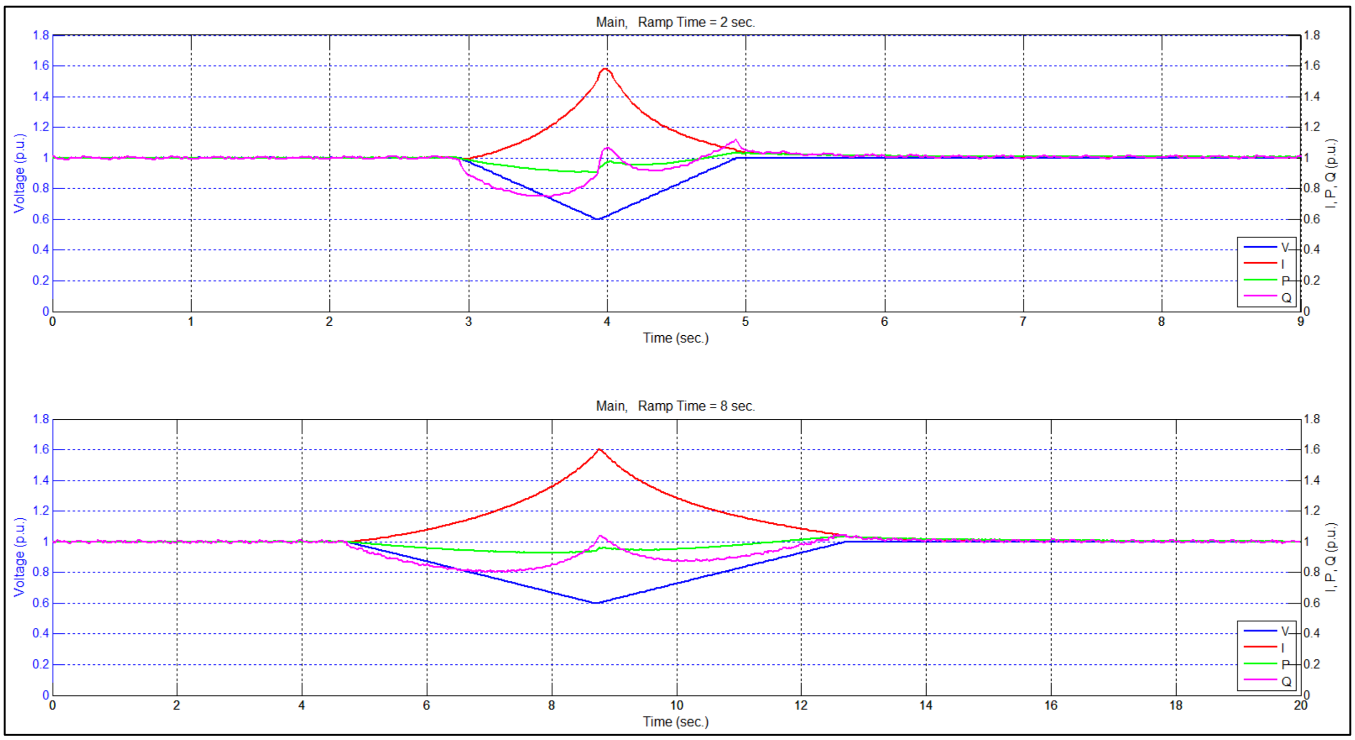

Figure 7.9.1 A/C #5 Voltage Ramp Down to 60% (2 & 8 sec.)

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

Current is slightly reduced by approximately 4% below nominal during the voltage ramp tests. Real power gradually ramps up to a maximum of 4% above steady state. Reactive power increases to approximately 19% above of nominal reactive load consumption.

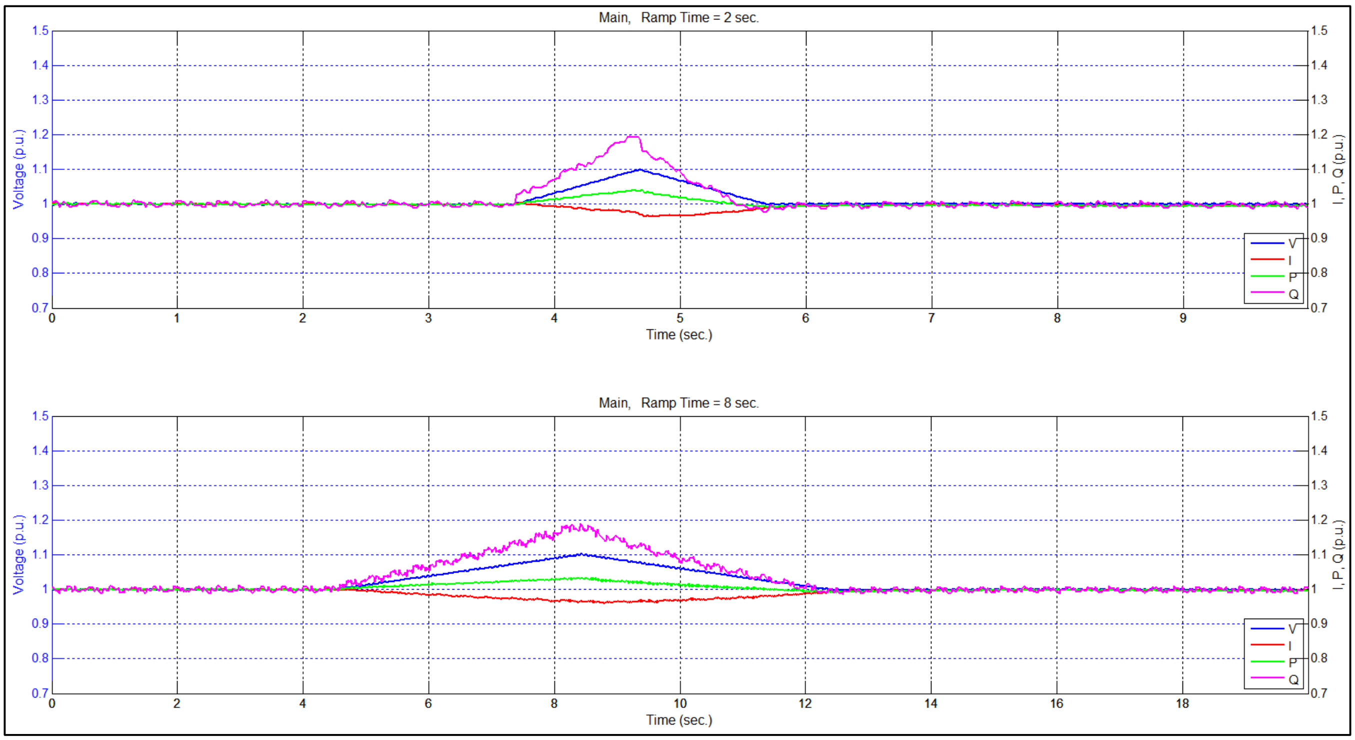

Figure 7.9.2 A/C #5 Voltage Ramp Up to 110% (in 2 & 8 sec.)

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.

Current magnitude is reduced to 9% below its nominal output during the under-frequency at 50 Hz. Real power consumption ramps down to approximately 19% below steady state. In contrast, reactive power actually ramps up to a maximum of 30% above of its normal consumption.

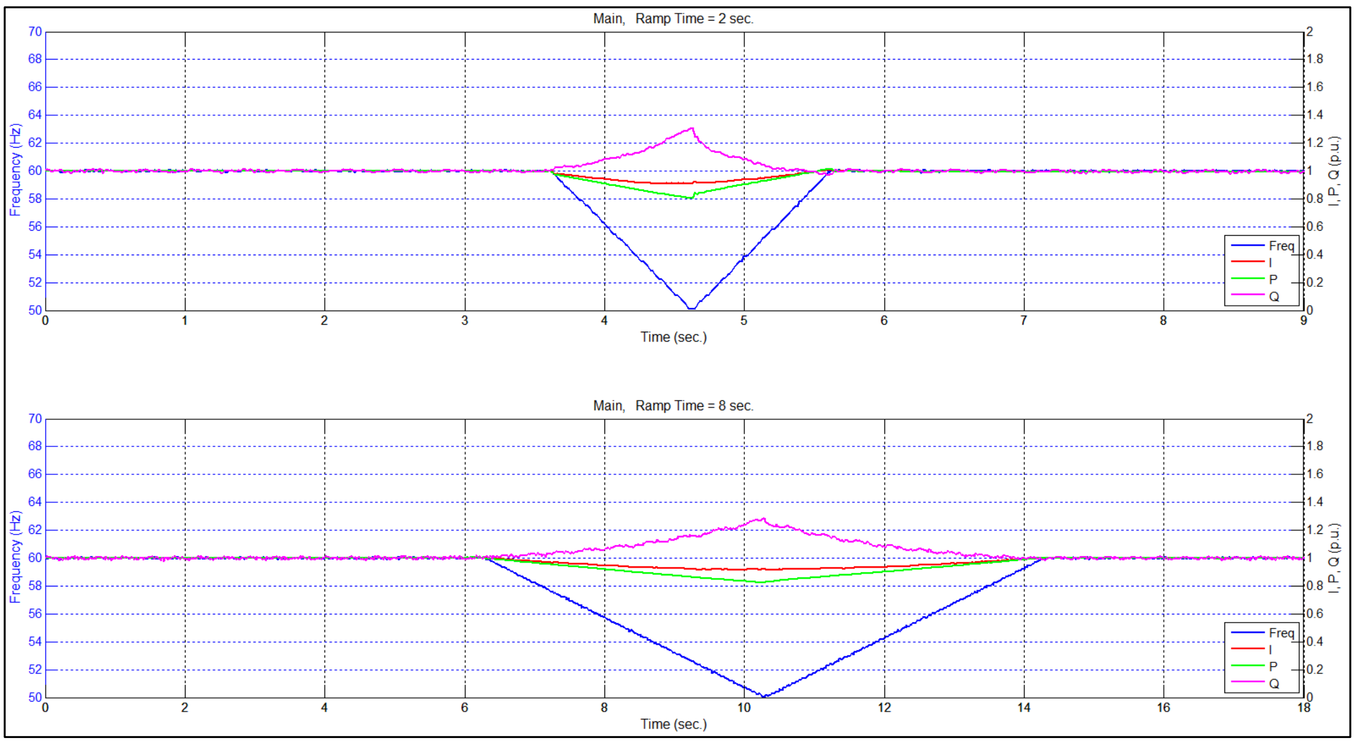

Figure 7.10.1 A/C #5 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

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.

Current and real power are observed ramping up with frequency, until peaking at 17% and 20% above their respective nominal values. Reactive power consumption is deviates slightly within ±4% of steady state during the frequency ramp.

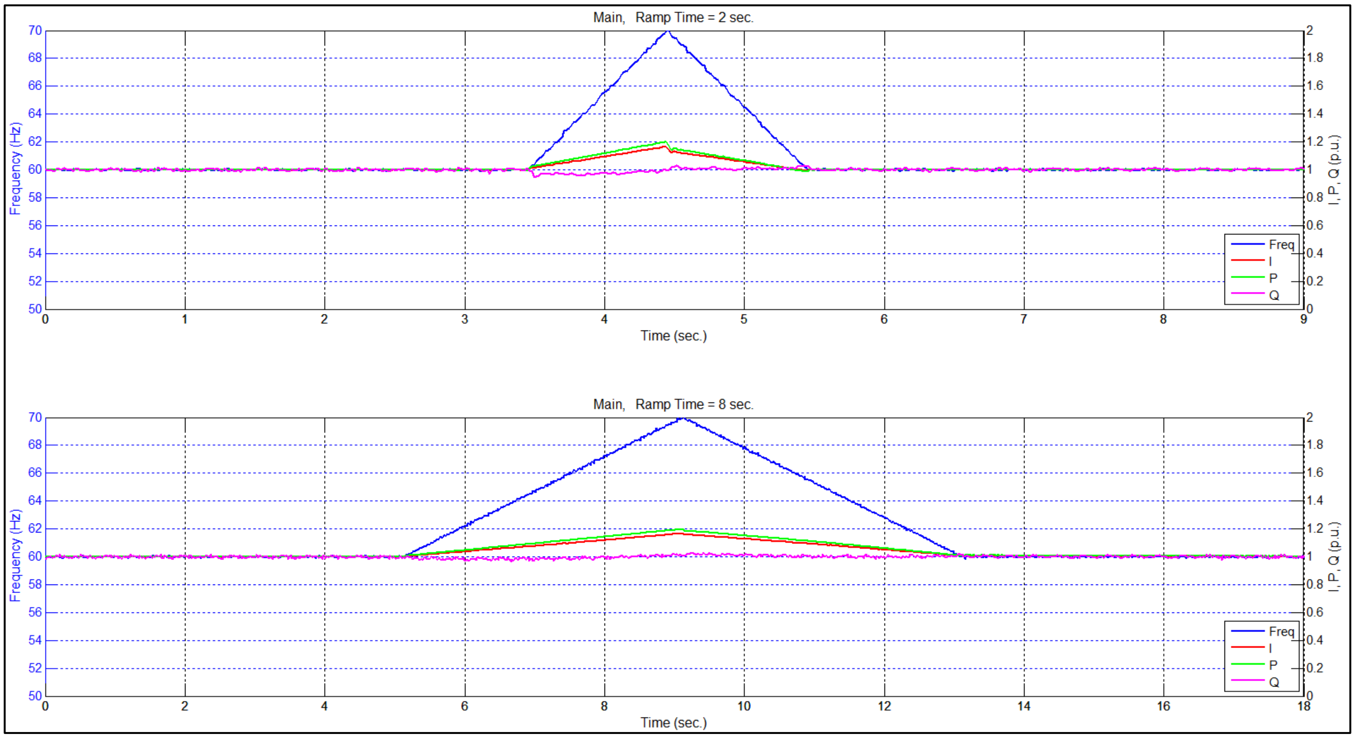

Figure 7.10.2 A/C #5 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

7.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times to calculate the harmonic contribution of A/C unit #5 to the grid. The total harmonic distortion of current on all phases was determined to be less 3% of the fundamental. The following table gives the total harmonic distortion for each phase ad the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)					
	$V_{A\ (L\text{-}N)}$	$V_{B\ (L\text{-}N)}$	$V_{C\ (L\text{-}N)}$	I_A	I_B	I_C
1	0.24	0.26	0.23	2.10	2.17	2.94
2	0.24	0.25	0.23	2.10	2.16	2.94
3	0.24	0.25	0.23	2.10	2.17	2.94

Table 7.11.1 A/C #5 Total Harmonic Distortion

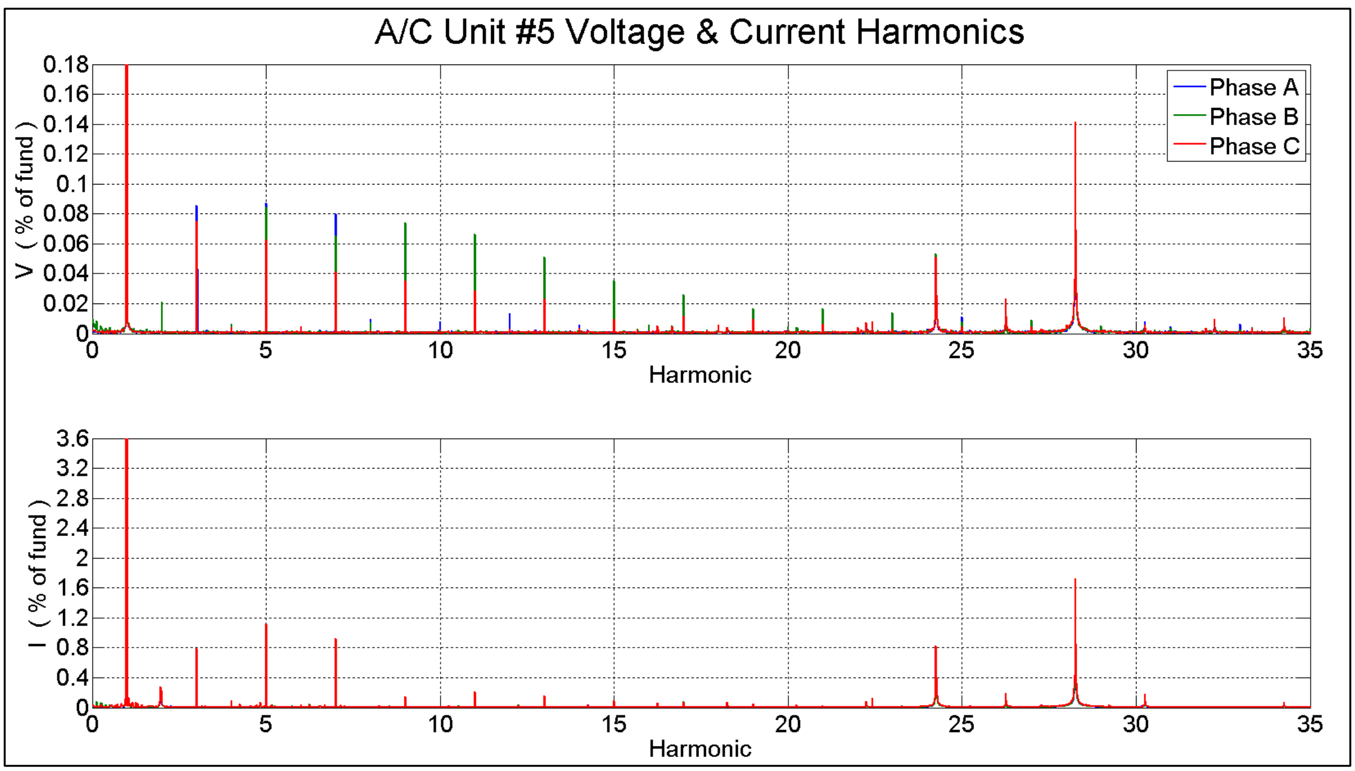

Figure 7.11.1 A/C #5 Harmonics Contribution

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. Although the outdoor conditions were warm the loading of the compressor was approximately 70% of the rated load amps.

Current increases by approximately 0.63% of nominal current for every 1% decrease in nominal voltage. Real power is reduced by a maximum of 3% below nominal consumption. Reactive power also steps down with the voltage, decreasing by 1.1% nominal reactive power for every 1% decrease in nominal voltage.

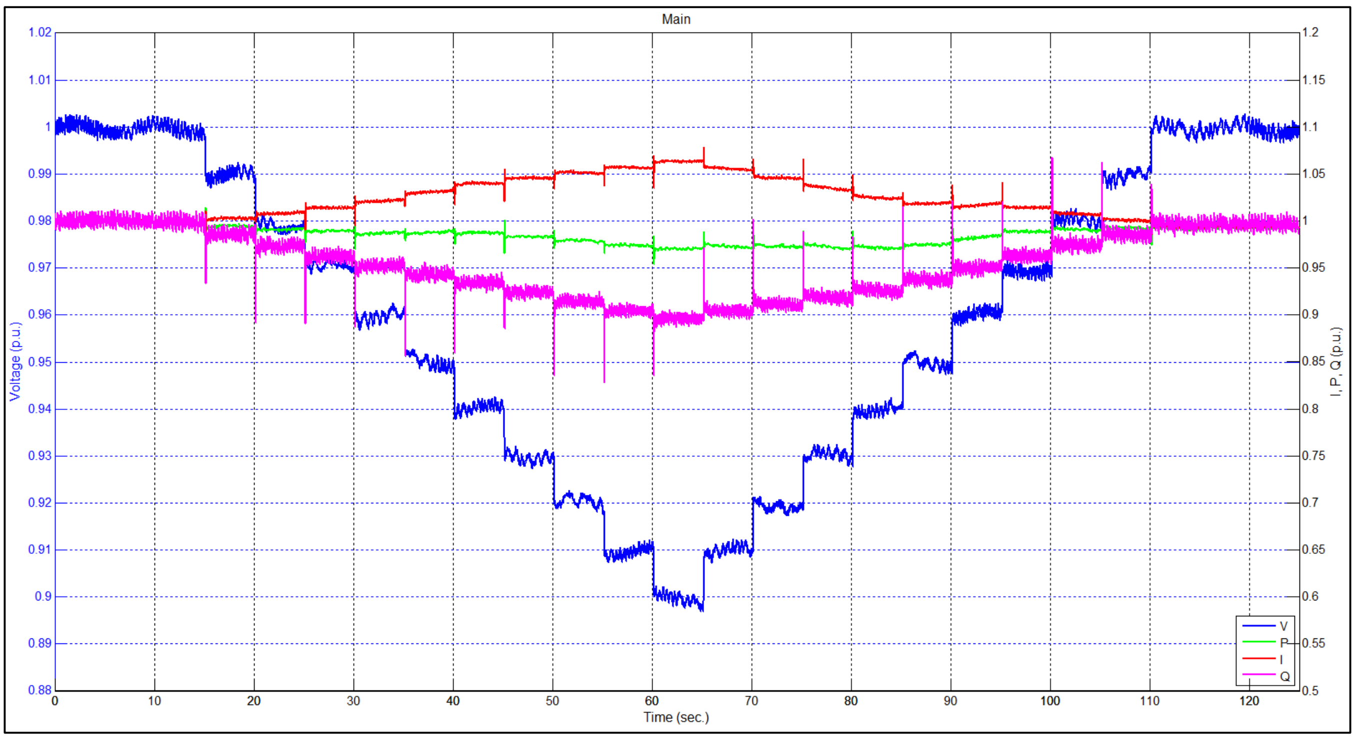

Figure 7.12.1 A/C #5 CVR Response Down to 90% Voltage

Alternatively, the service voltage at A/C #5 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 reduces by approximately 0.6% of nominal for every 1% increase in nominal voltage. Real power similarly stays near steady state conditions, only increasing by as much as 1% consumption. Reactive power is observed stepping up with the voltage and increases by 1.5% nominal reactive power for every 1% increase in nominal voltage.

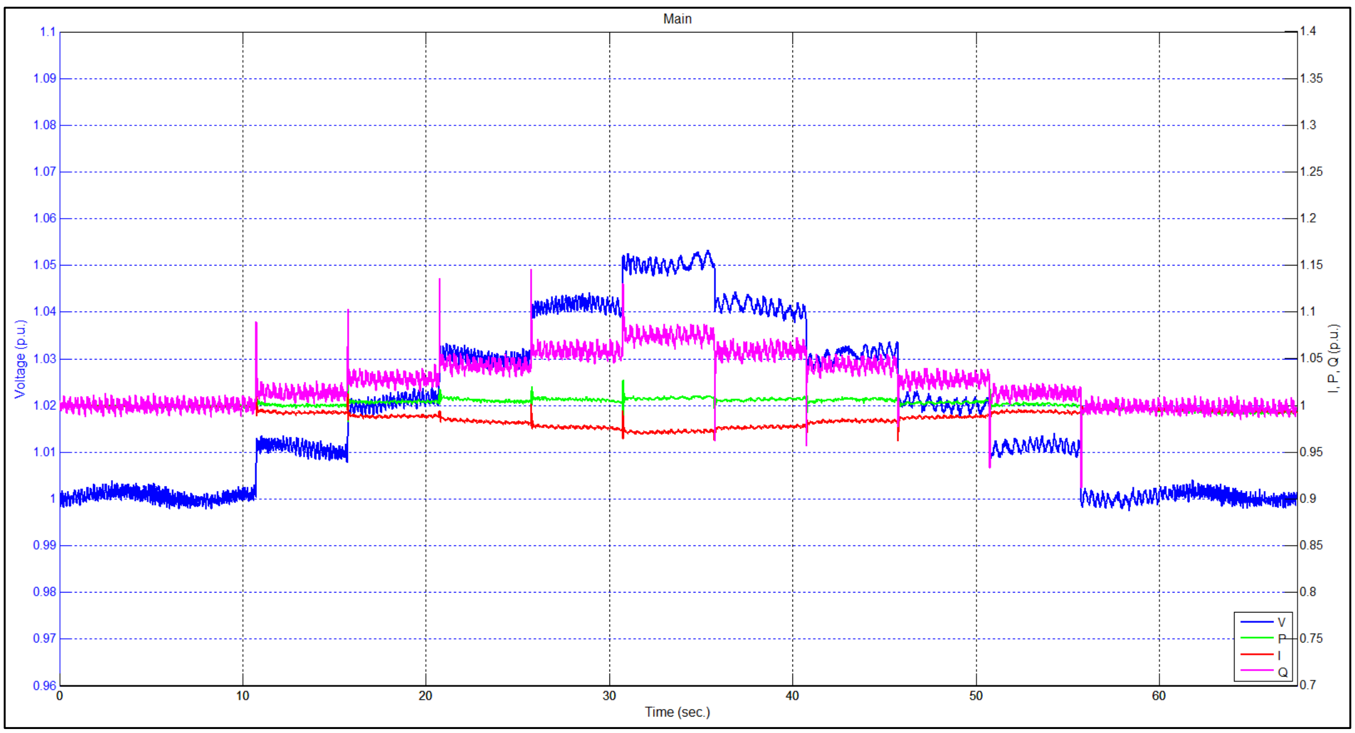

Figure 7.12.2 A/C #5 CVR Response Up to 105% Voltage

7.13 Compressor Stalling

While A/C unit #5 did reveal stalling behavior during instances of unbalanced under-voltages of at least two phases, compressor stalling did not occur during balanced under-voltage conditions. The contactor would open causing the compressor to shut down before reaching a voltage magnitude that could cause stalling. Additionally, the unit would restart normally, but only after the contactor reclosed several minutes later.

Therefore several additional under-voltage tests were performed after making modifications to the device controls in order to induce compressor stalling behavior during balanced under-voltage conditions. Rather than using the service voltage from the main terminals of the A/C unit to serve the step-down transformer (24 V output) and power the controls, a separate power supply was used to energize these controls (contactor coils, thermostat, etc.) to bypass any dropout behavior.

Prior tests revealed that dropout had occurred at 50% which was used as a starting point for these additional under-voltage tests. A series of under-voltage sags were performed in 1% voltage decrements with duration times of 3 seconds as shown in the following figures. The compressor began stalling during the 52% voltage dip but did not stall immediately. The A/C unit takes approximately 1.05 seconds to fully stall and enter locked rotor condition. Notice that stalling was identified by the dramatic increase in current and reactive power as well as the reduced mechanical vibration of the compressor. Lower voltage magnitudes resulted in faster stalling behavior as witnessed when stalling occurs in approximately 18 cycles at 42% nominal voltage.

The compressor restarted from its stalling condition in 4.8 cycles after voltage returns to nominal. It consistently restarts immediately after each and every voltage sag performed. Voltage was also held at 50% voltage indefinitely which caused thermal overload protection to occur nearly 70 seconds after stalling begins.

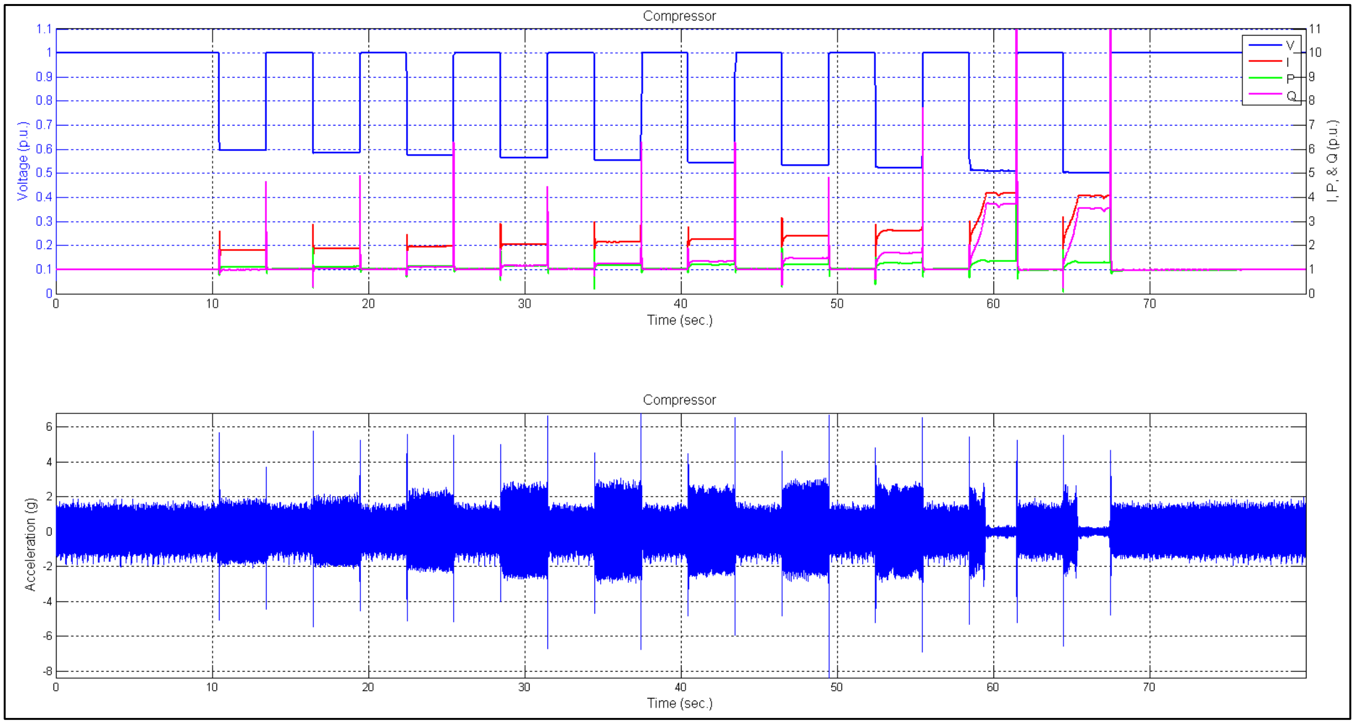

Figure 7.13.1 A/C #5 Compressor Stalling During Under-voltages (60% to 51% voltage)

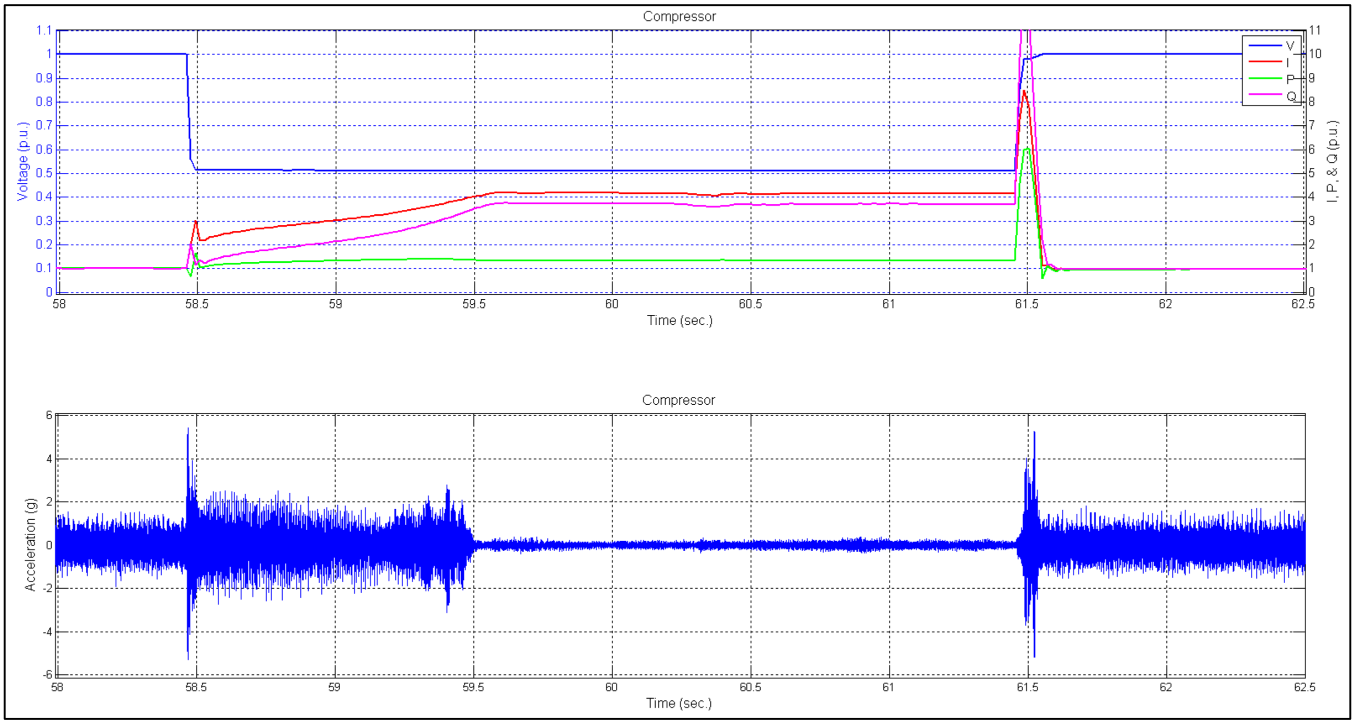

Figure 7.13.2 A/C #5 Compressor Stalling During Under-voltage (52% voltage)

Additionally, a voltage ramp test was performed to capture the compressor's current, real power, and reactive power consumption at different voltage levels as shown in the figure below. At the stalling point current, real power, and reactive power reached 4.1 pu, 1.4 pu, and 3.6 pu. At the restarting point current, real power, and reactive power increased to as large as 5.3 pu, 2.4 pu, and 5.8 pu.

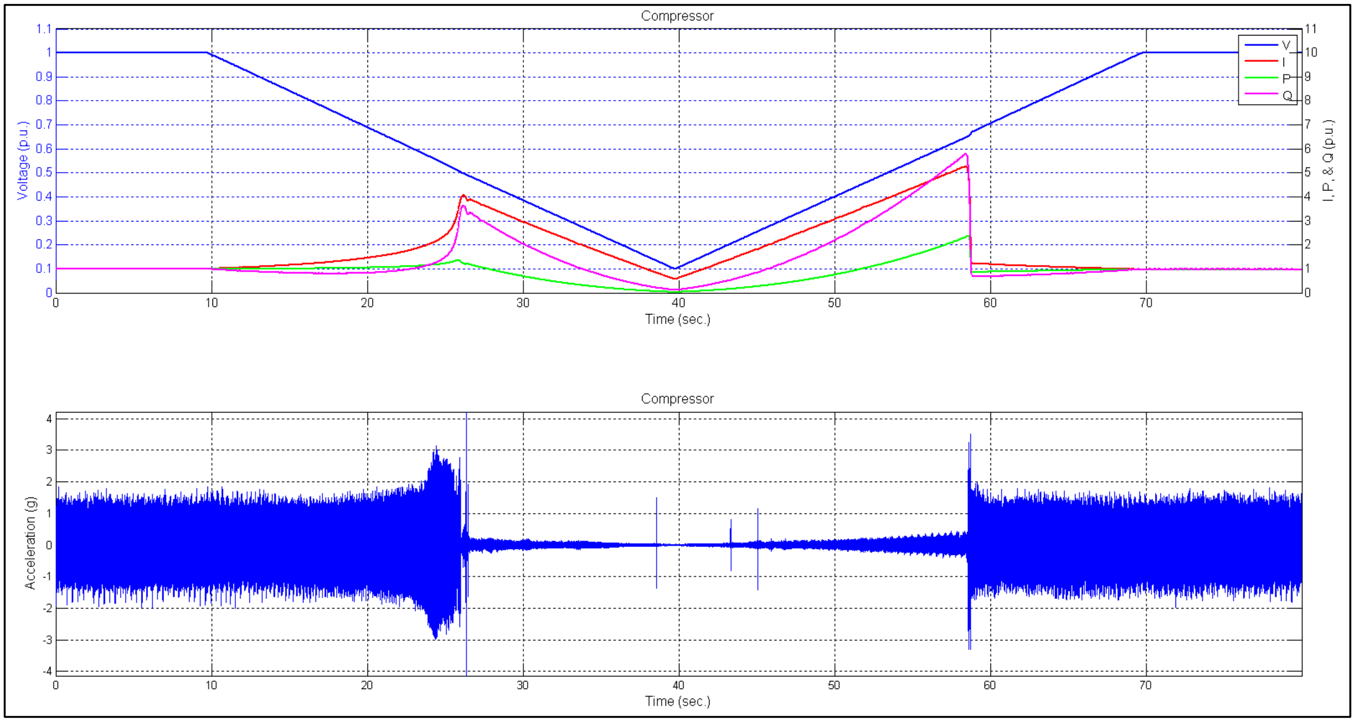

Figure 7.13.3 A/C #5 Compressor Stalling During Voltage Ramp

8.0 AIR CONDITIONER #6 TEST RESULTS

The sixth air conditioner tested is a 10-ton unit operated at 480 V line-to-line. The unit is comprised of a single indoor blower fan motor, outdoor fan motor, and two compressor motors. Both compressor motors were monitored individually (voltage, current, and acceleration) due to the fact that each compressor is connected with its own power contactor. The specifications for the individual components of A/C #6 are provided in the table below.

Main System		**Compressors**	
Manufacturer	Carrier	Manufacturer	Copeland
Model	50TCQD12A2A6-0A0A0	Model	ZP54K5E-TFD-130
Size (Tons)	10	Type	Scroll
Voltage (V)	460	Quantity	2
Refrig.	R-410A	RLA (Amps)	7.7
SEER	-	LRA (Amps)	52
EER	11	Test Press. High (PSI)	650
IEER	11.3	Test Press. Low (PSI)	450
Condenser Fan		**Blower Motor**	
Drive Type	Direct	Type	Belt
Quantity	1	Quantity	1
Motor HP	1-Jan	Motor HP	3
RPM	1175	RPM	Variable
FLA (Amps)	3.1	FLA (Amps)	5.3
Miscellaneous Components			
Contactor(s)	Tyco Electronics, HN52TCO24	Capacitor(s)	-
Transformer	Tyco Electronics, HT01BD702	Phase Balance Relay	-

Table 8.0.1 A/C #6 Specifications

8.1 Compressor Shutdown

A/C #6 was shut down during normal operation using the connected thermostat. The figure below displays the measurements taken at the main service connections as well as the behavior of the individual motors.

The compressors and outdoor fan motor shut down at the same time shortly after triggering the thermostat. The only power consumption after the compressors shut down was from the indoor fan motor operating at 3-phase 480 V with approximately 4.8 amps per phase (total of 2.8 kW or 3.9 kVA). However, this motor shuts down within 60 seconds of the other components.

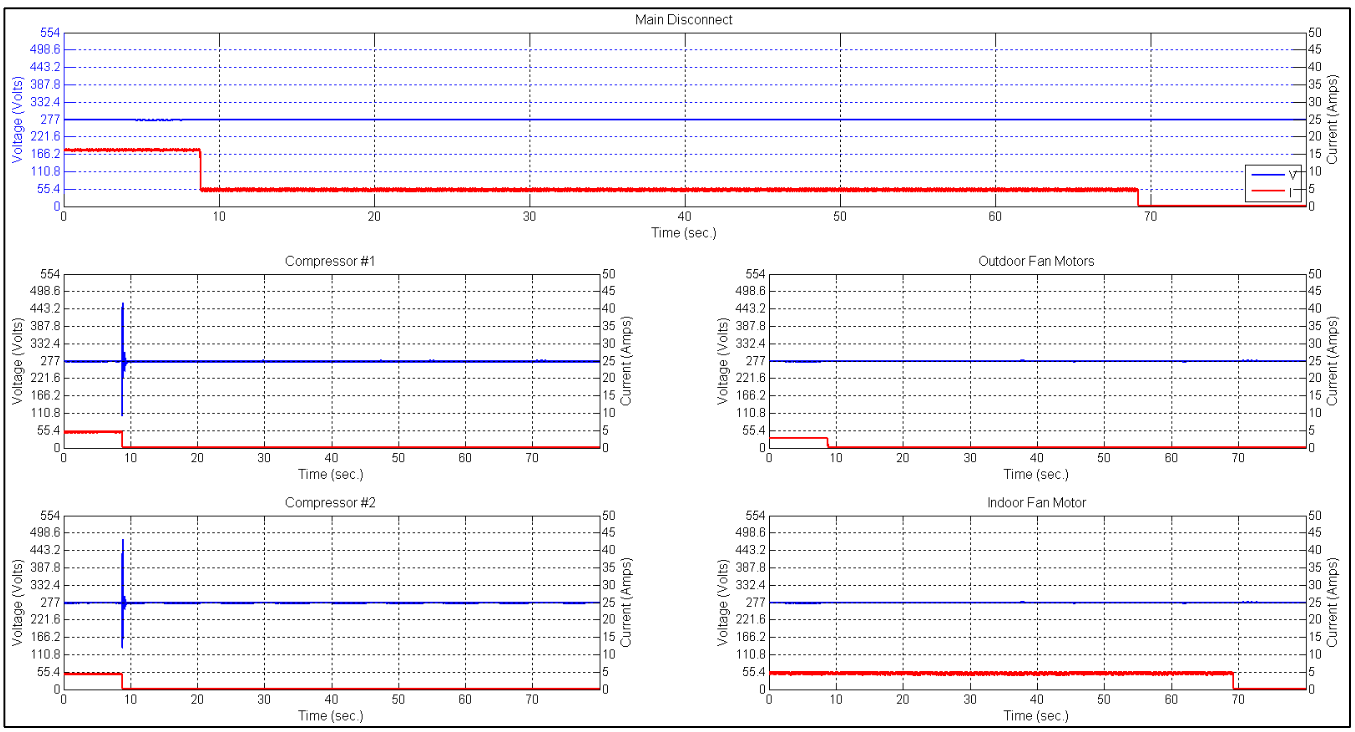

Figure 8.1.1 A/C #6 Compressor Shutdown

8.2 Inrush Current

After starting up A/C unit #6 via the programmable thermostat, compressor #1 starts up first followed by compressor #2, the outdoor fan motor, and finally the indoor fan motor. There is approximately 1 second between each of these startups. The largest inrush current observed at the main disconnect of the unit shows maximum value of 57.3 Amps within 5.4 cycles.

Compressor #1 Inrush: Maximum of 48.7 Amps and duration of 5.4 cycles

Compressor #1 Inrush: Maximum of 48.7 Amps and duration of 5.4 cycles

Outdoor Fan Motor Inrush: Maximum of 10.5 Amps and duration of 16 cycles

Indoor Fan: Maximum of 21.4 Amps and duration of 21 cycles

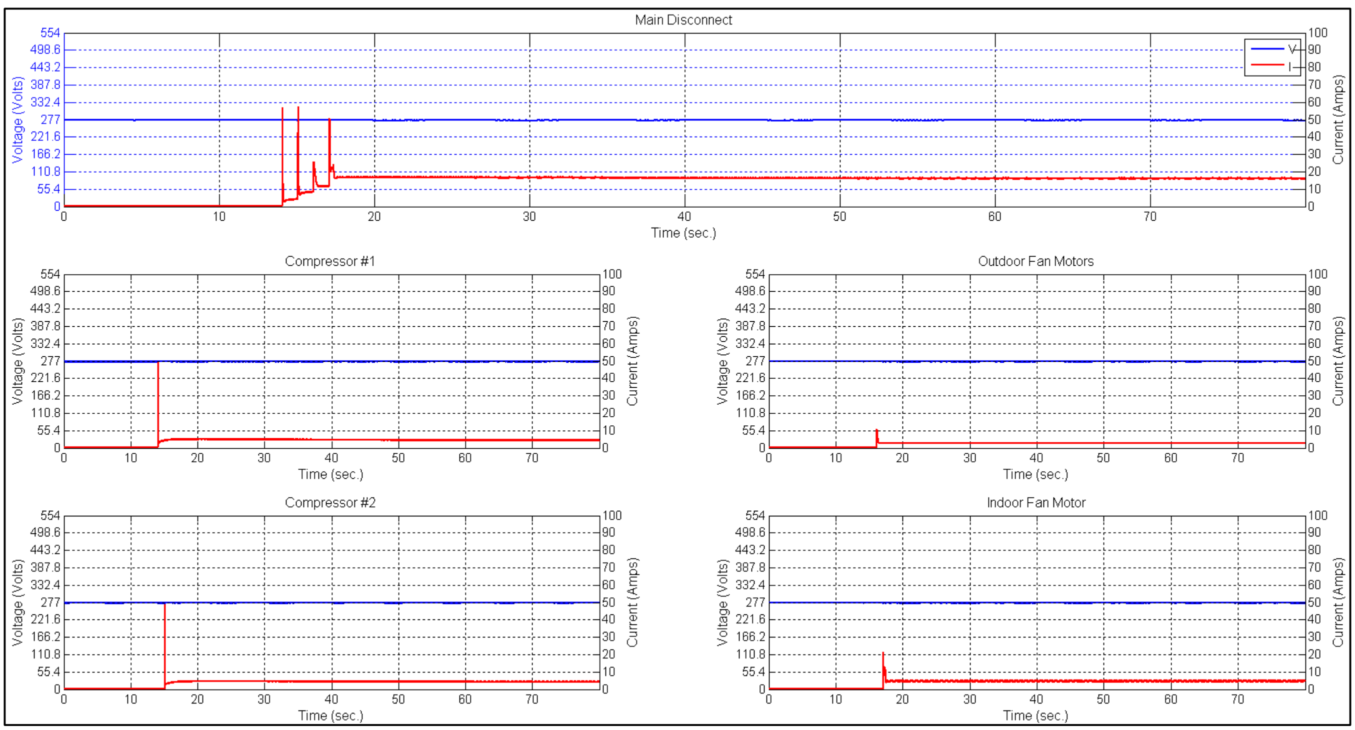

Figure 8.2.1 A/C #6 Inrush Current

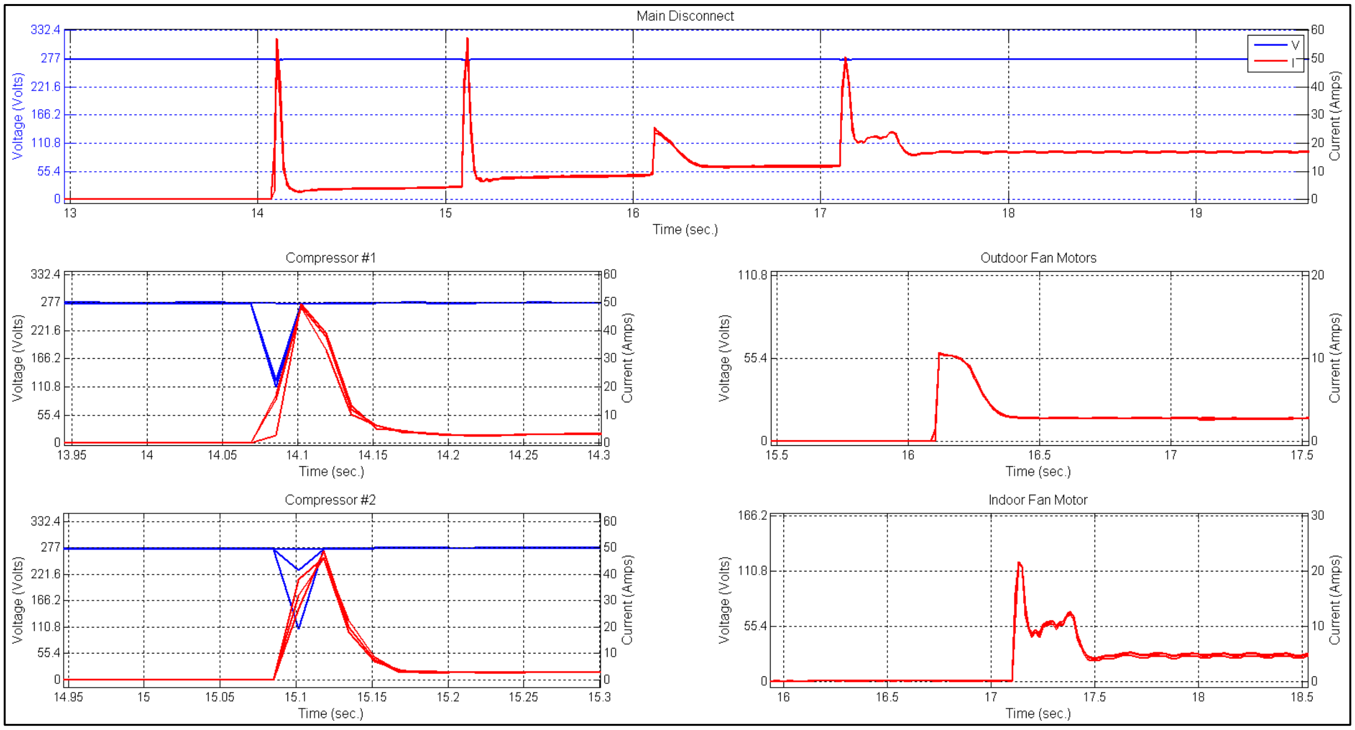

Figure 8.2.2 A/C #6 Inrush Current [Zoom In]

8.3 Balanced & Unbalanced Under-voltages

Control voltage measurements (24 V) were monitored at the thermostat output and at the compressor contactor coils to help determine the root cause of contactors opening during A/C #6 under-voltage tests. Stalling behavior was observed only during certain two-phase unbalanced under-voltage tests while all balanced tests resulted in the contactor opening before stalling could occur. Contactor chattering was observed during the voltage step changes during the voltage sag tests. Data captured several seconds after the disconnection of the compressor did not reveal immediate contactor reclosing for all tests, but there were a few exceptions.

Balanced voltage sags on all three phases in decrements of 10% revealed that the compressor would disconnect 50% nominal voltage for transients with a duration in the range of 3 to 130 cycles. Typically, the contactor would open within 2 cycles after the start of the voltage sag. Several of the shorter under-voltage tests showed the contactor reclosing after recovering to nominal voltage within 1.2 cycles, but then the contactor would open again sometime within the next 60 cycles and remain open until the unit restarted several minutes later. There were also two cases (12 and 3 cycle tests) where the contactors did not open until tens of cycles after voltage already recovered from the sag.

The only case where the contactor and compressor motor rode through balanced 0% under-voltage sags was during switching transients with a duration time of 1 cycle. “N/A” or “not applicable” as noted in the following tables represents these ride through situations where there is no trip voltage or trip time available.

The following figure visually displays one of the longer duration balanced under-voltage tests. The following table provides the details regarding the compressor contactors operation and control voltage measurements during the various tests. The trip voltage represents the magnitude where the contactors opened and where the control voltages (at the contactor coils and thermostat) disappeared. The trip time is how long this takes after the start of the voltage sag.

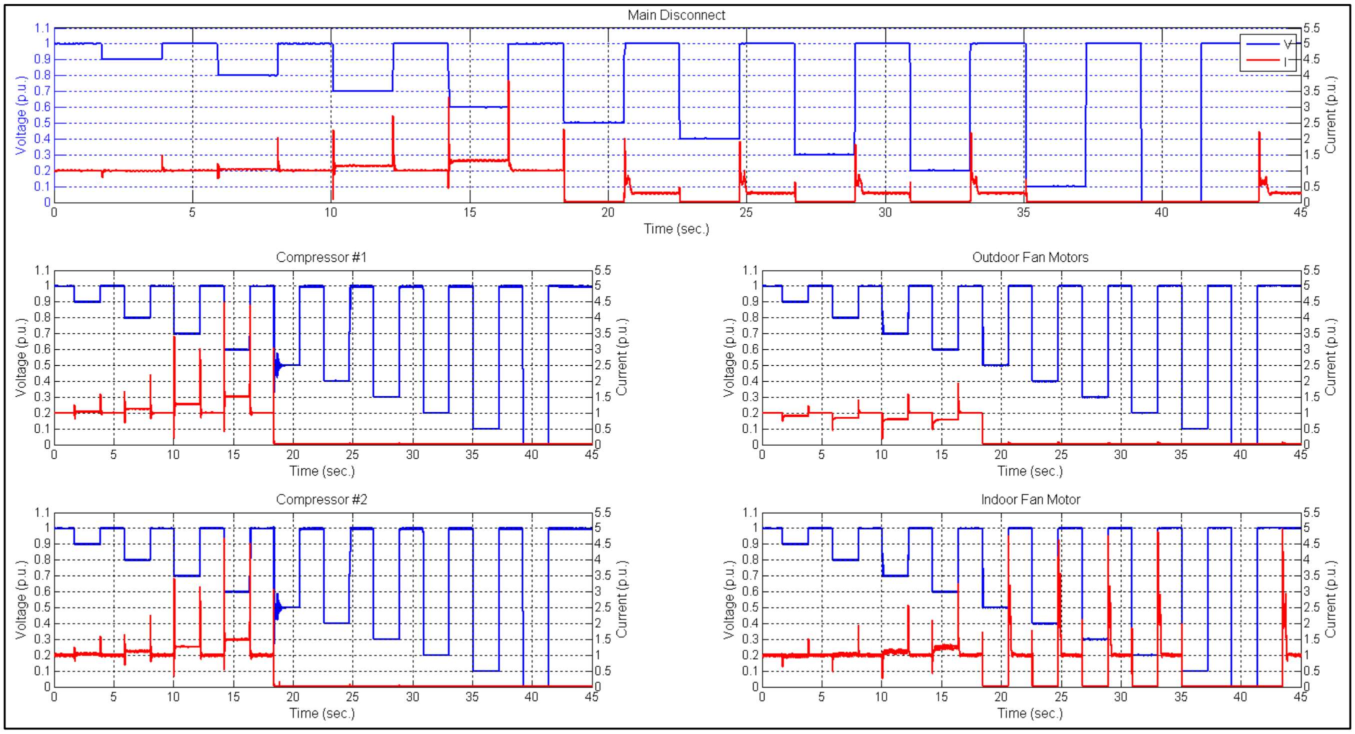

Figure 8.3.1 A/C #6 Balanced Under-voltage Response (130 cycles)

Under-Voltage Transient		**Compressor #1**		**Compressor #2**		**Cmp#1 Contactor Coil**		**Cmp#2 Contactor Coil**		**Thermostat (Y)**	
Volt Range	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
100%, 90%, 80%,... 0%	130	50%	1	50%	1	50%	28	50%	28	50%	5
		50%	2	50%	2	50%	56	50%	56	50%	6
		50%	2	50%	2	50%	68	50%	68	50%	6
100%, 90%, 80%,... 0%	12	50%	2	50%	2	50%	35	50%	35	50%	6
		50%	21	50%	21	50%	21	50%	21	50%	6
		50%	2	50%	2	50%	66	50%	67	50%	6
100%, 90%, 80%,... 0%	6	50%	1	50%	1	50%	50	50%	50	50%	5
		50%	2	50%	2	50%	13	50%	13	50%	6
		50%	1	50%	1	50%	40	50%	40	50%	5
100%, 90%, 80%,... 0%	3	50%	36	50%	36	50%	36	50%	36	50%	6
		50%	1	50%	1	50%	27	50%	27	50%	5
		50%	2	50%	2	50%	42	50%	42	50%	6
100%, 90%, 80%,... 0%	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

In order to narrow down the voltage where the compressors are disconnected from the contactors opening, additional balanced under-voltage tests were performed in decrements of 1% nominal voltage. The contacts opened or began chattering at either 59% or 58% nominal voltage. Additionally, the same test was performed where the contactor coil is energized directly by service voltage using the step-down controls transformer where the contactor opened between 51% and 53% voltage between 1.2 and 2.4 cycles after the start of the voltage sag. The following table provides the details of the various 1% voltage decrement tests.

Under-Voltage Transient		Compressor #1		Compressor #2	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
60%, 59%, 58%, …	130	59%	30	59%	30
60%, 59%, 58%, …	130	59%	79.8	59%	79.8
60%, 59%, 58%, …	130	59%	40.8	59%	40.8
60%, 59%, 58%, …	12	58%	19.8	58%	19.8
60%, 59%, 58%, …	12	58%	45.6	58%	45.6
60%, 59%, 58%, …	130	51%	2.4	51%	2.4
60%, 59%, 58%, …	130	53%	1.8	53%	1.8
60%, 59%, 58%, …	130	53%	1.2	53%	1.2

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

Unbalanced under-voltages on A/C unit #6 resulted in lower magnitude trip voltages because the controls (including the contactor coils) are energized only using one of the line-to-line supply voltages, phase A to phase B. Phase A to B under-voltages are therefore similar to the results of the balanced under-voltage tests and phase C under-voltage transients do not result in contactor dropout.

Stalling behavior was discovered during the 130 cycle unbalanced under-voltages for $V_{\Phi B-\Phi C}$ and $V_{\Phi C-\Phi A}$. When phases B and C experience under-voltage, the compressor takes approximately 30 cycles to completely stall at 20% nominal voltage. When phases C and A experience under-voltage, the compressor takes approximately 60 cycles to completely stall at 20% nominal voltage. The compressors restarts from stalling condition within 5.4 cycles after the voltage sag recovers to nominal. The following two figures display this stalling behavior.

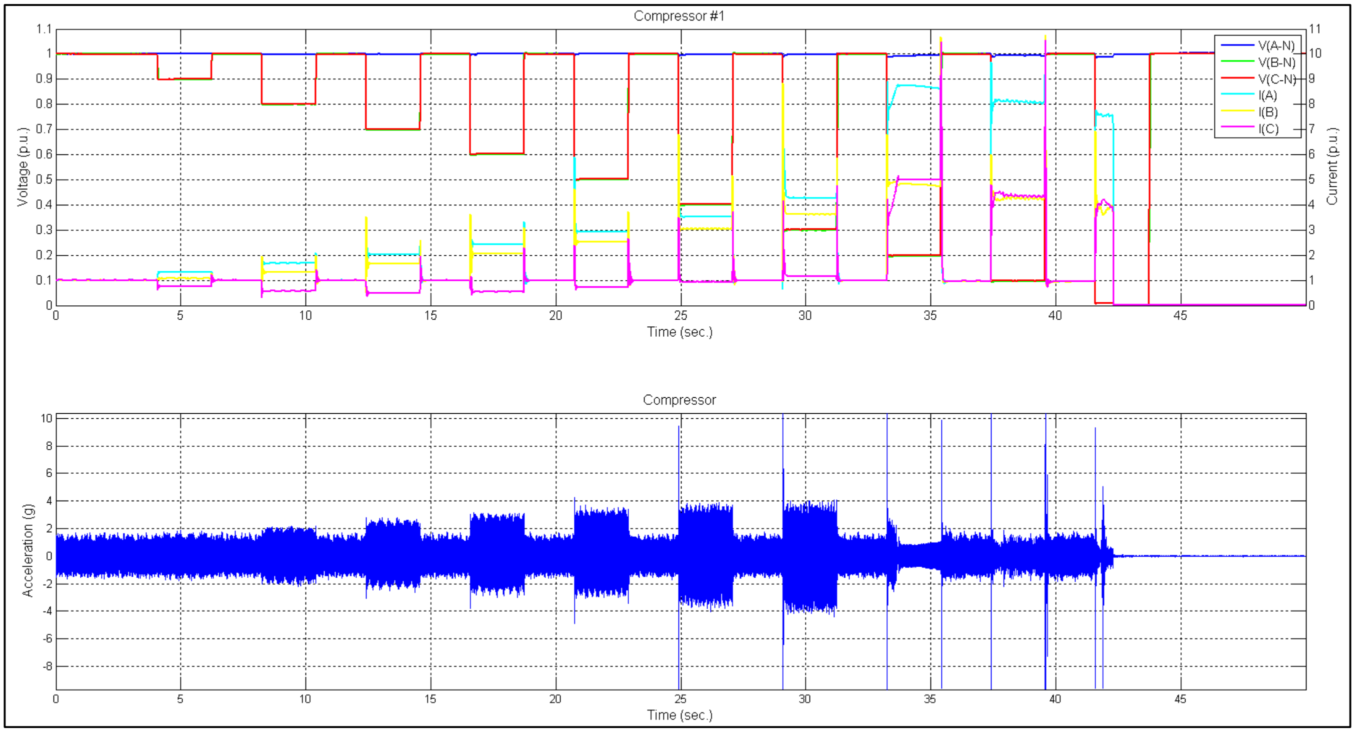

Figure 8.3.2 A/C #6 Unbalanced Under-voltage Response (Phases B & C, 130 cycles)

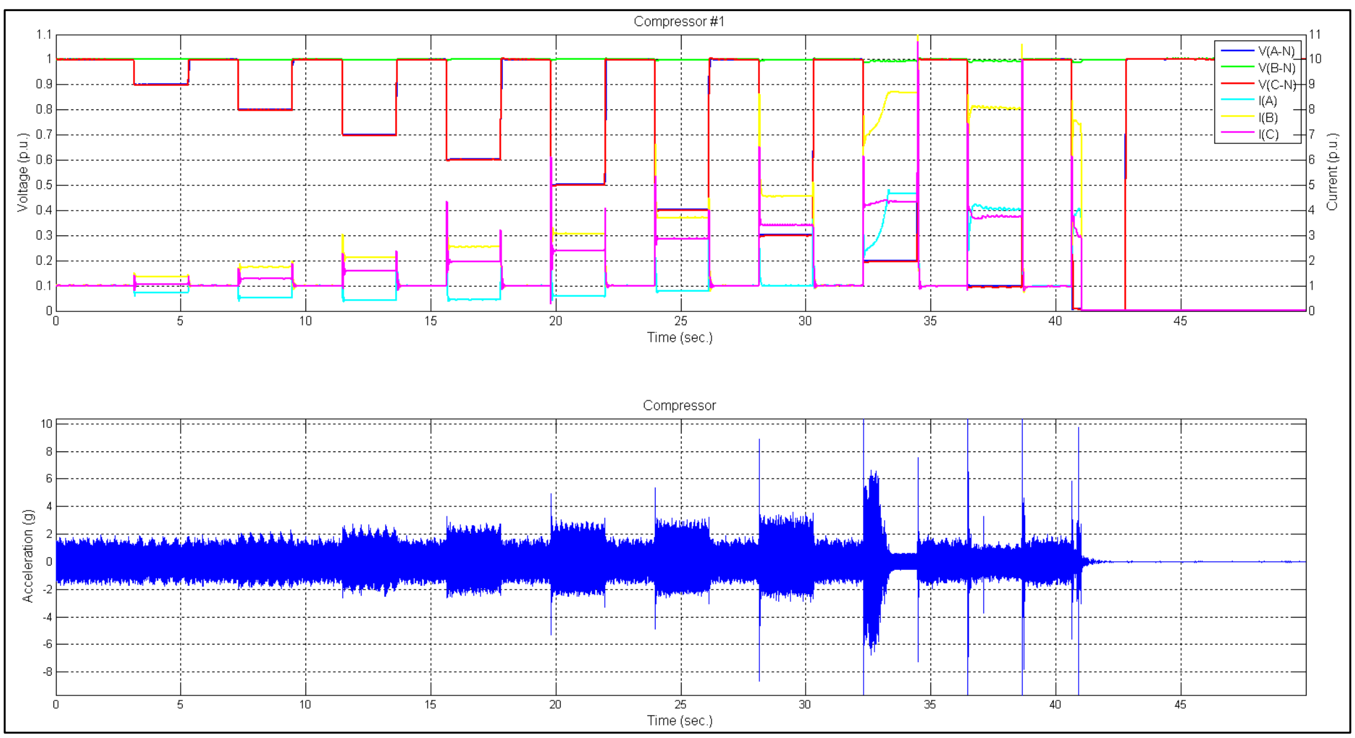

Figure 8.3.3 A/C #6 Unbalanced Under-voltage Response (Phases C & A, 130 cycles)

Under-Voltage Transient			Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Thermostat (Y)	
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
A	100%, 90%,... 0%	130	0%	47	0%	47	0%	47	0%	47	0%	6
		12	0%	54	0%	1	0%	53	0%	53	0%	8
		9	0%	36	0%	36	0%	35	0%	35	0%	8
		6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 90%,... 0%	130	10%	38	10%	38	10%	37	10%	37	10%	6
		12	0%	38	0%	38	0%	38	0%	38	0%	6
		9	0%	1	0%	1	0%	58	0%	59	0%	5
		6	0%	40	0%	40	0%	39	0%	39	0%	7
		3	0%	2	0%	2	0%	33	0%	33	0%	9
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 90%,... 0%	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 90%,... 0%	130	50%	2	50%	2	50%	68	50%	68	50%	6
		12	50%	2	50%	2	50%	68	50%	68	50%	6
		9	50%	2	50%	2	50%	36	50%	36	50%	8
		6	50%	2	50%	2	50%	56	50%	56	50%	8
		3	50%	2	50%	2	50%	50	50%	50	50%	5
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 90%,... 0%	130	0%	43	0%	43	0%	43	0%	43	0%	7
		12	0%	1	0%	1	0%	30	0%	30	0%	8
		9	10%	68	10%	68	10%	67	10%	67	10%	6
		6	0%	2	0%	2	0%	65	0%	65	0%	6
		3	10%	57	10%	57	10%	57	10%	57	10%	9
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 90%,... 0%	130	0%	23	0%	23	0%	23	0%	23	0%	7
		12	0%	1	0%	1	0%	28	0%	28	0%	6
		9	0%	51	0%	51	0%	51	0%	51	0%	7
		6	0%	2	0%	2	0%	52	0%	52	0%	9
		3	0%	2	0%	2	0%	28	0%	28	0%	9
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

8.4 Balanced & Unbalanced Over-voltages

The A/C unit was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve to avoid damage. Multiple voltage swells were performed in 2% increments for up to 120% nominal voltage for each test. The following figure shows the balanced over-voltage test and the following table specifies the tests performed that resulted in voltage ride-through.

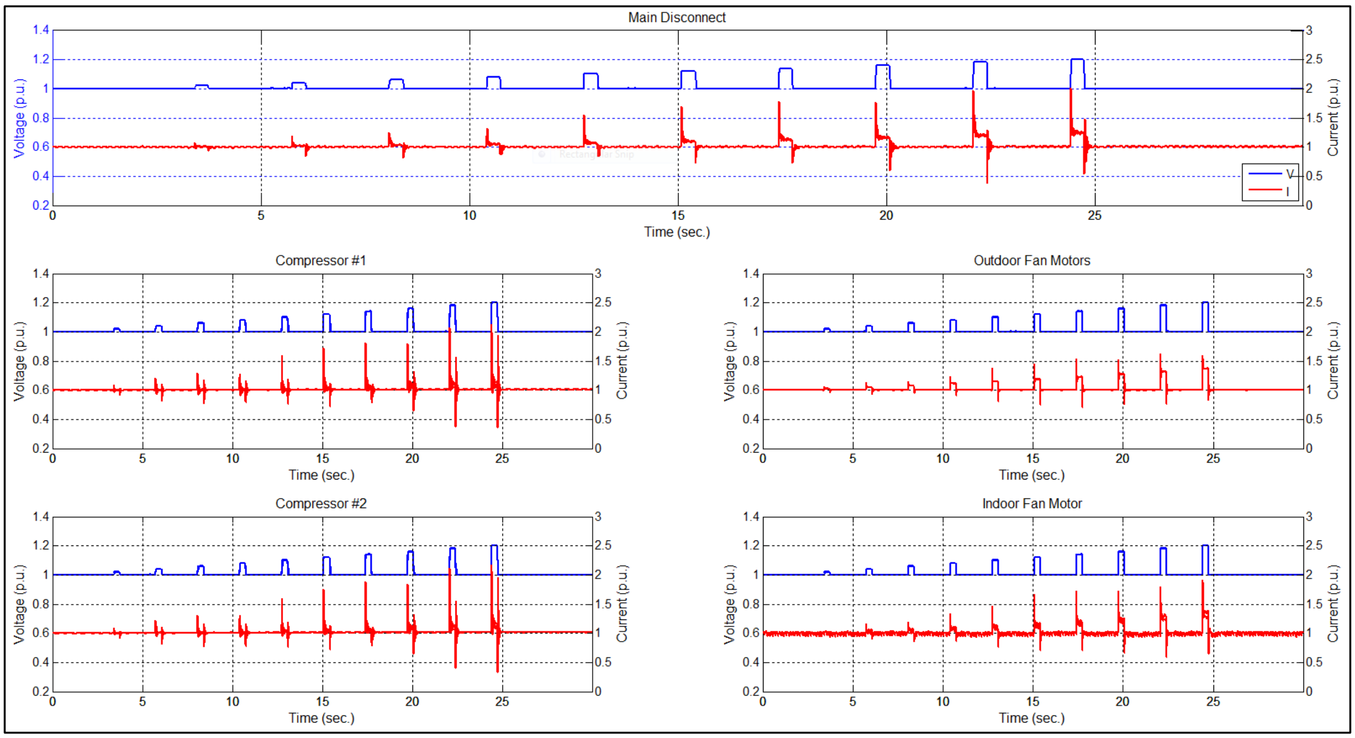

Figure 8.4.1 AC #6 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Thermostat (Y)	
Φ	**Volt Range**	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
ABC	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 102%,,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

8.5 Voltage Oscillations

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

Current and real power remain within +3% of steady state for slower oscillation rates (0.10 Hz and 0.25 Hz). However at faster oscillation rates, these values deviate slightly more but remain within +5% of nominal. Reactive power consumption experiences the largest oscillations (-23% to -26% deviation) in the same direction as voltage. At higher swing frequencies, deviations become larger both above and below steady state.

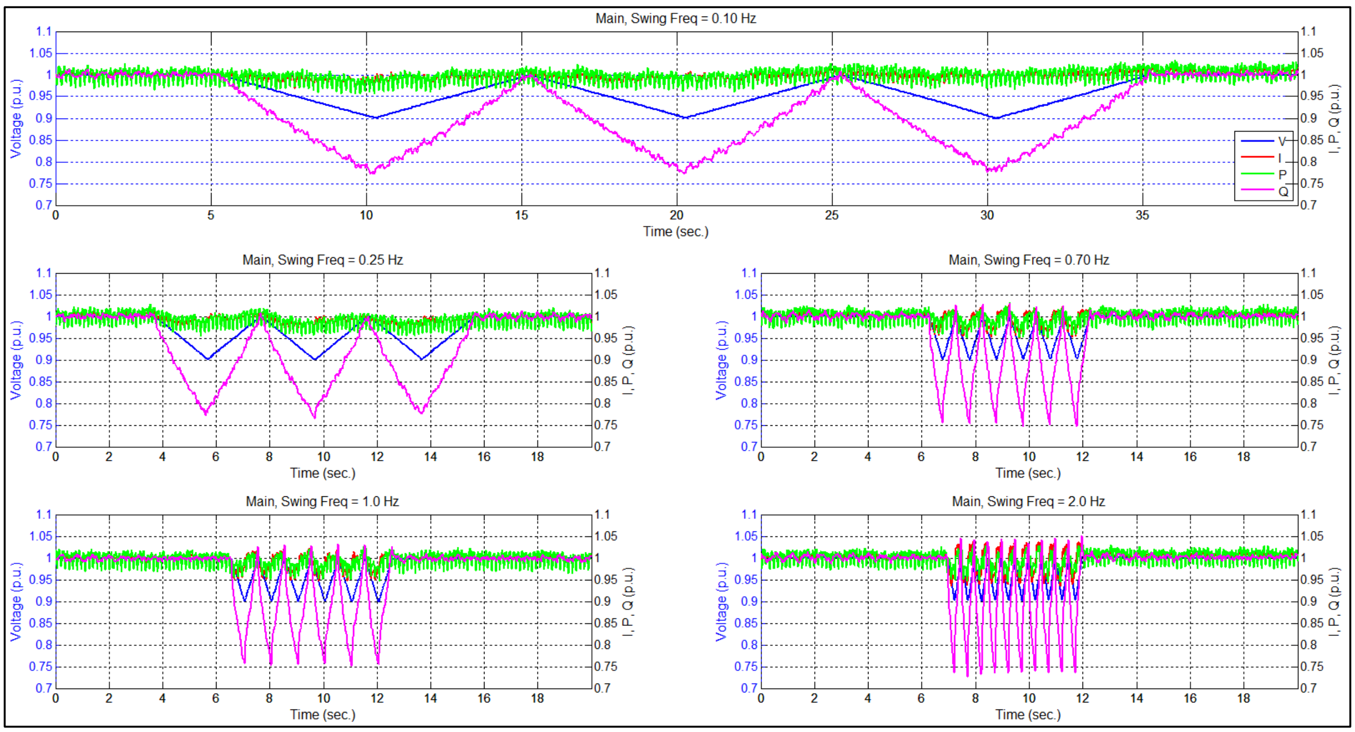

Figure 8.5.1 AC #6 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

8.6 Under-frequency Events

After subjecting A/C #6 to multiple under-frequency transients with different duration times, the device does not appear to have under-frequency protection down to 58 Hz. The unit simply rides through these frequency conditions. The following figure and table identify the tests that were performed.

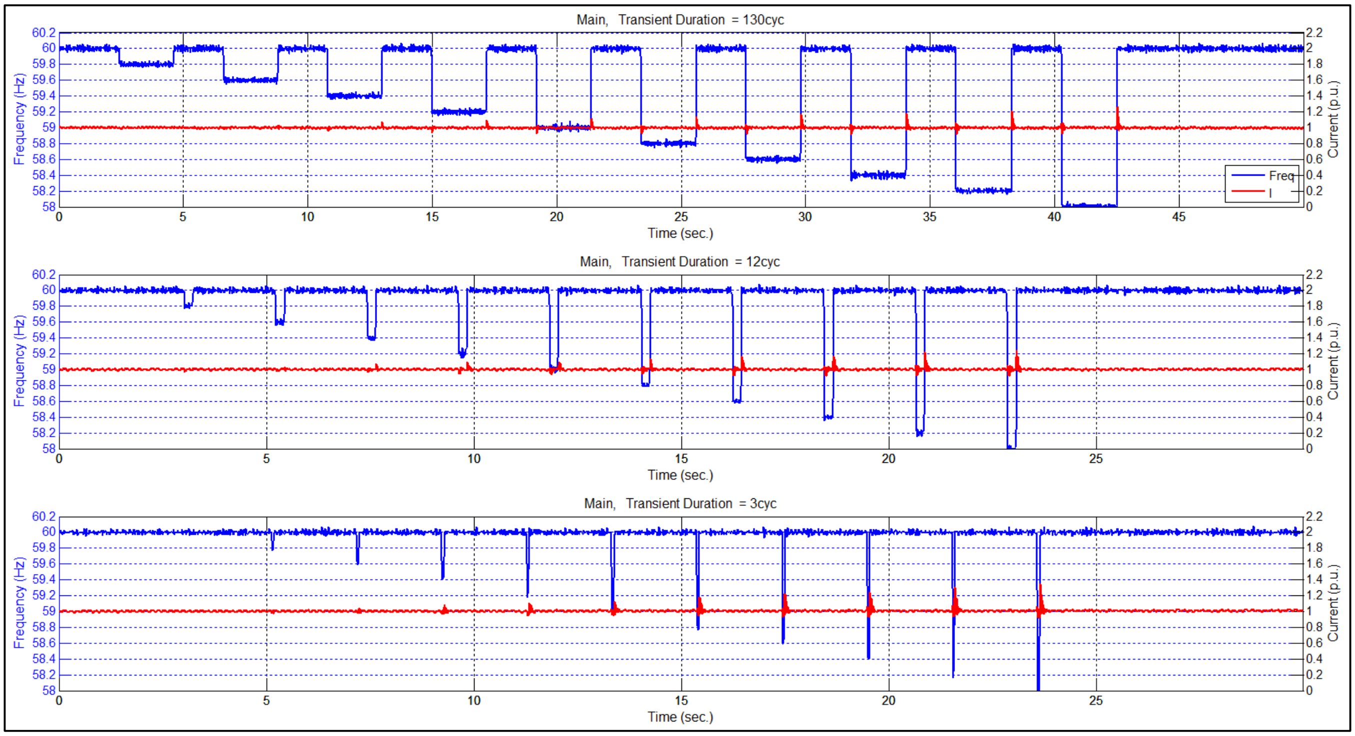

Figure 8.6.1 A/C #6 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Thermostat (Y)	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz,... 58Hz	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 59.8Hz,... 58Hz	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 59.8Hz,... 58Hz	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

8.7 Over-frequency Events

Similar to the under-frequency tests, A/C #6 was subjected over-frequency transients with different duration times up to 62 Hz. The unit did not trigger any over-frequency protection and continued operating as normal. The following figure and table identify the over-frequency tests that were performed.

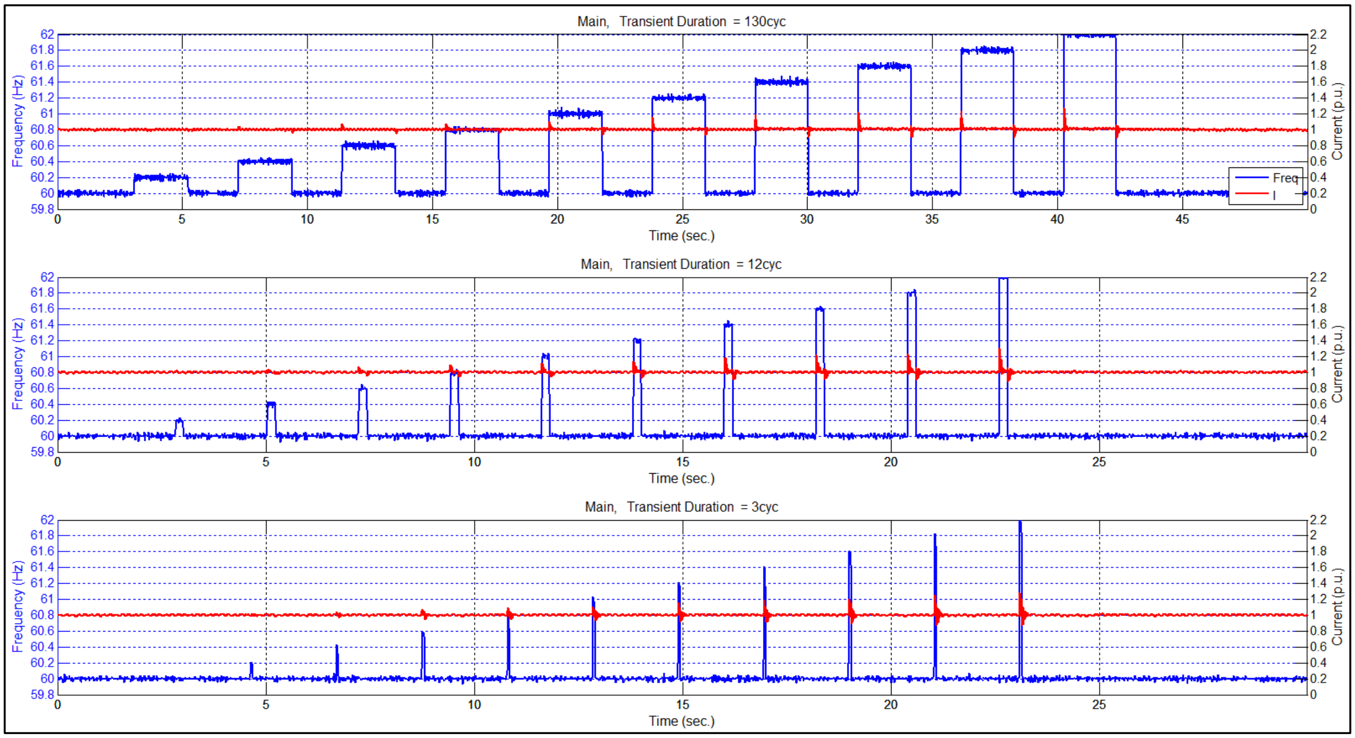

Figure 8.7.1 A/C #6 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Thermostat (Y)	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 60.2Hz,... 62Hz	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz,... 62Hz	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz,... 62Hz	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

8.8 Frequency Oscillations

The following figure shows the performance of A/C unit #6 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates.

Current, real power, and reactive power remain within +3% of their nominal values for swing frequencies 0.10 Hz and 0.25 Hz. Faster oscillation rates, such as swing frequencies of 0.70, 1.0, and 2.0 Hz, reveal deviation up to +8.5% from their nominal consumption values.

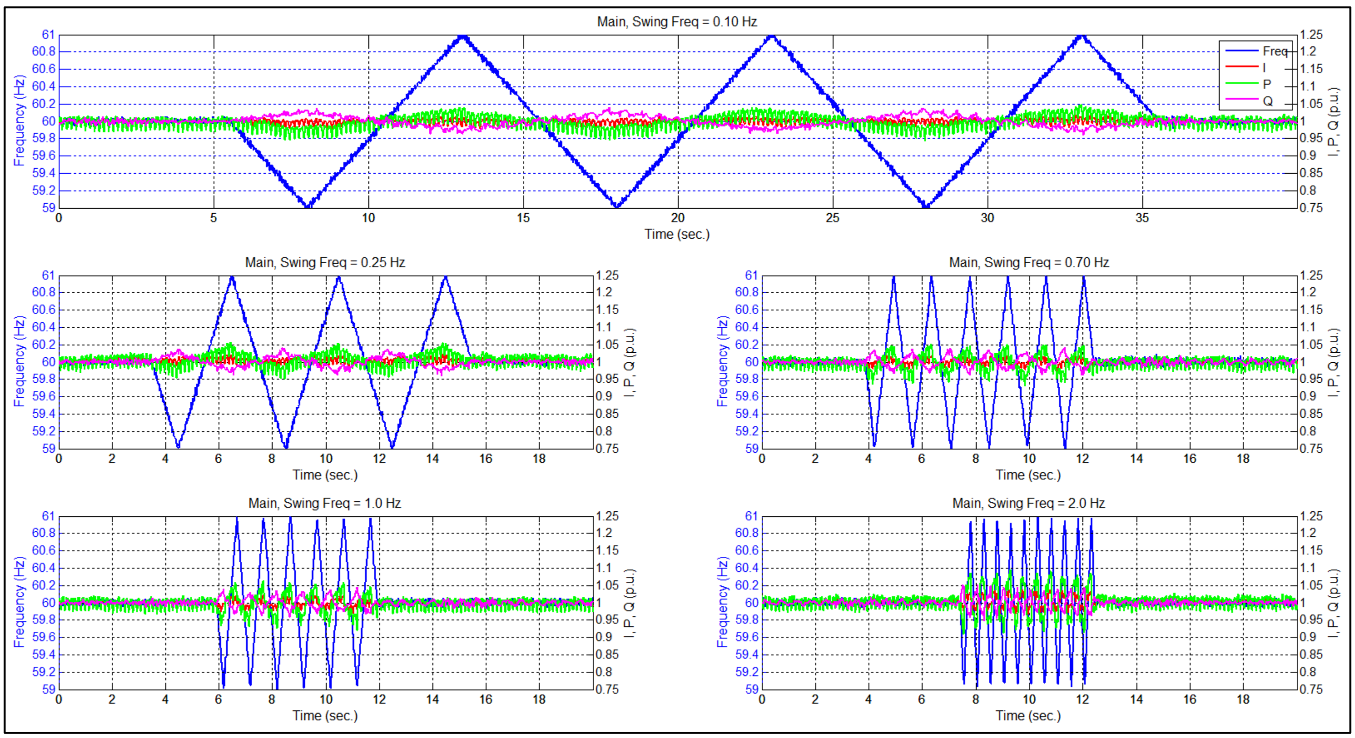

Figure 8.8.1 A/C #6 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

8.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit was found to trip when ramping down to 50% nominal voltage. Therefore the following figure shows the load performance at different voltage levels during voltage ramping down to 60% of nominal.

Current ramps up opposite of voltage to approximately 28% above nominal. Real power consumption begins drooping during the voltage ramp tests down to 7% below nominal. Reactive power deviates the greatest ramping down to 54% below its nominal value.

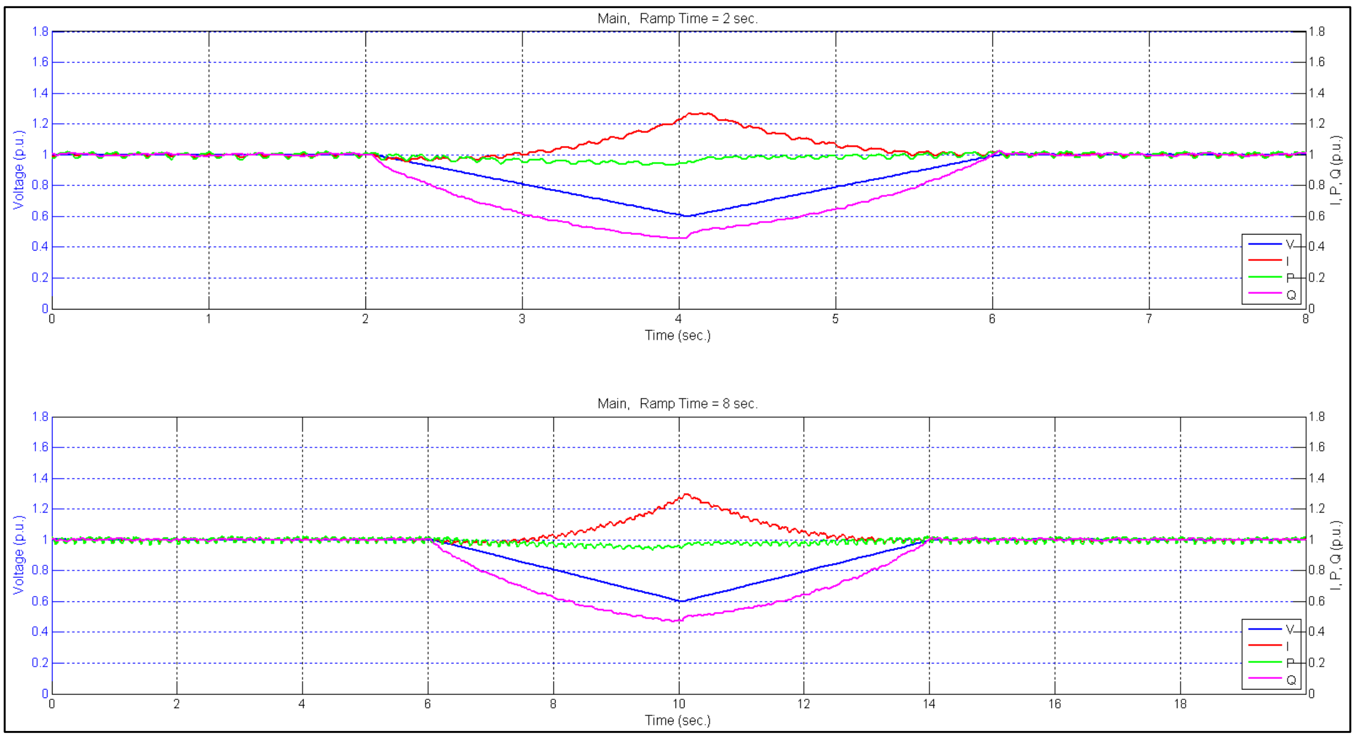

Figure 8.9.1 A/C #6 Voltage Ramp Down to 60% (2 & 8 sec.)

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

Current and real power gradually ramps up with voltage to 7% and 4% above their respective steady state values. Reactive power ramps up to approximately 35% above of nominal reactive load consumption at the peak of the voltage ramp before returning to steady state.

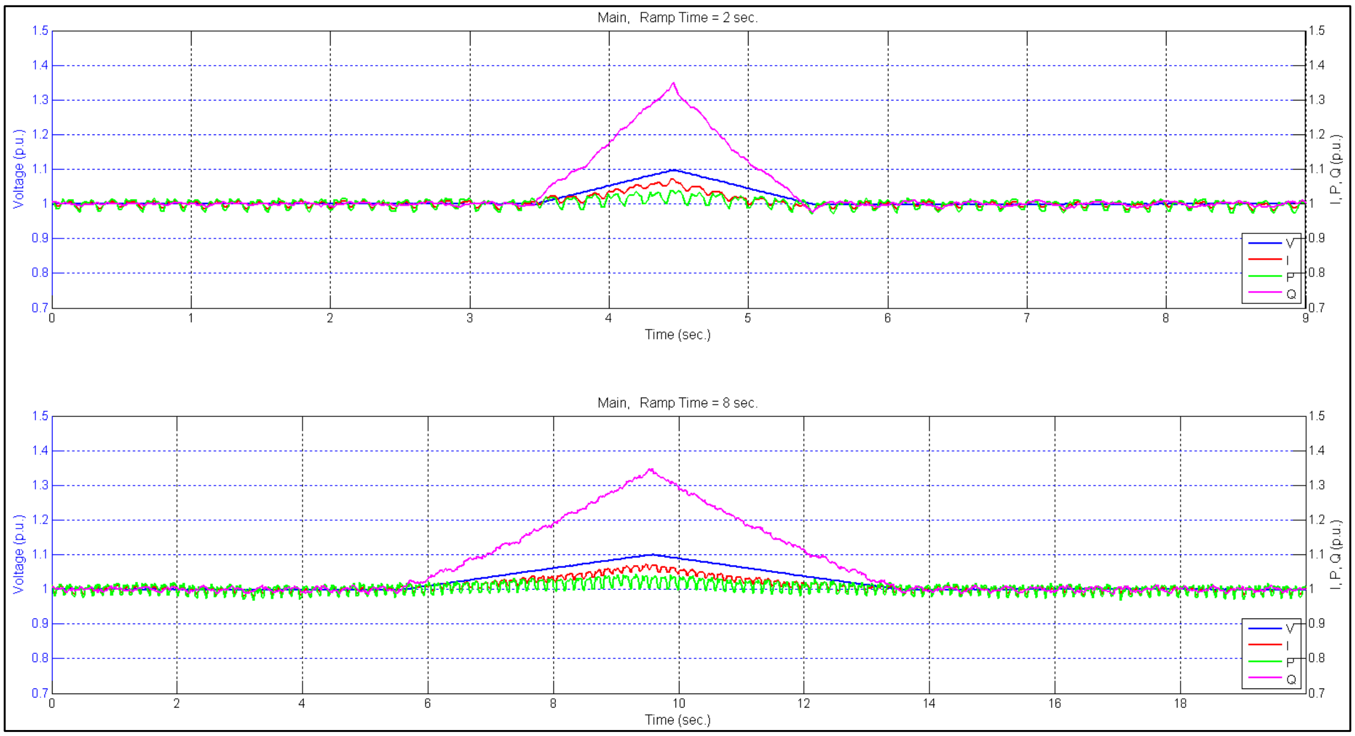

Figure 8.9.2 A/C #6 Voltage Ramp Up to 110% (in 2 & 8 sec.)

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.

Current ramps up, opposite of frequency, to 23.5% above its nominal output at the peak of the frequency ramp test. Real power consumption gradually decreases reducing consumption by as much as 20% below steady state. In contrast, reactive power actually ramps up to a maximum of 60% above of its normal consumption.

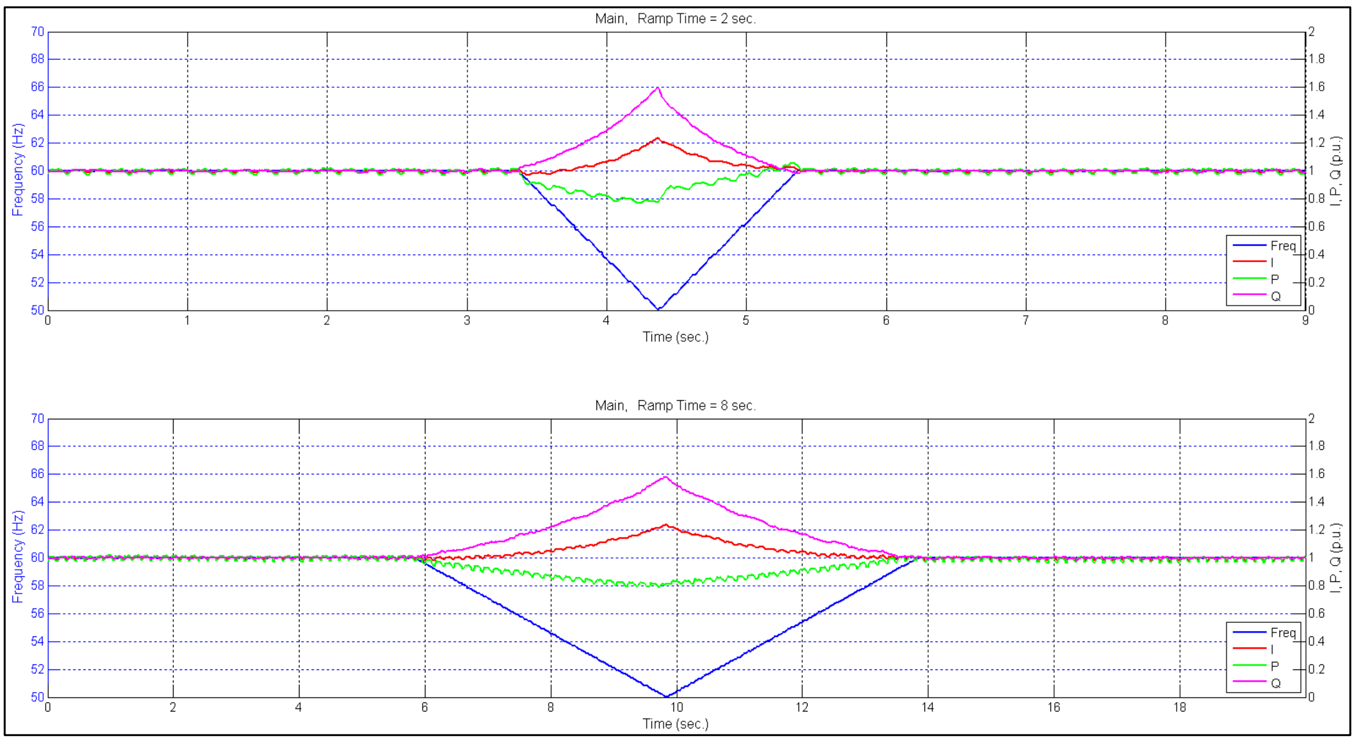

Figure 8.10.1 A/C #6 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

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 and real power are observed ramping up with frequency. Current peaks at 17% and 14% above steady state during the two frequency ramp tests. Similarly real power peaks at 38% and 33% above nominal consumption. Reactive power consumption is slowly reduced by nearly 15% below steady state during the frequency ramp.

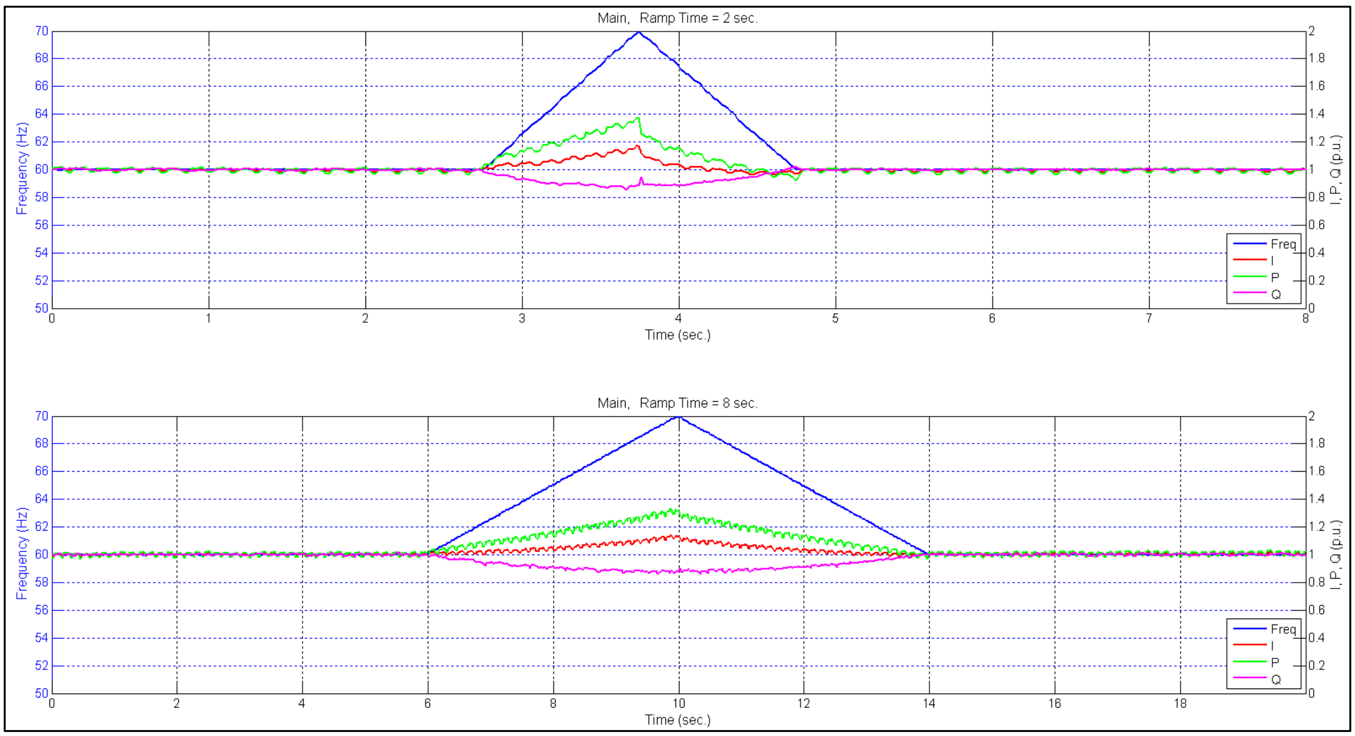

Figure 8.10.2 A/C #6 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

8.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times to calculate the harmonic contribution of A/C unit #6 to the grid. The total harmonic distortion of current on all phases was determined to be just over 2% of the fundamental. The following table gives the total harmonic distortion for each phase ad the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)					
	$V_{A\,(L\text{-}N)}$	$V_{B\,(L\text{-}N)}$	$V_{C\,(L\text{-}N)}$	I_A	I_B	I_C
1	0.11	0.11	0.11	1.86	1.66	2.03
2	0.11	0.11	0.11	1.85	1.65	2.02
3	0.11	0.11	0.11	1.92	1.70	2.07

Table 8.11.1 A/C #6 Total Harmonic Distortion

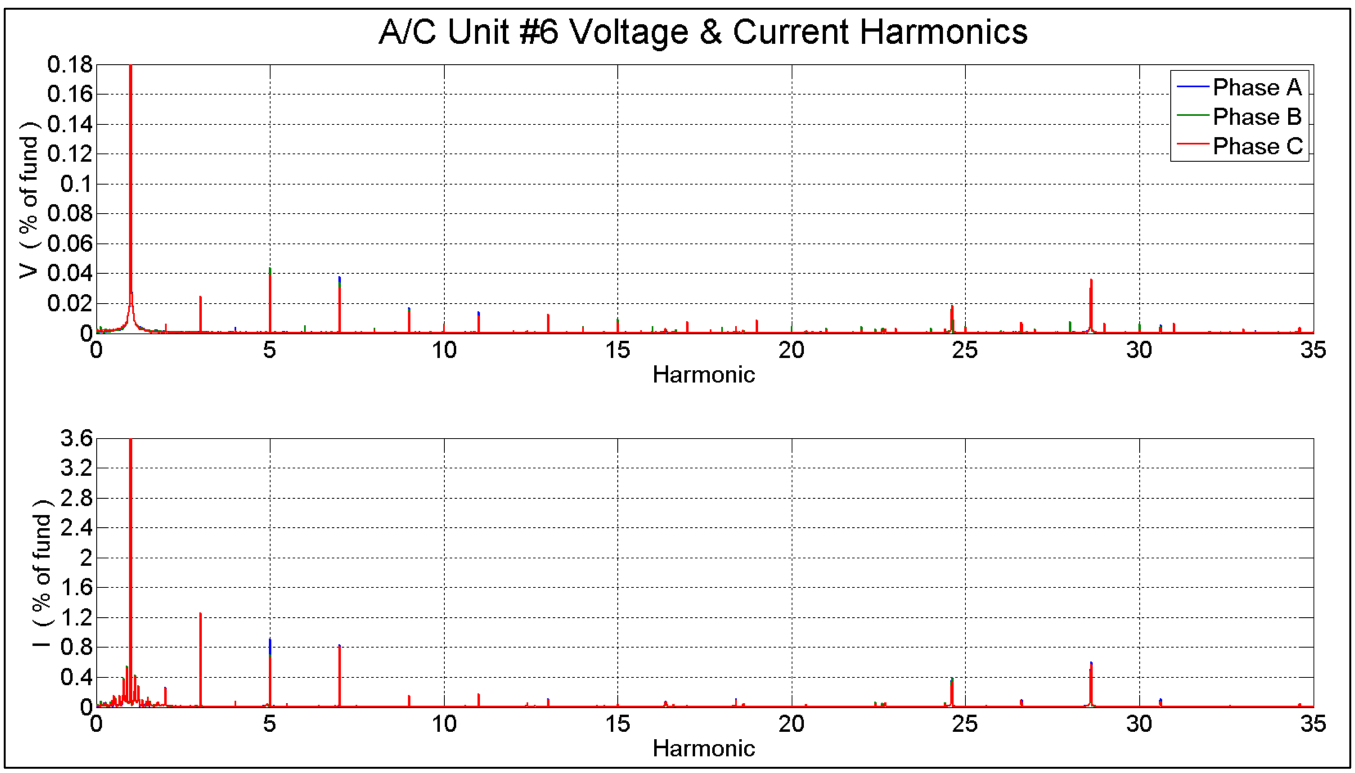

Figure 8.11.1 A/C #6 Harmonics Contribution

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. Although the outdoor conditions were warm the loading of the compressor was approximately 68% of the rated load amps.

CVR has little impact on current and real power consumption. Current increases slightly but remains within 2% of nominal and real power remains within 3% of nominal over the course the entire test. Reactive power load does step down with the voltage, decreasing by approximately 2.14% nominal reactive power for every 1% decrease in nominal voltage.

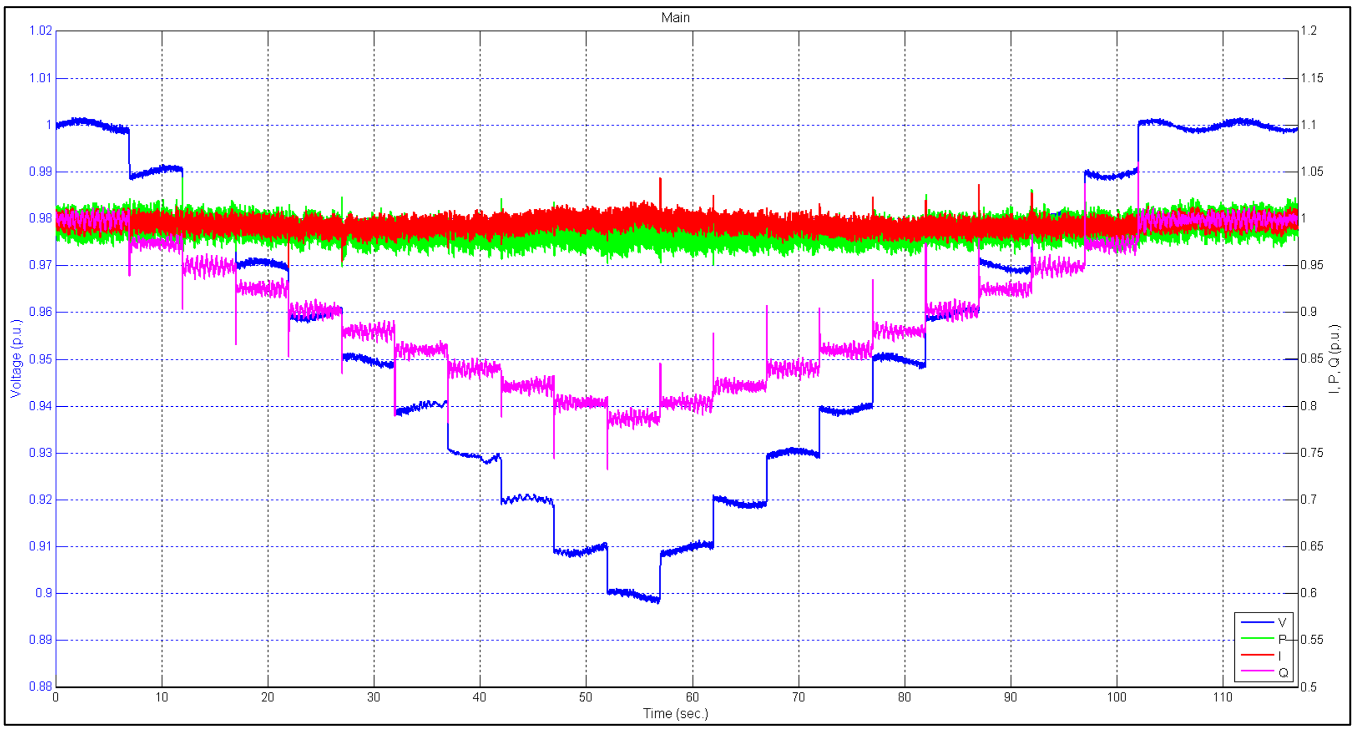

Figure 8.12.1 A/C #6 CVR Response Down to 90% Voltage

Alternatively, the service voltage at A/C #6 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.

Similar to the CVR test during under-voltage values, current and real power remain close to steady state. The average values for both of these parameters remain within 2% of nominal consumption. Reactive power is observed stepping up with the voltage and increases by 3% nominal reactive power for every 1% increase in nominal voltage.

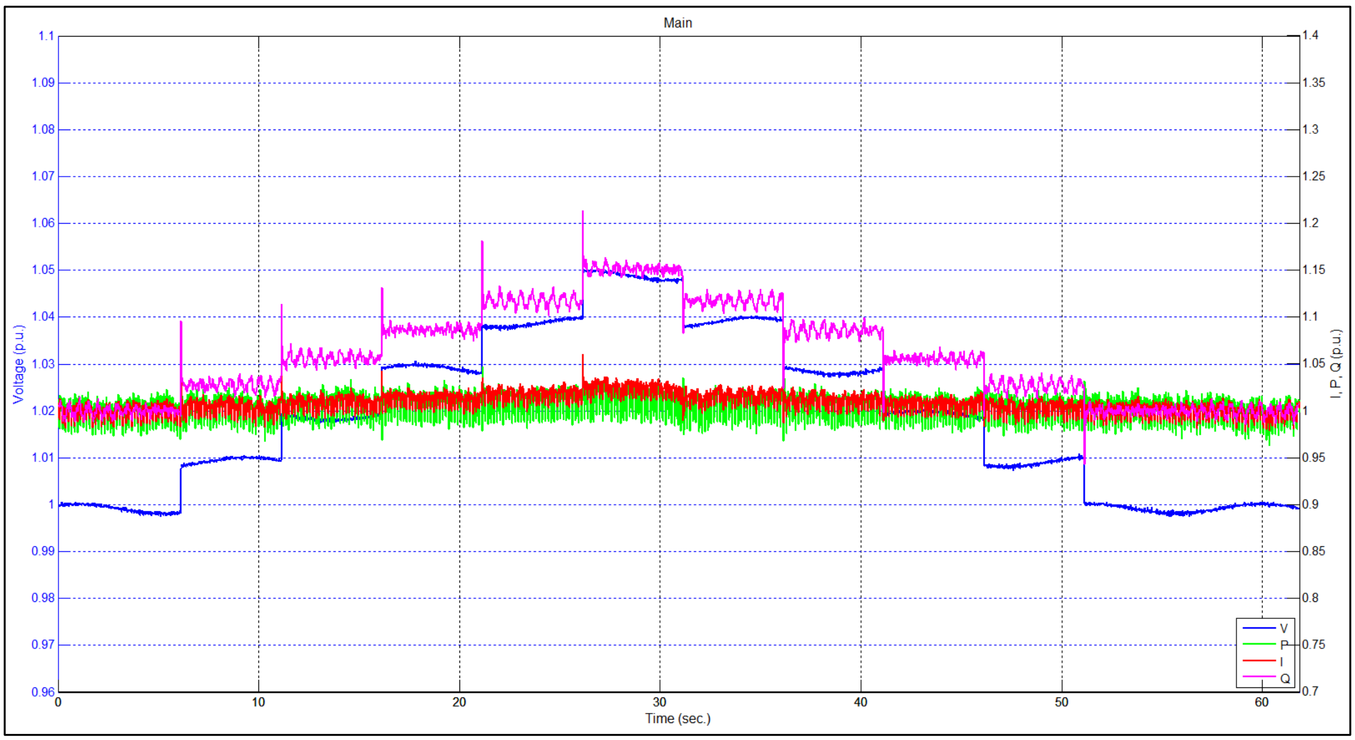

Figure 8.12.2 A/C #6 CVR Response Up to 105% Voltage

8.13 Compressor Stalling

While A/C unit #6 did reveal stalling behavior during certain instances of unbalanced under-voltages of at least two phases, compressor stalling did not occur during balanced under-voltage conditions. The contactors and/or controls dropped out causing the compressor to shut down before stalling was possible. Additionally, the unit would restart normally after the contactor reclosed several minutes later.

Therefore several additional under-voltage tests were performed after making modifications to the device controls in order to induce compressor stalling behavior during balanced under-voltage conditions. Rather than using the service voltage from the main terminals of the A/C unit to serve the step-down transformer (24 V output) and power the controls, a separate power supply was used to energize these controls (contactor coils, thermostat, etc.) to bypass any dropout behavior.

Previous tests revealed that dropout had consistently occurred at 50% which was used as a starting point for these additional under-voltage tests. A series of under-voltage sags were performed in 1% voltage decrements with duration times of 3 seconds as shown in the following figures. Compressor #1 began stalling during the 45% voltage dip and compressor #2 at the 44% voltage dip, but neither of them stalled immediately. Compressors #1 and #2 take approximately 39 and 48 cycles to fully stall and enter locked rotor condition at these voltages. Notice that stalling was identified by the dramatic increase in current and reactive power as well as the reduced mechanical vibration of the compressor. Lower voltage magnitudes resulted in faster stalling behavior as witnessed when stalling occurs within approximately 20 cycles at 41% nominal voltage.

The compressors restarted from their stalling condition in 4.2 cycles after voltage returns to nominal. Both consistently restarts after each and every voltage sag performed. Voltage was also held below 44% voltage indefinitely which caused thermal overload protection to occur between 24 and 30 seconds after stalling begins.

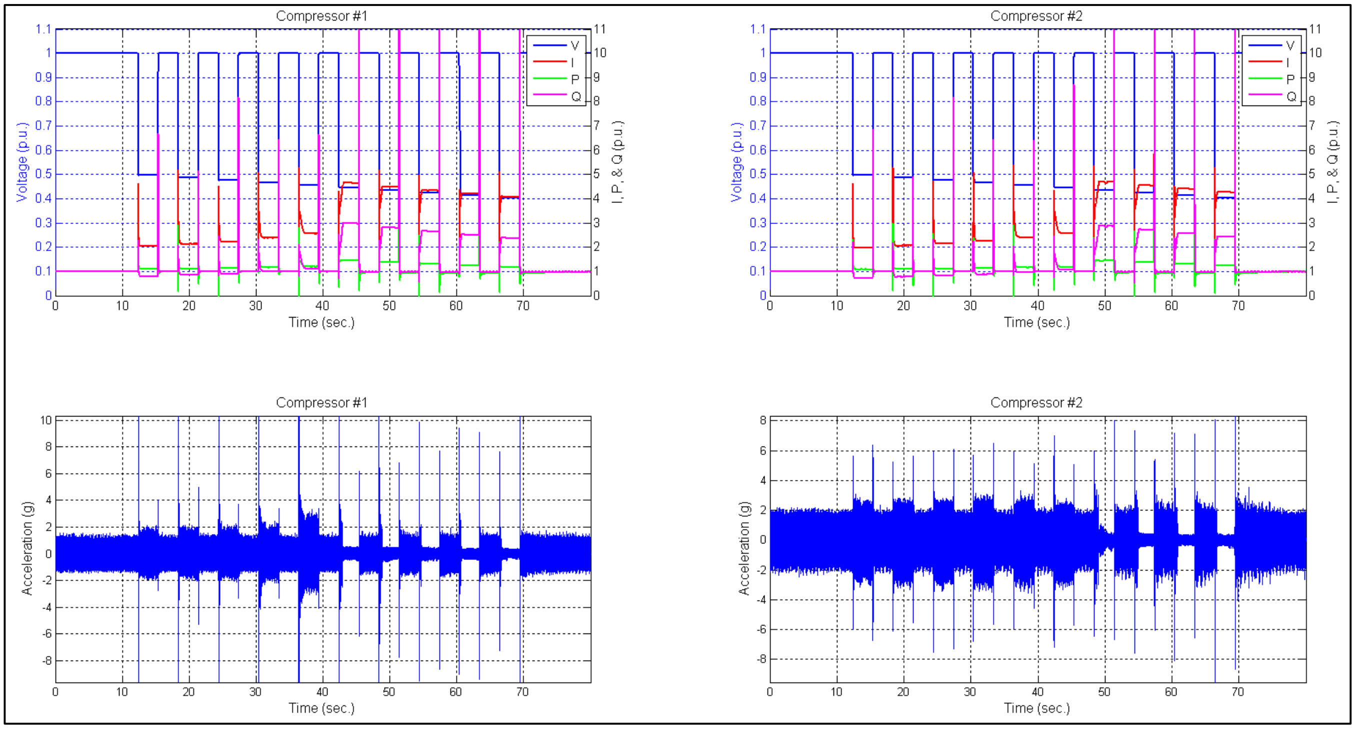

Figure 8.13.1 A/C #6 Compressor Stalling During Under-voltages (50% to 41% voltage)

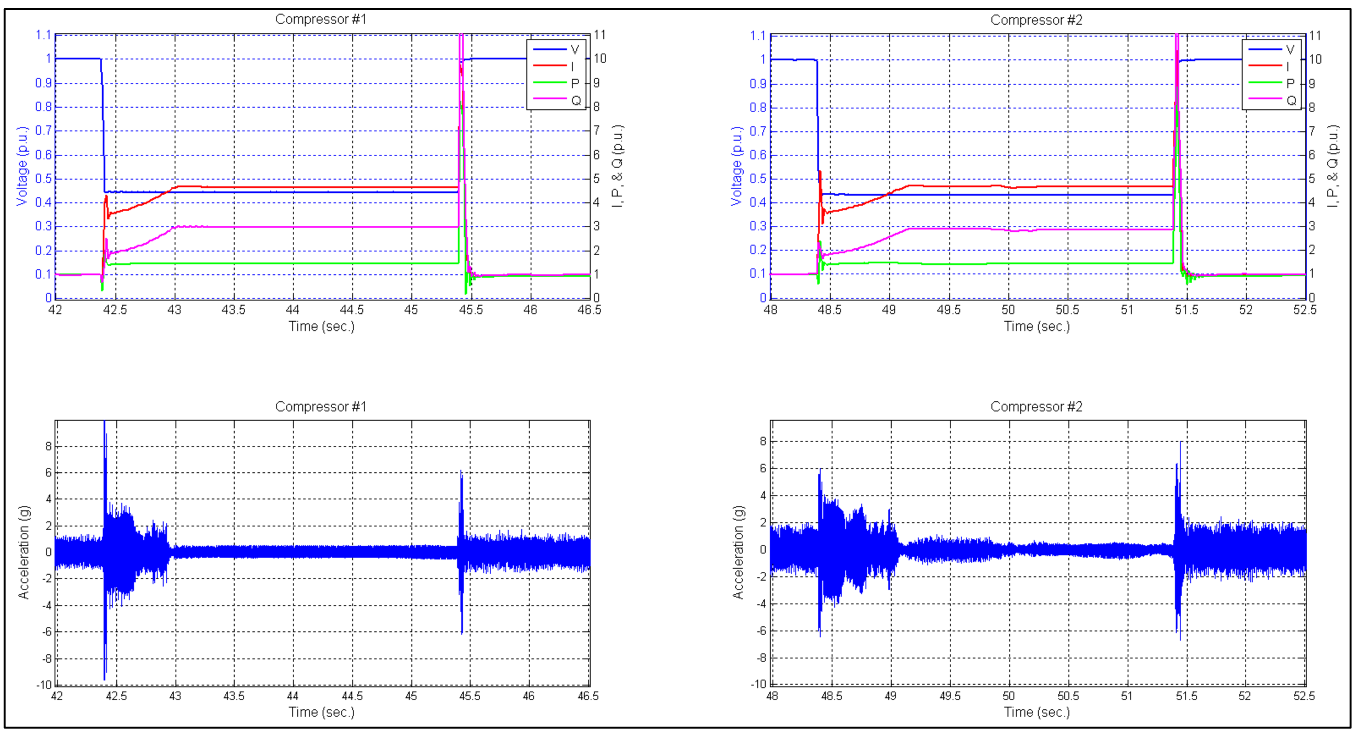

Figure 8.13.2 A/C #6 Compressor Stalling During Under-voltage (45% & 44% voltage)

Additionally, a voltage ramp test was performed to capture the dual compressor's current, real power, and reactive power consumption at different voltage levels as shown in the figure below. The stalling point for compressor #1 current, real power, and reactive power reached 4.4 pu, 1.4 pu, and 2.7 pu while the restarting points for the same parameters increased to as large as 4.2 pu, 1.5 pu, and 2.5 pu. The stalling point for compressor #2 current, real power, and reactive power reached 4.4 pu, 1.4 pu, and 2.7 pu while the restarting points for the same parameters increased to as large as 4.5 pu, 1.5 pu, and 2.8 pu.

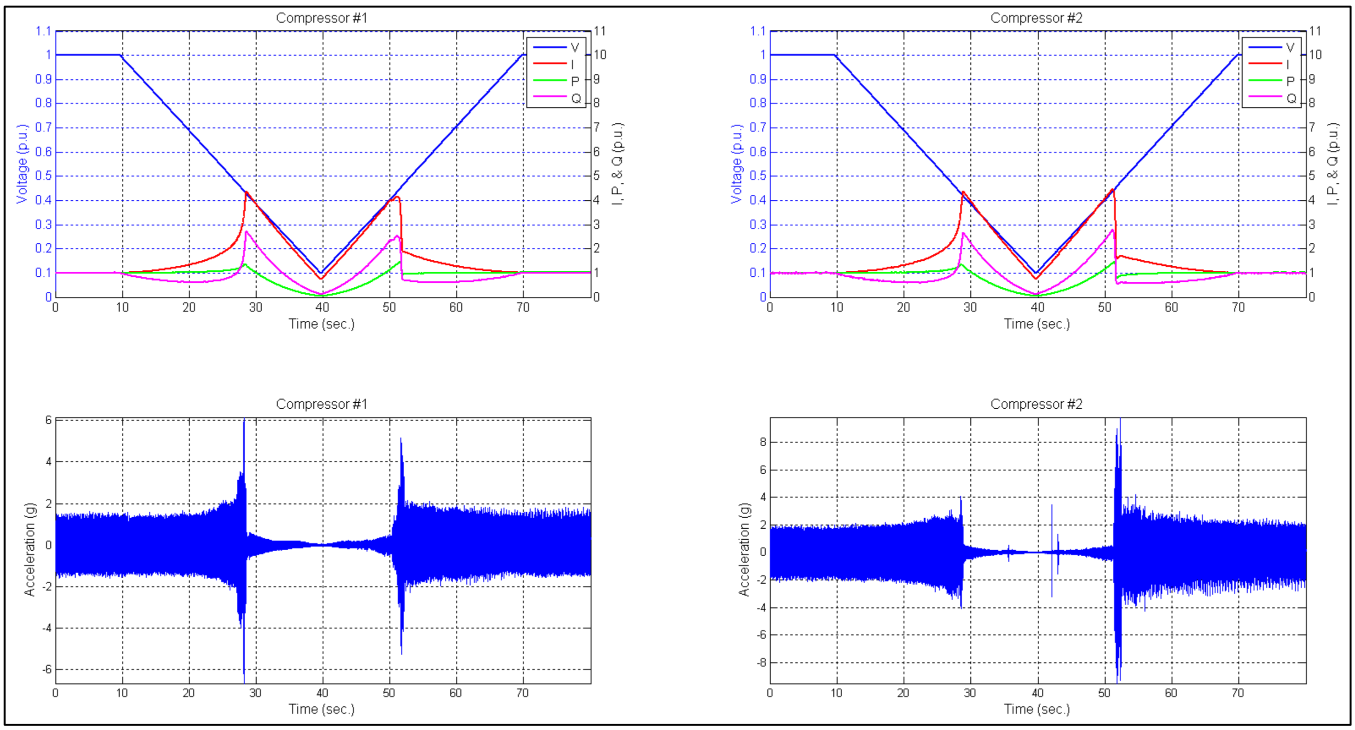

Figure 8.13.3 A/C #6 Compressor Stalling During Voltage Ramp

9.0 AIR CONDITIONER #7 TEST RESULTS

The seventh air conditioner tested is a 10-ton unit operated at 480 V line-to-line. The unit is comprised of a single indoor blower fan motor, outdoor fan motor, and dual compressor motors. Both compressor motors were monitored individually (voltage, current, and acceleration) due to the fact that each compressor is connected with its own power contactor. The specifications for the individual components of A/C #7 are provided in the table below.

Main System		**Compressors**	
Manufacturer	Trane	Manufacturer	Alliance
Model	WSC120E4R0A	Model	SPA054A4BPA
Size (Tons)	10	Type	Scroll
Voltage (V)	460	Quantity	2
Refrig.	R-410A	RLA (Amps)	9
SEER	-	LRA (Amps)	62
EER	11.2	Test Press. High (PSI)	449
IEER	13.1	Test Press. Low (PSI)	238
Condenser Fan		**Blower Motor**	
Drive Type	Direct	Type	Direct
Quantity	1	Quantity	1
Motor HP	3/4	Motor HP	3.75
RPM	1100	RPM	Variable
FLA (Amps)	1.5	FLA (Amps)	4.3
Miscellaneous Components			
Contactor(s)	Homer, XMCO-323-EBBCOOF	Capacitor(s)	-
Transformer	Trane, x13550266020	Phase Balance Relay	Trane, X13100407-3

Table 9.0.1 A/C #7 Specifications

9.1 Compressor Shutdown

A/C #7 was shut down during normal operation using the connected thermostat. The figure below displays the measurements taken at the main service connections as well as the behavior of the individual motors.

The compressors and outdoor fan motor shut down at the same time shortly after triggering the thermostat. The only power consumption after the compressors shut down was from the indoor fan motor operating at 3-phase 480 V with approximately 0.65 amps per phase (total of 500 W or 525 VA). However, this motor shuts down 62 seconds after the other components.

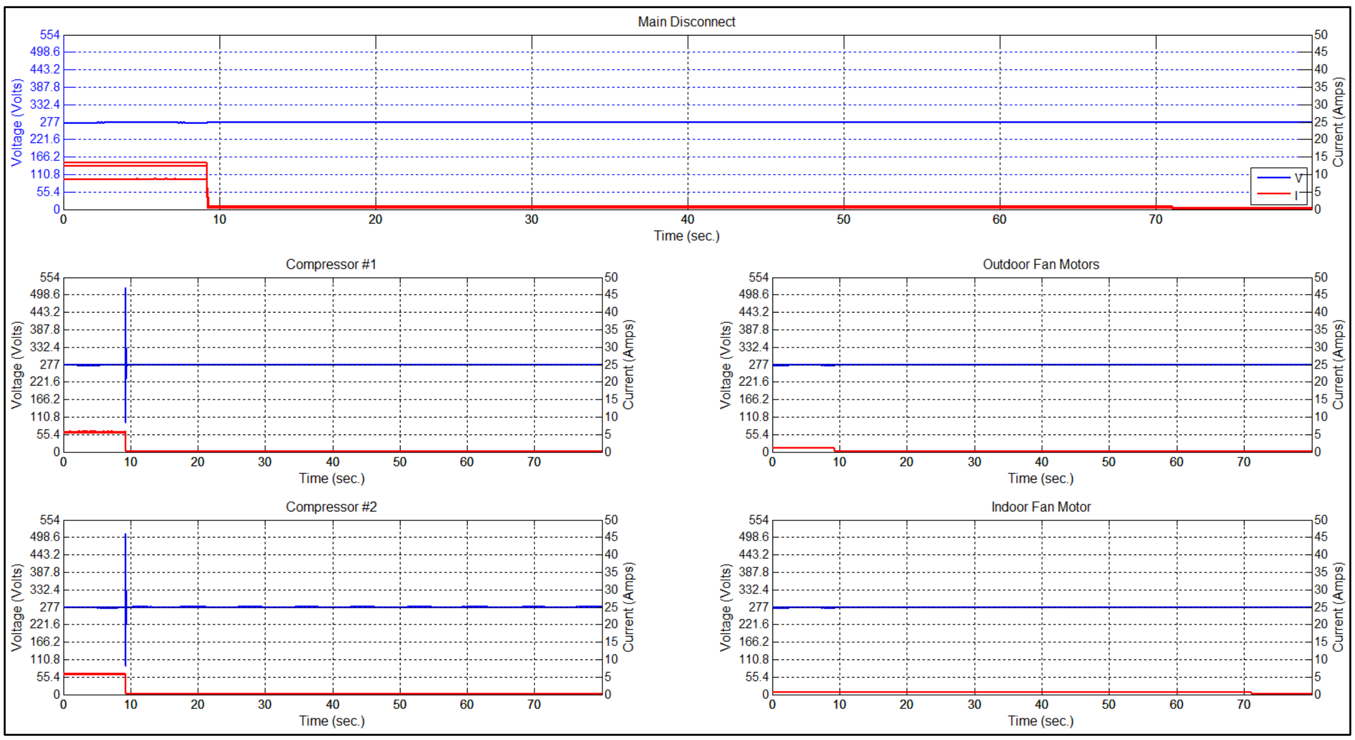

Figure 9.1.1 A/C #7 Compressor Shutdown

9.2 Inrush Current

After starting up A/C unit #7 via the programmable thermostat, compressor #1 starts up first followed almost immediately by both the indoor and the outdoor fan motors approximately 20 cycles later. However the compressor #2 does not start up for approximately 180 seconds later. The largest inrush currents observed at the main disconnect of the unit indicates a maximum value of 75.8 Amps and a duration time of 6 cycles.

Compressor #1 Inrush: Maximum of 69.7 Amps and duration of 5 cycles

Compressor #2 Inrush: Maximum of 72.1 Amps and duration of 6 cycles

Outdoor Fan Motor Inrush: Maximum of 5.3 Amps and duration of 1.2 seconds

Indoor Fan Motor Inrush: Maximum of 1 Amp and a duration of 8 seconds

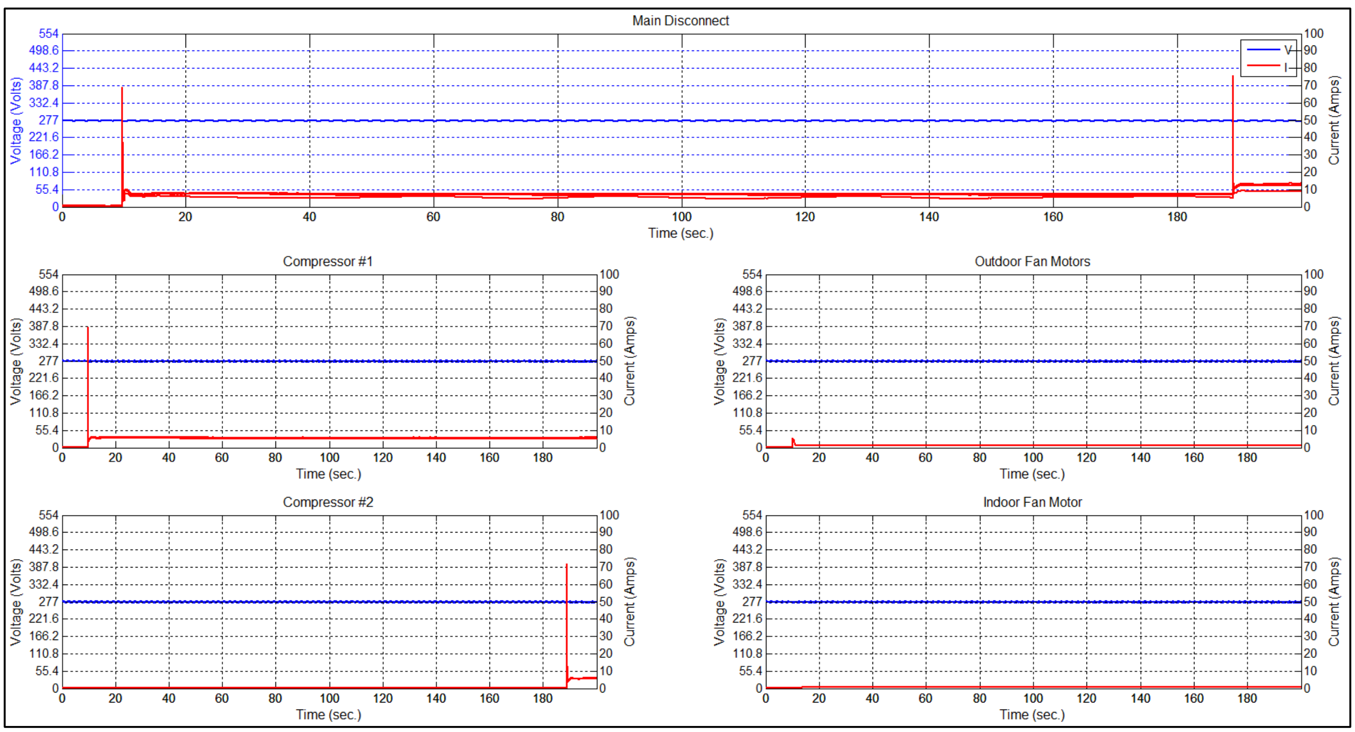

Figure 9.2.1 A/C #7 Inrush Current

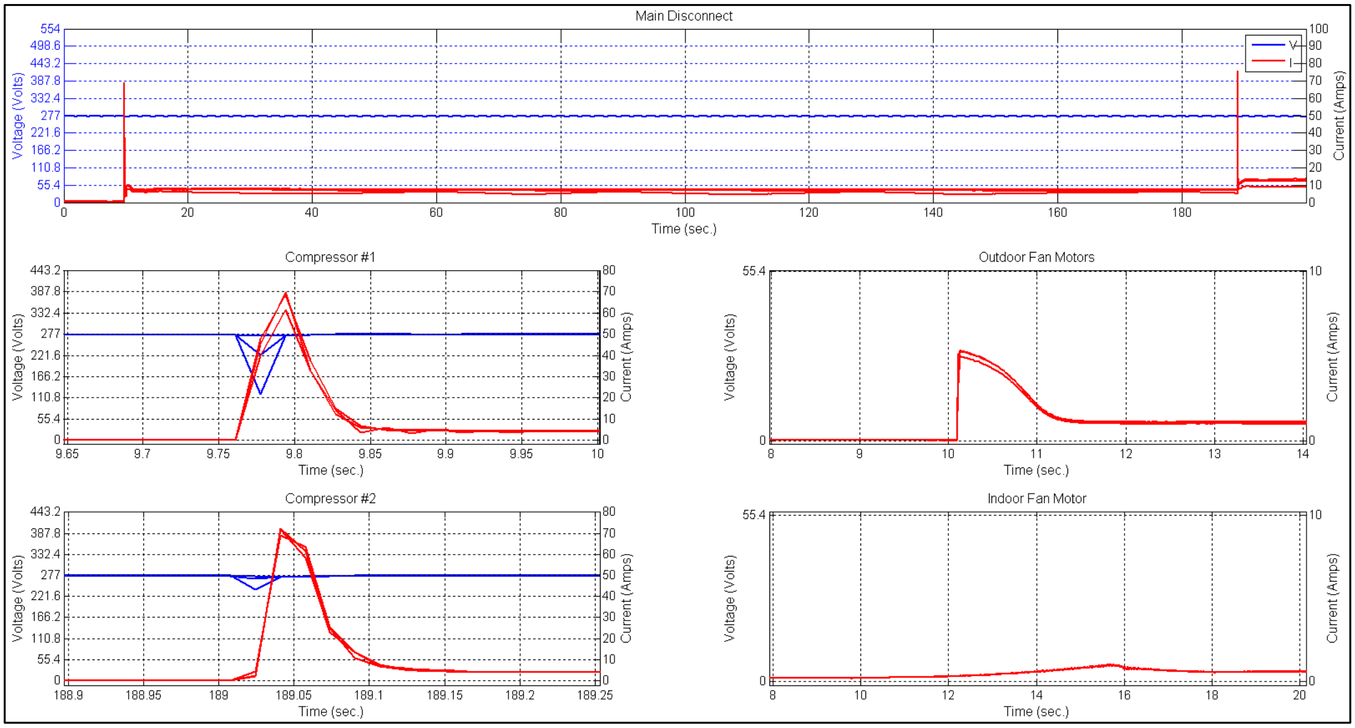

Figure 9.2.2 A/C #7 Inrush Current [Zoom In]

9.3 Balanced & Unbalanced Under-voltages

Control voltage measurements (24 V) were monitored at the phase monitor relay and contactor coils to help determine the root cause of compressor tripping during A/C #7 under-voltage tests. Stalling behavior was only observed during one of the two-phase (B and C) unbalanced under-voltage tests. All balanced voltage sag tests resulted in the contactor opening before stalling could occur. Contactor chattering was sometimes observed during the voltage step changes during the voltage sag tests. Data captured several seconds after the disconnection of the compressor did not reveal immediate contactor reclosing for all tests. However, the contactor for compressor #2 did reclose on several occasions after voltage recovered.

Balanced voltage sags on all three phases in decrements of 10% revealed that the contactors would consistently open at 50% nominal voltage for transients with a duration in the range of 3 to 130 cycles. Contactors would open during the first 2 cycles of the voltage sag. Several of the under-voltage tests showed that the compressor #2 contactor reclosed within 1.2 cycles after recovering from 50% to nominal voltage, and would repeat the process for the remaining voltage sags (Notice that there are no trip voltages/times for “Cmp#2 Contactor Coil” for these cases in Table 9.3.1 since voltage across the coil never went to zero). Most of the balanced under-voltage tests resulted in the compressor contactors remaining open until the unit restarted several minutes later.

The only case where the contactor remained closed and the compressor motor rode through balanced 0% under-voltage sags was during switching transients with a duration time of 1 cycle. “N/A” or “not applicable” is placed in the following tables under “Compressor #1” and “Compressor #2” to represent these ride through situations where there is no trip voltage or trip time available.

A/C unit #7 is equipped with a phase monitor relay, like A/C #1, to detect any imbalances between the three phases. From Table 9.3.1, we see that the phase monitor relay dropped out at 20% nominal voltage in 11 cycles after the start of the voltage sag. Therefore it was not the cause of the contactors opening at 50% voltage during the various balanced under-voltage tests.

The following figure visually displays one of the longer duration (130 cycle) balanced under-voltage tests as measured at the main disconnect and at the various motors.

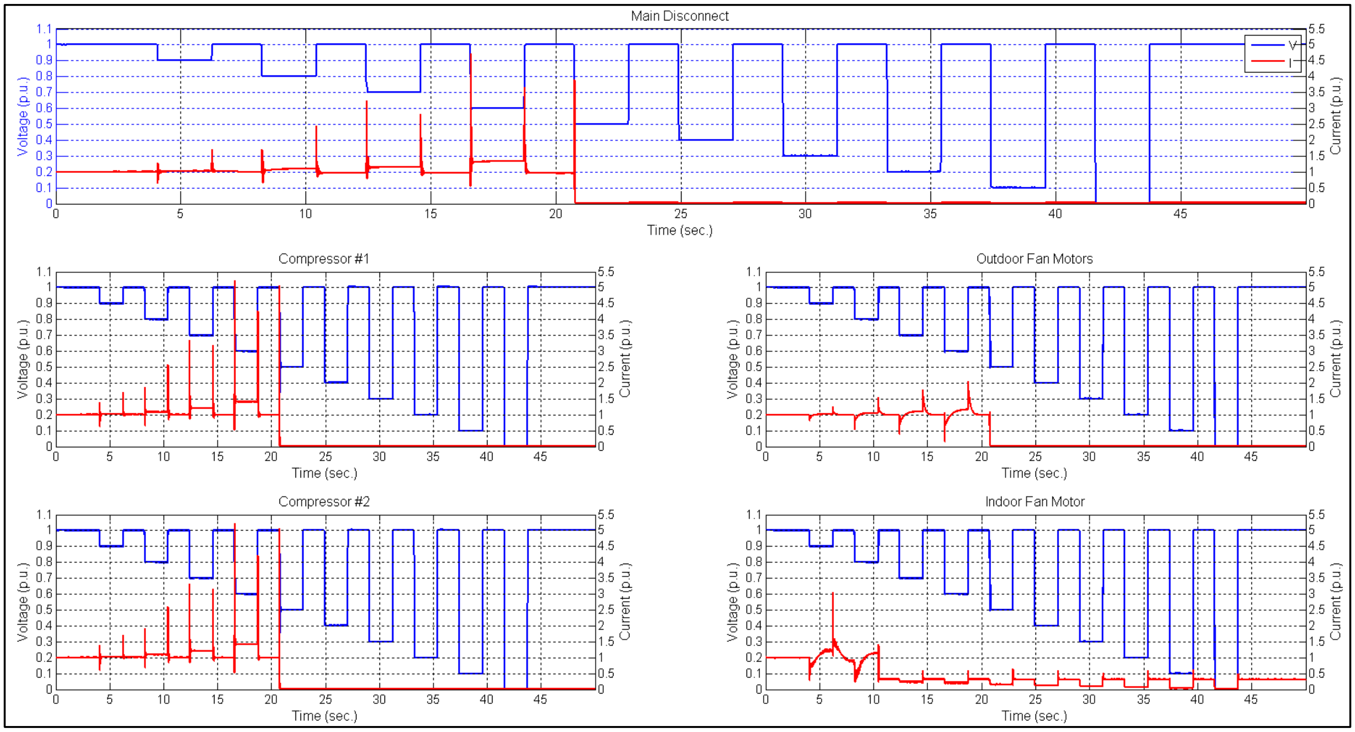

Figure 9.3.1 A/C #7 Balanced Under-voltage Response (130 cycles)

The following table provides the details regarding the compressor contactors operation and control voltage measurements during the various under-voltage tests with different duration times. The trip voltage represents the magnitude where the compressor contactors opened and where the control voltages (at the contactor coils and phase monitor relay) disappeared. The trip time is how long it takes for this action to occur after the start of the voltage sag.

Under-Voltage Transient		Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Phase Monitor Relay	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
100%, 90%, 80%,... 0%	130	50%	2	50%	2	50%	30	30%	67	20%	10
		50%	2	50%	2	50%	29	50%	29	20%	10
		50%	2	50%	2	50%	30	50%	30	20%	10
100%, 90%, 80%,... 0%	12	50%	2	50%	2	50%	28	N/A	N/A	20%	11
		50%	2	50%	2	50%	30	50%	30	20%	10
		50%	2	50%	2	50%	29	50%	29	20%	10
100%, 90%, 80%,... 0%	6	50%	2	50%	2	50%	37	N/A	N/A	N/A	N/A
		50%	1	50%	2	50%	34	50%	35	N/A	N/A
		50%	2	50%	2	50%	29	N/A	N/A	N/A	N/A
100%, 90%, 80%,... 0%	3	50%	2	50%	2	50%	29	N/A	N/A	N/A	N/A
		50%	2	50%	2	50%	30	50%	30	NA	NA
		50%	2	50%	1	50%	34	50%	34	NA	NA
100%, 90%, 80%,... 0%	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

In order to narrow down the voltage where the compressors are disconnected and dropout occurs for the contactor and/or controls, additional balanced under-voltage tests were performed in decrements of 1% nominal voltage. The contacts opened or began chattering between 59% and 52% nominal voltage. Some cases resulted in quick dropout behavior, only 1.8 to 3 cycles after the start of the voltage sag, while others showed the contactors opening tens of cycles after voltage had already recovered. The following table provides the trip voltages and trip times measured from the start of the voltage sag for various 1% voltage decrement tests.

Under-Voltage Transient		Compressor #1		Compressor #2	
Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
60%, 59%, 58%, …	130	59%	64.92	59%	64.92
60%, 59%, 58%, …	130	59%	60.96	54%	1.8
60%, 59%, 58%, …	12	58%	44.94	56%	3
60%, 59%, 58%, …	12	57%	41.2	52%	3

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

Unbalanced under-voltages on A/C unit #7 resulted in lower magnitude trip voltages because the controls (including the contactor coils) are energized using one of the line-to-line supply voltages, phase A to phase B. Phase A to B under-voltages are therefore similar to the results of the balanced under-voltage tests and phase C under-voltage transients do not result in contactor dropout.

Table 9.3.3 shows the detailed results for the unbalanced under-voltage tests where the phase monitor relay drops out consistently at 40% voltage between 85 and 98 cycles after the start of the voltage sag. Stalling behavior was also discovered during one of the 130 cycle unbalanced under-voltages for $V_{\Phi B\text{-}\Phi C}$. When phases B and C experience under-voltage, the compressor takes approximately 16.2 cycles to completely stall at 20% nominal voltage before tripping off at 10% nominal voltage as shown in the following figure. The unit immediately restarts within 5 cycles after voltage returns to nominal.

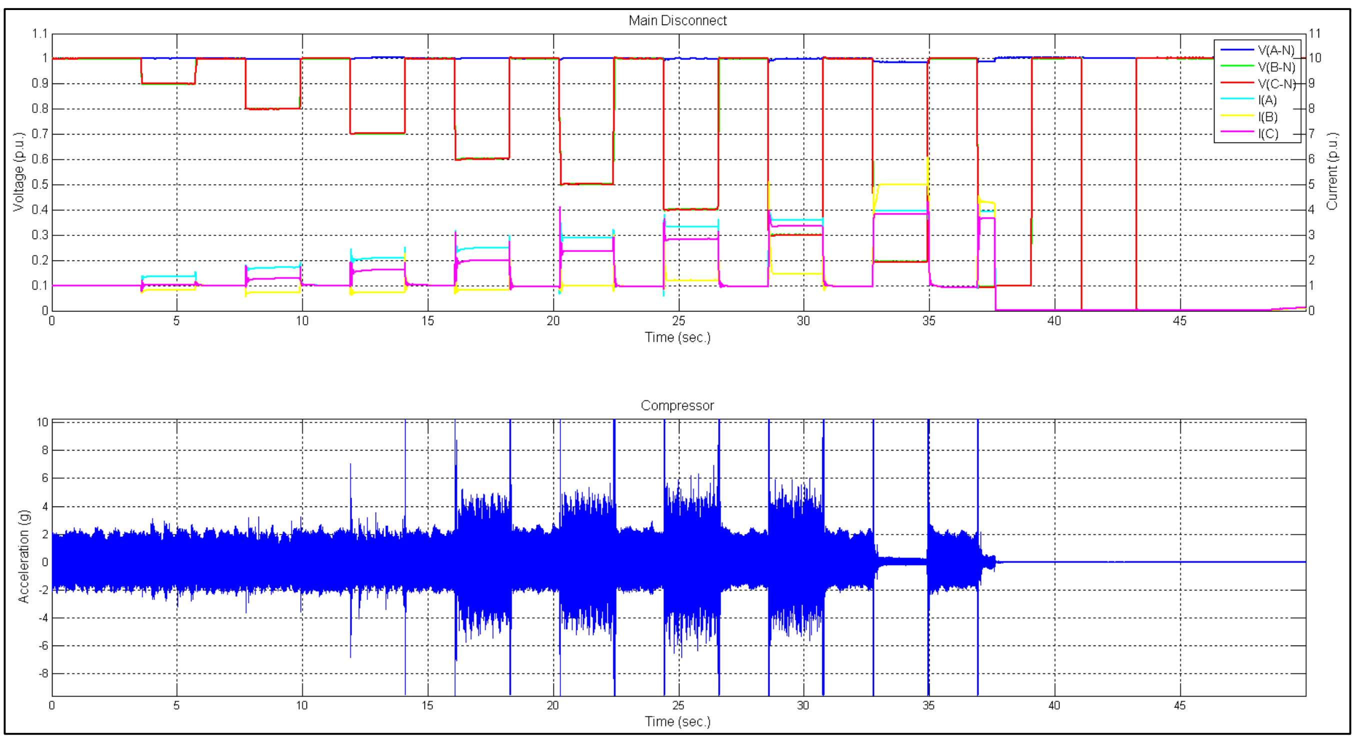

Figure 9.3.2 A/C #7 Unbalanced Under-voltage Response (Phases B & C, 130 cycles)

Under-Voltage Transient			Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Phase Monitor Relay	
Φ	**Volt Range**	**Duration (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**	**V_{trip} (%)**	**t_{trip} (cyc)**
A	100%, 90%,... 0%	130	40%	115	40%	115	40%	116	40%	116	40%	89
		12	0%	35	0%	35	0%	36	0%	36	N/A	N/A
		9	0%	34	0%	2	0%	33	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 90%,... 0%	130	40%	103	40%	103	40%	103	40%	103	40%	77
		12	0%	29	0%	29	0%	28	0%	28	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 90%,... 0%	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 90%,... 0%	130	50%	2	50%	2	50%	30	50%	120	50%	98
		12	50%	2	50%	2	50%	34	50%	34	20%	11
		9	50%	2	50%	2	50%	28	N/A	N/A	N/A	N/A
		6	50%	2	50%	2	50%	28	50%	28	N/A	N/A
		3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 90%,... 0%	130	10%	43	10%	43	10%	42	10%	42	40%	96
		12	0%	33	0%	33	0%	32	0%	32	N/A	N/A
		9	0%	30	0%	30	0%	30	0%	30	NA	NA
		6	0%	31	0%	2	0%	30	N/A	N/A	N/A	N/A
		3	0%	35	N/A	N/A	0%	34	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 90%,... 0%	130	40%	110	40%	110	40%	110	40%	110	40%	85
		12	10%	34	10%	34	10%	33	10%	33	N/A	N/A
		9	0%	36	0%	36	0%	35	0%	35	N/A	N/A
		6	0%	35	0%	2	0%	34	N/A	N/A	N/A	N/A
		3	0%	35	0%	2	0%	34	N/A	N/A	N/A	N/A
		1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

9.4 Balanced & Unbalanced Over-voltages

The A/C unit was subjected to balanced and unbalanced over-voltages within the parameters of the ITIC (CBEMA) curve to avoid damage. Multiple voltage swells were performed in 2% increments for up to 120% nominal voltage for each test. The following figure shows the balanced over-voltage test and the following table specifies the tests performed that resulted in voltage ride-through.

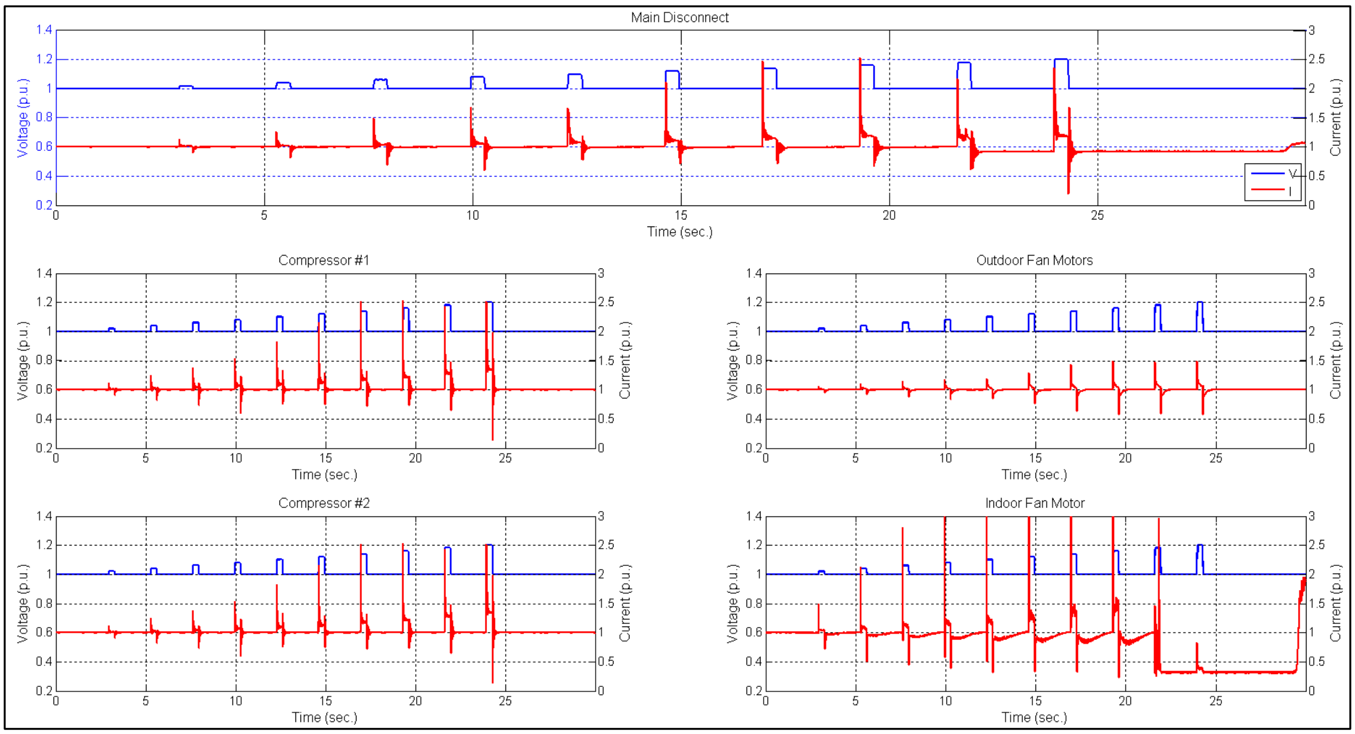

Figure 9.4.1 AC #7 Balanced Over-voltage Response (20 cycles)

Over-Voltage Transient			Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Phase Monitor Relay	
Φ	Volt Range	Duration (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)	V_{trip} (%)	t_{trip} (cyc)
ABC	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
A	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
B	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
AB	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
BC	100%, 102%,,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CA	100%, 102%,... 120%	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

9.5 Voltage Oscillations

The following figure shows the performance of A/C unit #7 at the main disconnect 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 2.5% above nominal for swing frequencies up to 1 Hz and up to 5% above nominal for 2 Hz. There appears to be a delay in the current response, especially as the swing frequency increases. Real power responds with a delay similar to current, but remains within approximately ±3% of nominal. Reactive power consumption experiences the largest oscillations (-22% to -30% deviation) in the same direction as voltage. At higher swing frequencies, deviations become larger both above and below steady state.

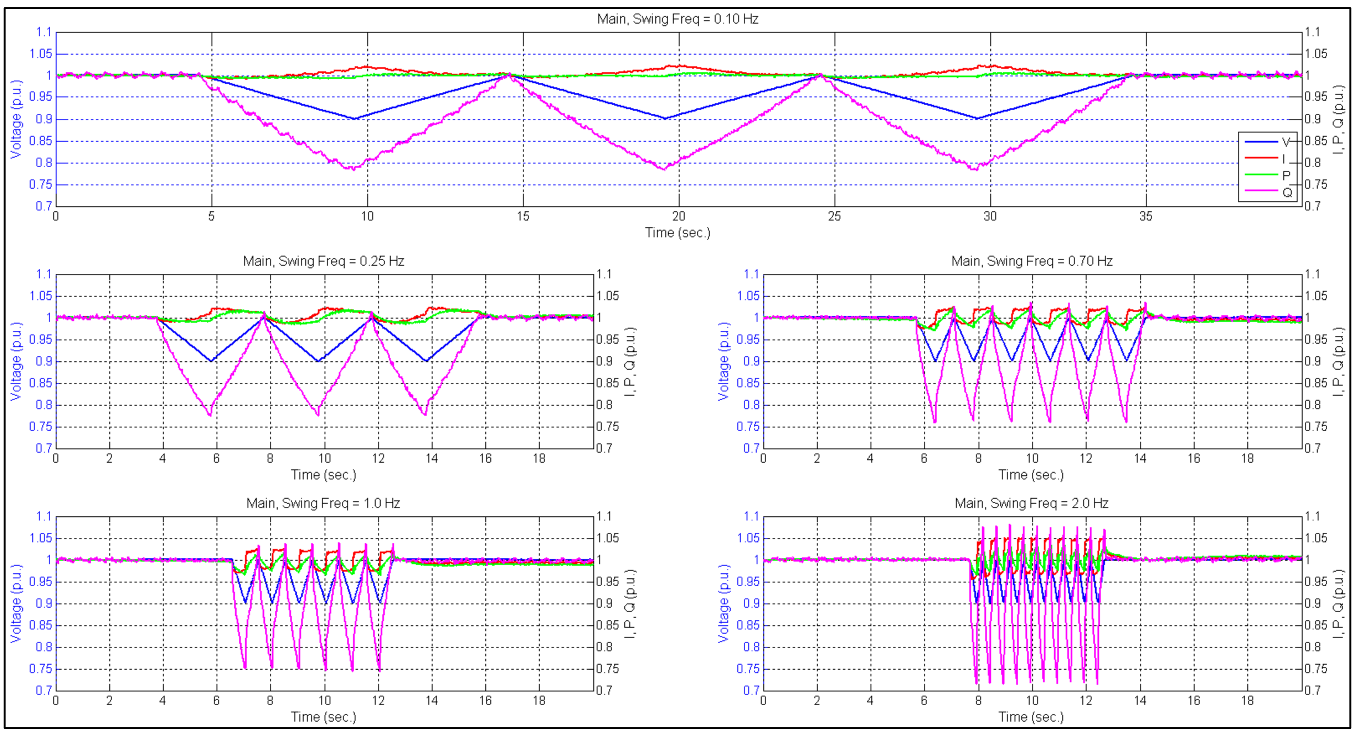

Figure 9.5.1 AC #7 Voltage Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

9.6 Under-frequency Events

After subjecting A/C #7 to multiple under-frequency transients with different duration times, the device does not appear to have under-frequency protection down to 58 Hz. The unit simply rides through these frequency conditions. The following figure and table identify the tests that were performed.

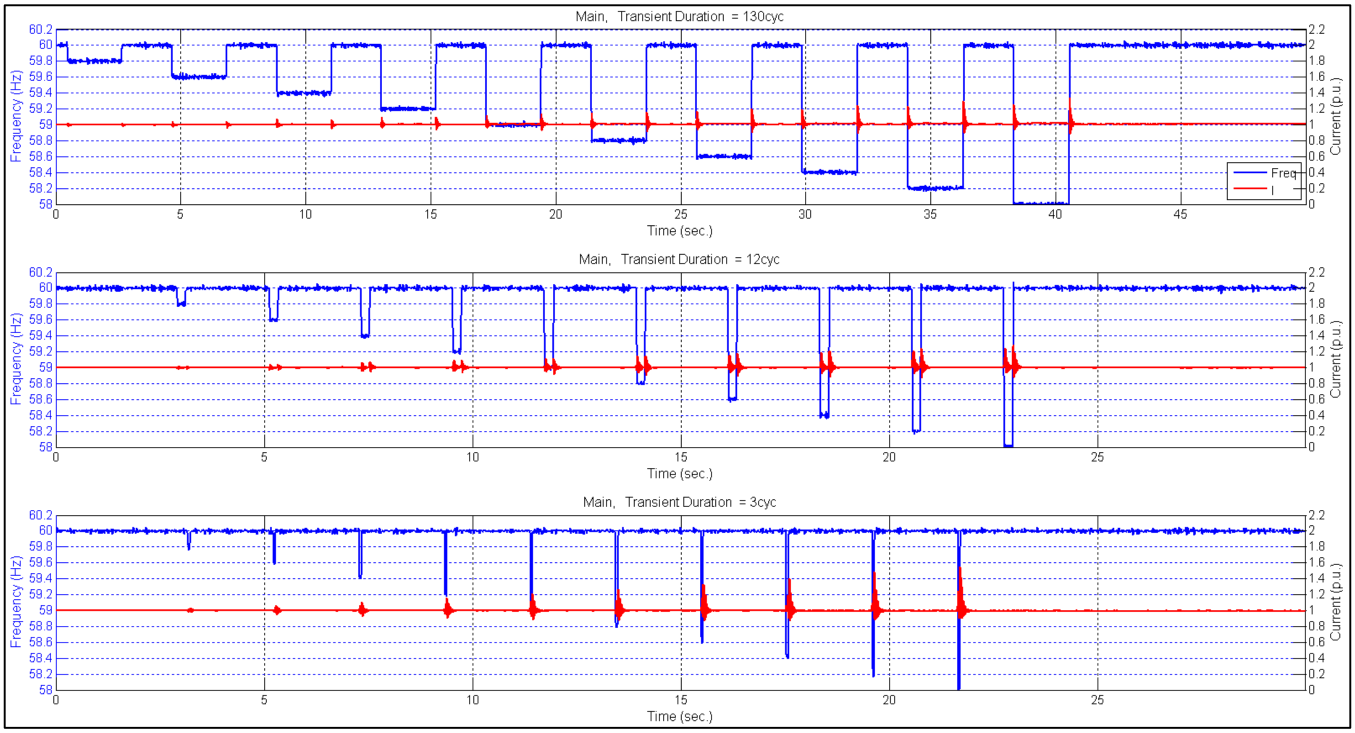

Figure 9.6.1 A/C #7 Under-frequency Response (130, 12, 3 cycles)

Under-Frequency Transient		Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Phase Monitor Relay	
Frequency Range	Duration (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)	F_{trip} (Hz)	t_{trip} (cyc)
60Hz, 59.8Hz,... 58Hz	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 59.8Hz,... 58Hz	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 59.8Hz,... 58Hz	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

9.7 Over-frequency Events

Similar to the under-frequency tests, A/C #7 was subjected over-frequency transients with different duration times up to 62 Hz. The unit did not trigger any over-frequency protection and continued operating as normal. The following figure and table identify the over-frequency tests that were performed.

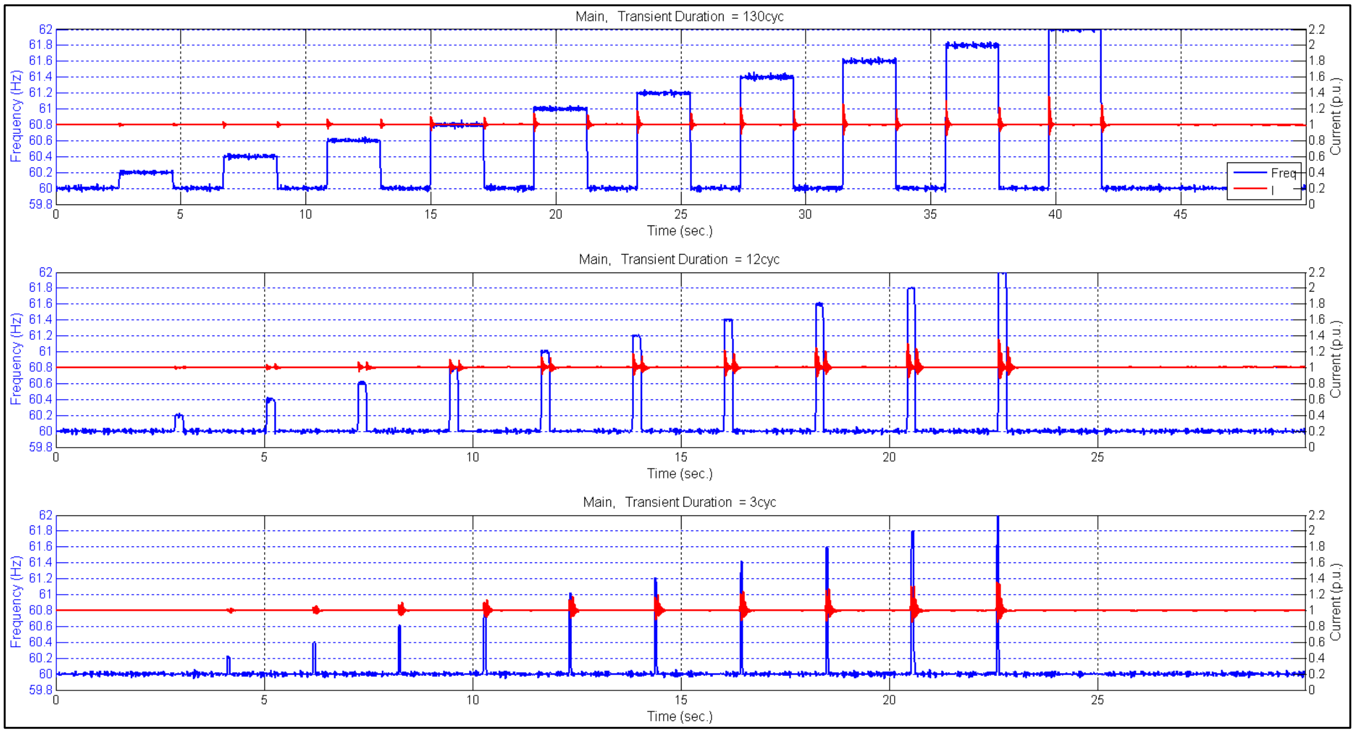

Figure 9.7.1 A/C #7 Over-frequency Response (130, 12, 3 cycles)

Over-Frequency Transient		Compressor #1		Compressor #2		Cmp#1 Contactor Coil		Cmp#2 Contactor Coil		Phase Monitor Relay	
Frequency Range	**Duration (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**	**F_{trip} (Hz)**	**t_{trip} (cyc)**
60Hz, 60.2Hz,... 62Hz	130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz,... 62Hz	12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60Hz, 60.2Hz,... 62Hz	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

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

9.8 Frequency Oscillations

The following figure shows the performance of A/C unit #7 during frequency oscillations between 59 Hz and 61 Hz for different swing frequencies or oscillation rates.

Current remains constant within +1% of its steady state value for all swing frequencies. Both real and reactive power experience larger deviations from nominal at higher swing frequencies or faster oscillation rates. Real power oscillates in the same direction as frequency while reactive power oscillates in the opposite direction of frequency, but both remain within approximately +5% of their nominal consumption.

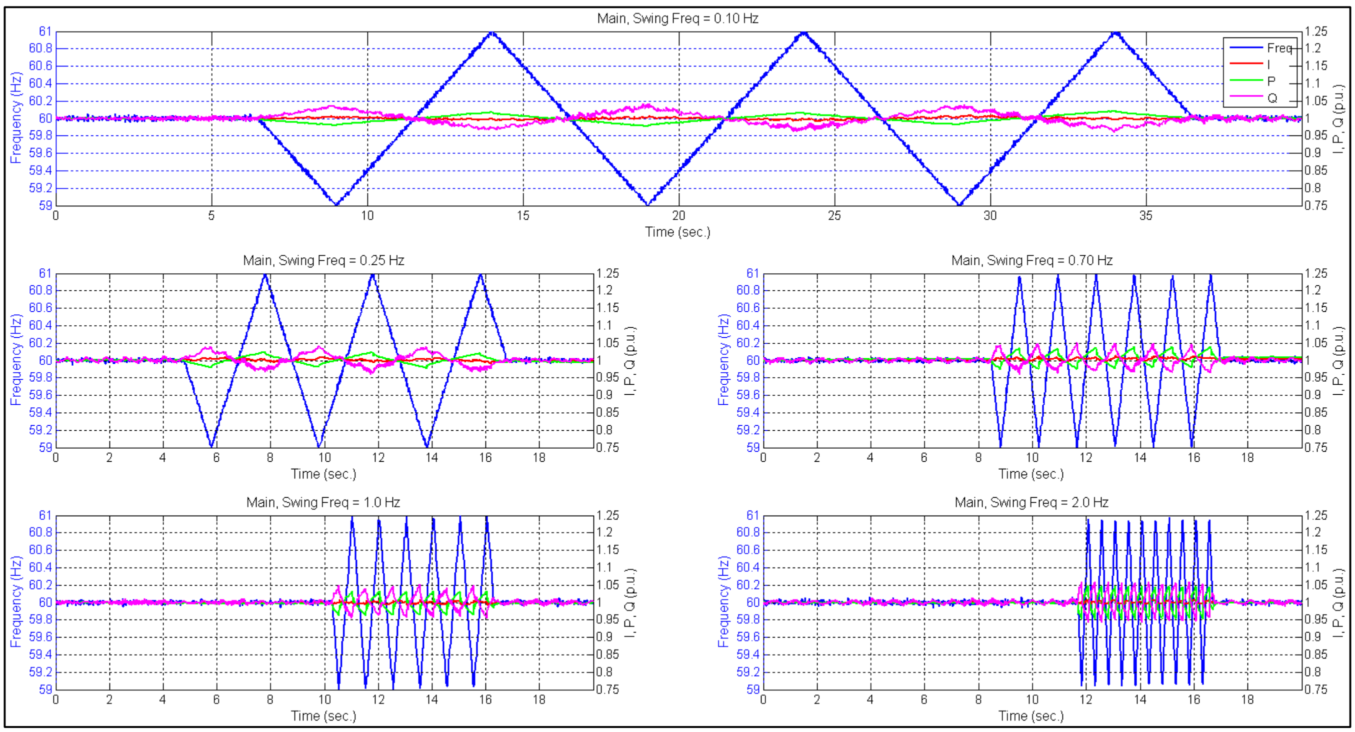

Figure 9.8.1 A/C #7 Frequency Oscillation Response (0.10, 0.25, 0.70, 1.0, 2.0 Hz)

9.9 Voltage Ramps

Voltage was ramped down and back up multiple times in 10% decrements until the A/C unit was found to trip when ramping down to 50% nominal voltage. Therefore the following figure shows the load performance at different voltage levels during voltage ramping down to 60% of nominal.

Current ramps up opposite of voltage to approximately 33% above nominal. Real power consumption reduces by approximately 7% below nominal during the voltage ramp. As voltage recovers, real power overshoots to 12% above nominal during the 2 second ramp test and to 4% above nominal during the 8 second ramp test. Reactive power decreases by 51% to 55% below its nominal value during the voltage ramp.

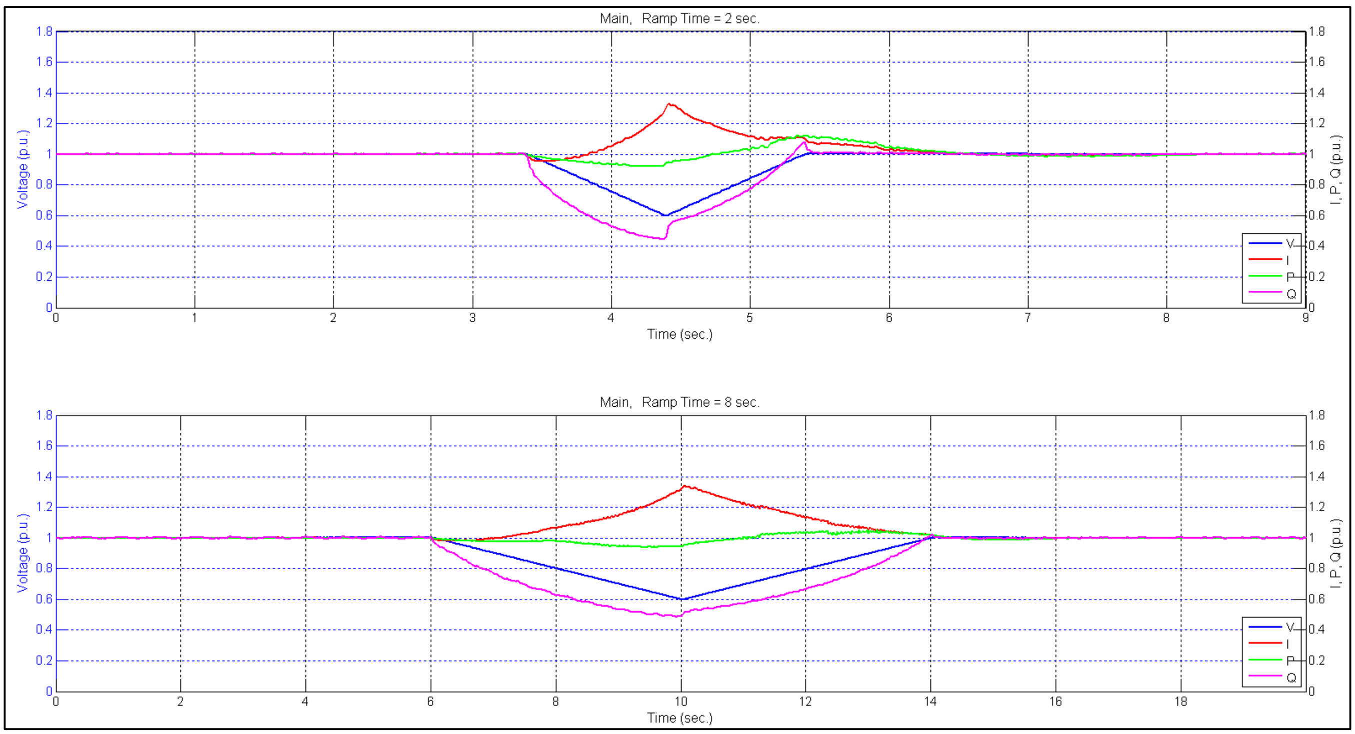

Figure 9.9.1 A/C #7 Voltage Ramp Down to 60% (2 & 8 sec.)

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

Current increases with voltage peaking at 8% and 6% above nominal for different ramp tests. Real power remain relatively constant, only slightly increasing consumption by nearly 3% above steady state. Reactive power ramps in the same direction as voltage peaking at approximately 36% above of nominal reactive load consumption.

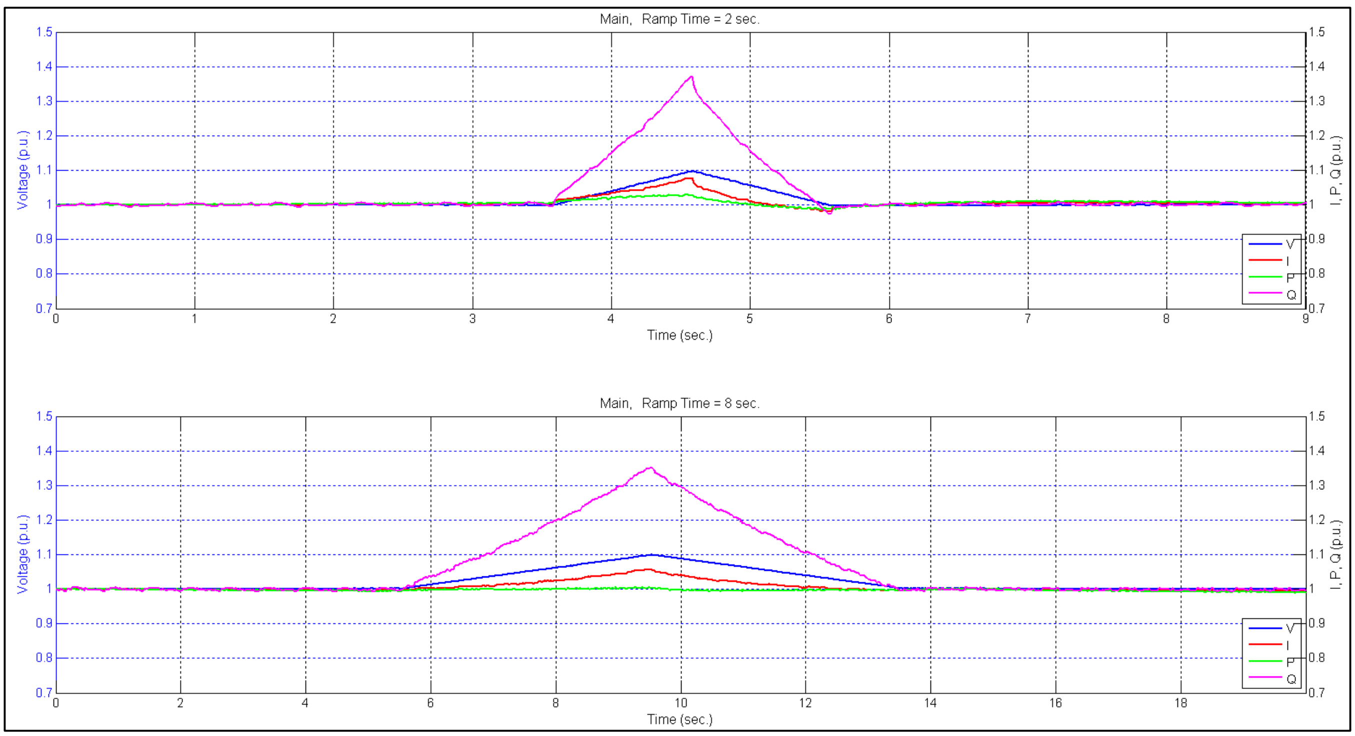

Figure 9.9.2 A/C #7 Voltage Ramp Up to 110% (in 2 & 8 sec.)

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 increases in response to the frequency peaking at 32% above its nominal output. Real power consumption decreases down to approximately 15% below steady state. Reactive power ramps up to a maximum of 73% above of its normal consumption.

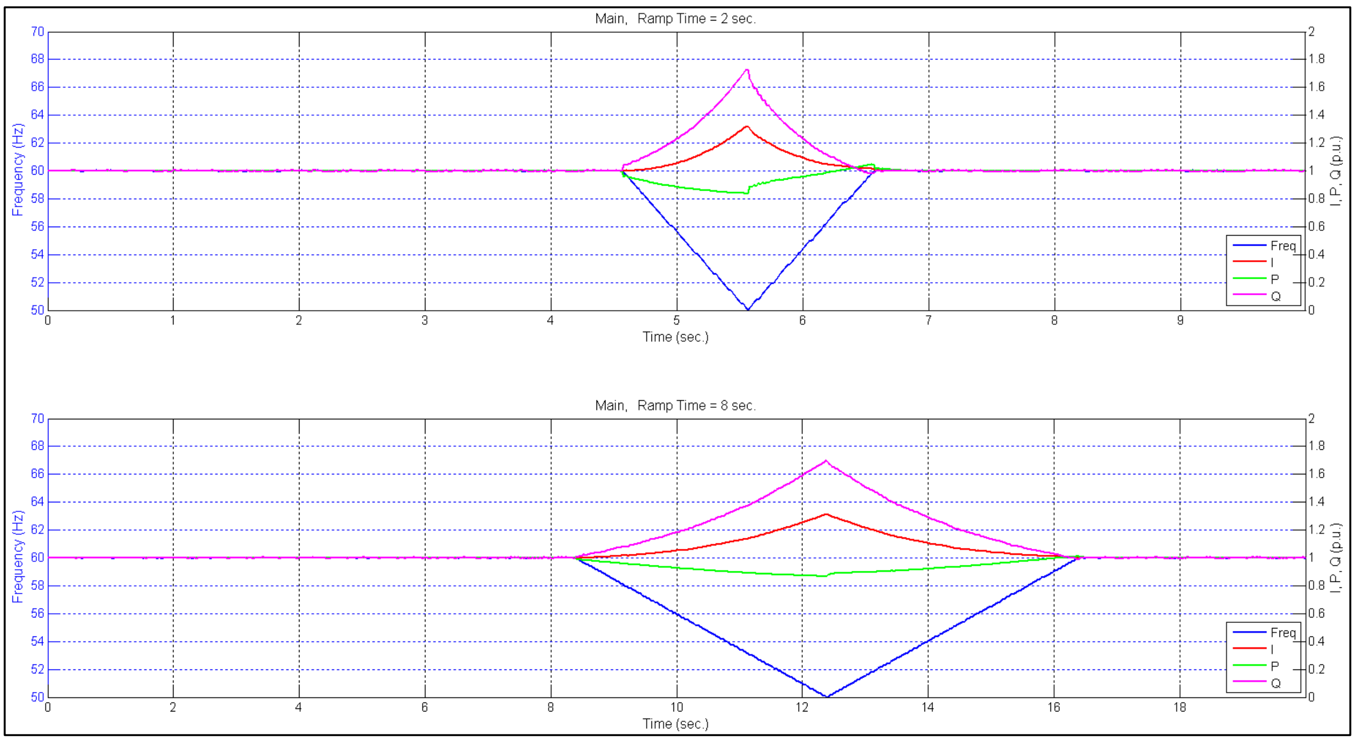

Figure 9.10.1 A/C #7 Frequency Ramp Down to 50 Hz (in 2 & 8 sec.)

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 as shown in the figure below.

Current and real power are observed ramping up with frequency. Current increases until reaching approximately 7% and 5% above nominal during the two ramp tests shown. Real power peaks at 25% and 21% above nominal consumption. Reactive power consumption is decreases to 20% below steady state.

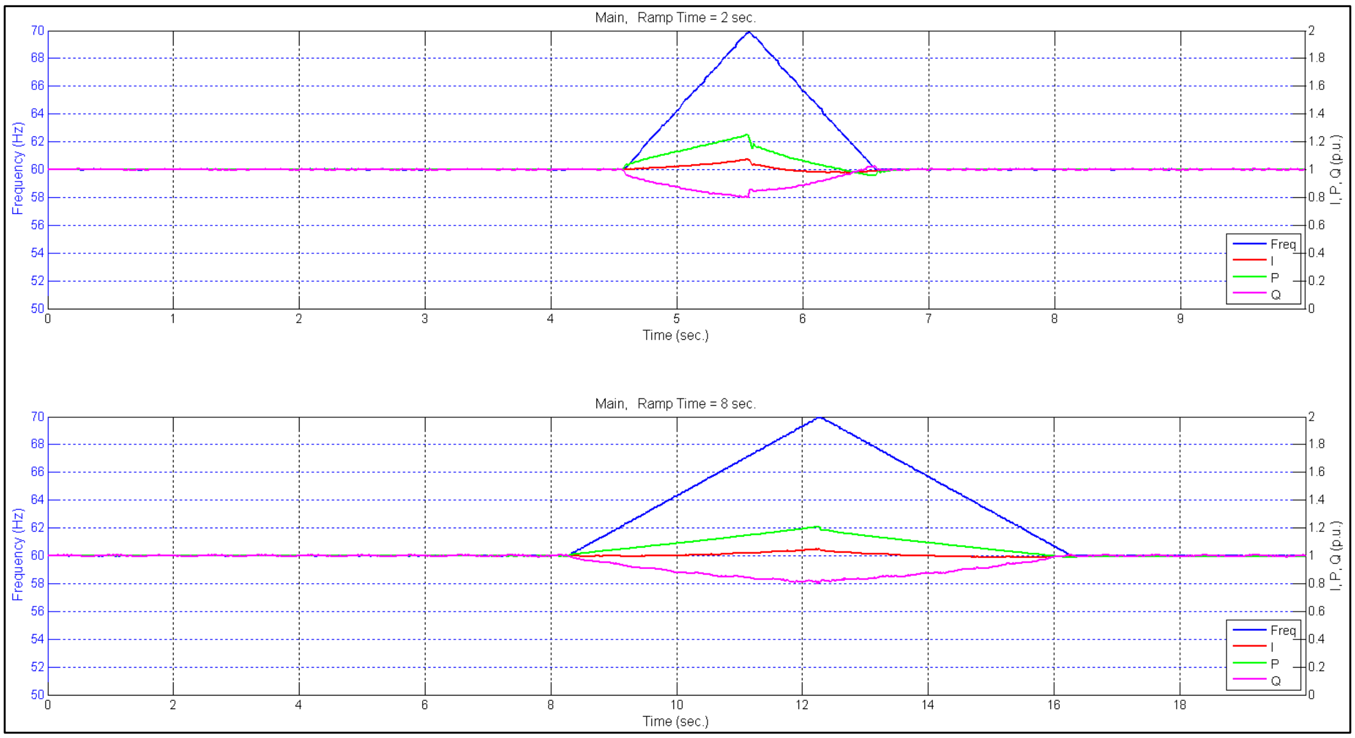

Figure 9.10.2 A/C #7 Frequency Ramp Up to 70 Hz (in 2 & 8 sec.)

9.11 Harmonics Contribution

Steady state voltage and current sinusoidal waveform data was captured multiple times to calculate the harmonic contribution of A/C unit #7 to the grid. The total harmonic distortion of current on all phases was determined to be less than 4.5% of the fundamental. The following table gives the total harmonic distortion for each phase ad the figure plots the individual harmonic values.

Data Set #	THD (% of Fundamental)					
	$V_{A\ (L-N)}$	$V_{B\ (L-N)}$	$V_{C\ (L-N)}$	I_A	I_B	I_C
1	0.12	0.13	0.13	4.21	3.88	4.46
2	0.12	0.13	0.12	3.99	3.66	4.26
3	0.12	0.13	0.13	4.12	3.81	4.37

Table 9.11.1 A/C #7 Total Harmonic Distortion

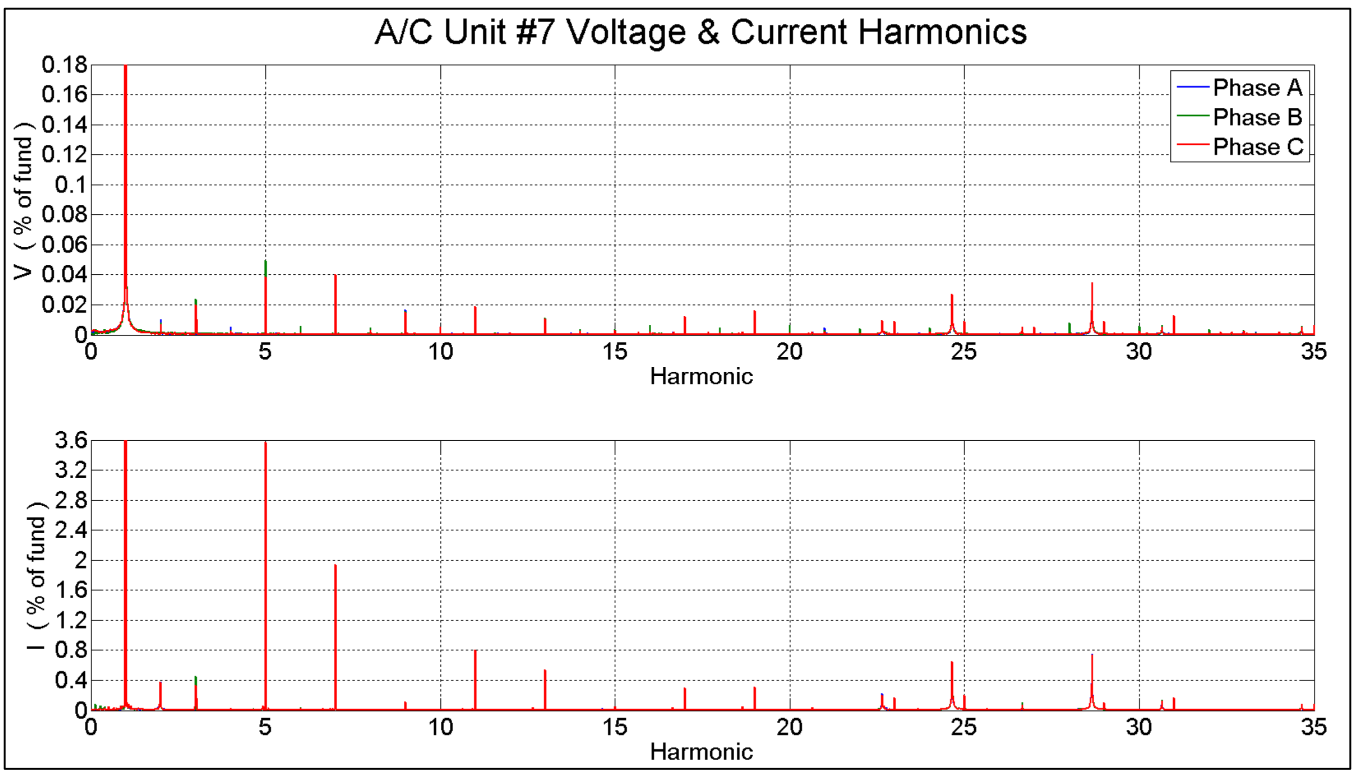

Figure 9.11.1 A/C #7 Harmonics Contribution

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. Although the outdoor conditions were warm the loading of the compressor was approximately 66% of the rated load amps.

CVR is not effective in reducing real power consumption for this A/C unit. Current increases by approximately 0.25% of nominal current for every 1% decrease in nominal voltage. Real power consumption increases slightly, but remain within approximately 1% of nominal. Reactive power also steps down with the voltage, decreasing by nearly 2.2% nominal reactive power for every 1% decrease in nominal voltage.

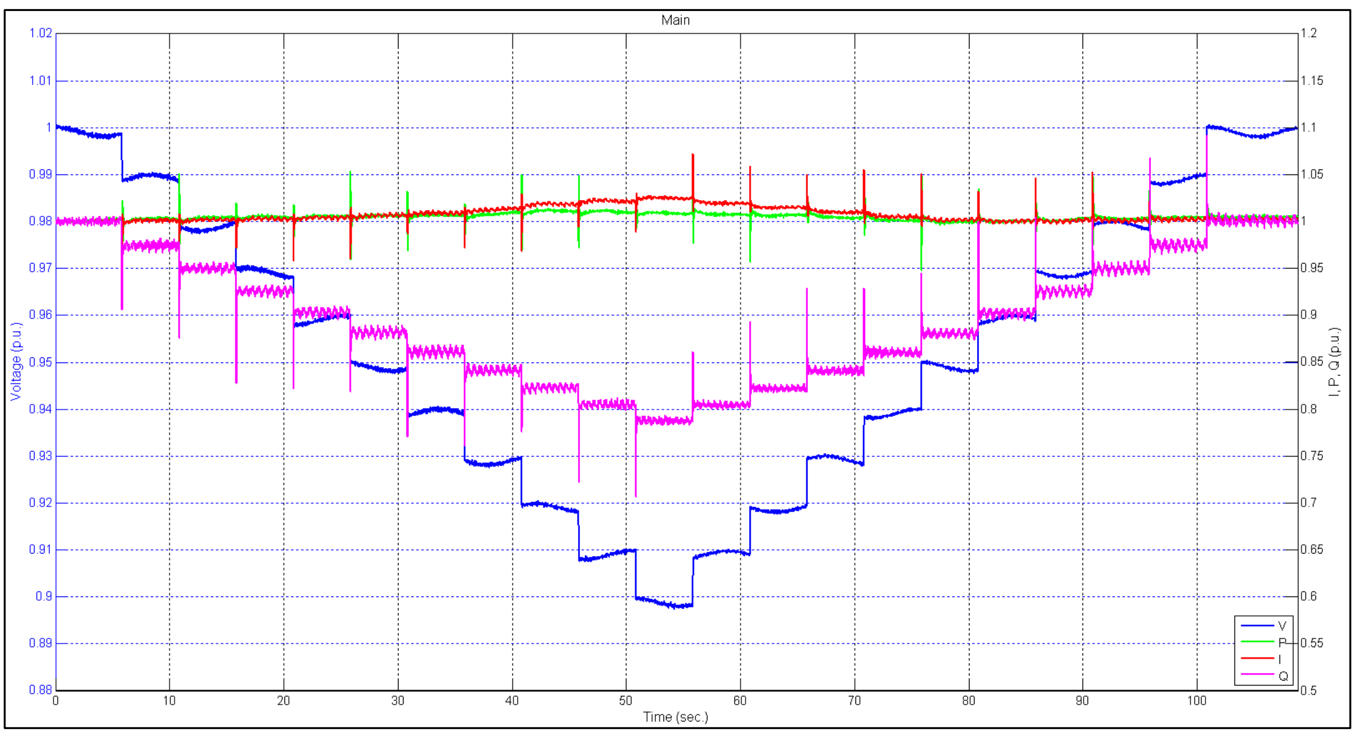

Figure 9.12.1 A/C #7 CVR Response Down to 90% Voltage

Alternatively, the service voltage at A/C #7 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 remains relatively close to steady state increasing up to 2% above nominal over the course the entire CVR test. Real power similarly stays near steady state conditions, only increasing consumption by as much as 1.5% above nominal consumption. Reactive power is observed stepping up with the voltage and increases by 3% nominal reactive power for every 1% increase in nominal voltage.

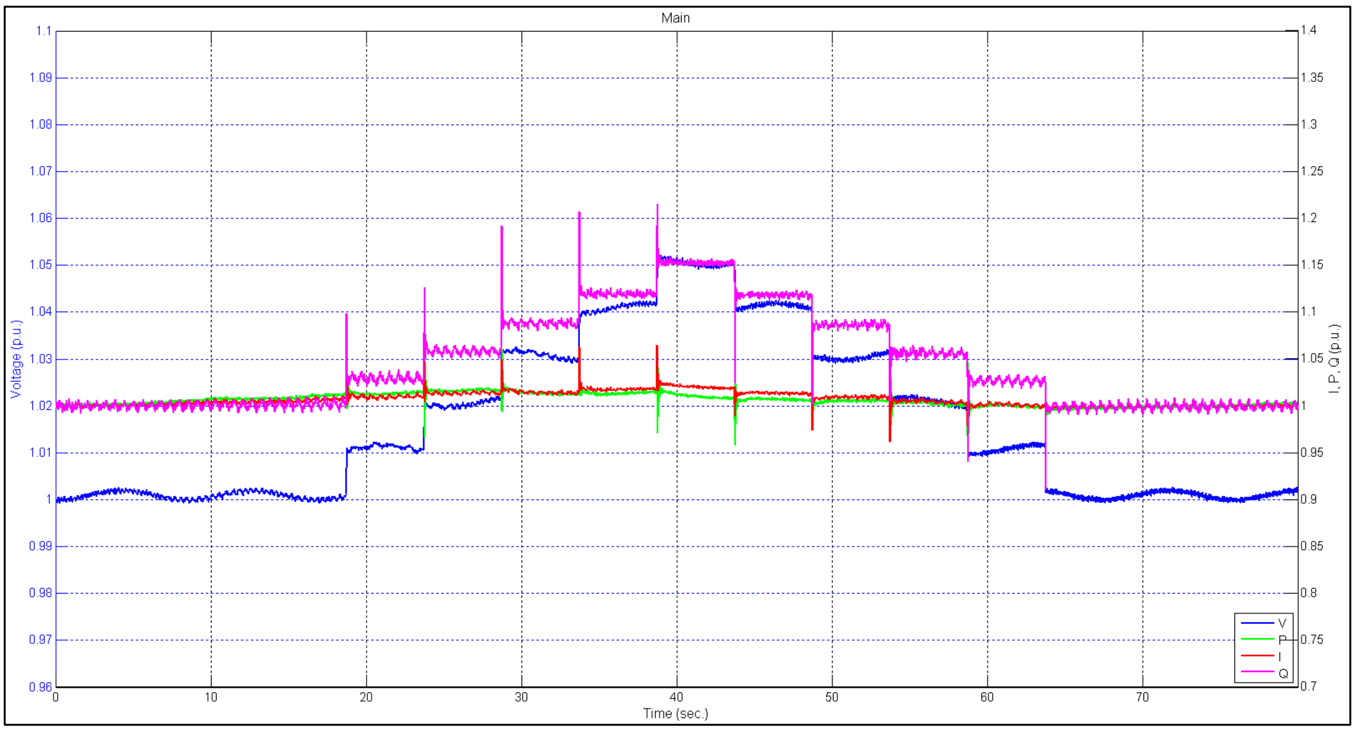

Figure 9.12.2 A/C #7 CVR Response Up to 105% Voltage

9.13 Compressor Stalling

Although A/C unit #7 did stall during a two-phase unbalanced under-voltage test, compressor stalling did not occur during balanced under-voltage conditions. The contactors would open causing the compressor to shut down before reaching a voltage that would cause stalling. The unit would restart normally after the contactor reclosed whether it was right after voltage recovered or several minutes later.

Therefore several additional under-voltage tests were performed after making modifications to the device controls in order to induce compressor stalling behavior during balanced under-voltage conditions. Rather than using the service voltage from the main terminals of the A/C unit to serve the step-down transformer (24 V output) and power the controls, a separate power supply was used to energize these controls (contactor coils, relays, thermostat, etc.) to bypass any dropout behavior.

Prior tests showed that dropout occurred consistently at 50% and therefore it was used as a starting point for these additional under-voltage tests. A series of under-voltage sags were performed in 1% voltage decrements with duration times of 3 seconds as shown in the following figures. Compressor #1 began stalling during the 42% voltage dip in approximately 34 cycles of the voltage sag. Compressor #2 began stalling at the 43% voltage dip in approximately 56 cycles. Neither of the two compressors entered locked rotor condition immediately at these voltages. Notice that stalling was identified by the dramatic increase in current and reactive power as well as the reduced mechanical vibration of the compressor. Lower voltage magnitudes resulted in faster stalling behavior.

The compressors restarted from their stalling condition within 4.2 cycles after voltage returns to nominal. Both consistently restart after each and every voltage sag performed. Voltage was also held below 42% voltage indefinitely which caused thermal overload protection to occur between 17.2 and 21 seconds after stalling begins.

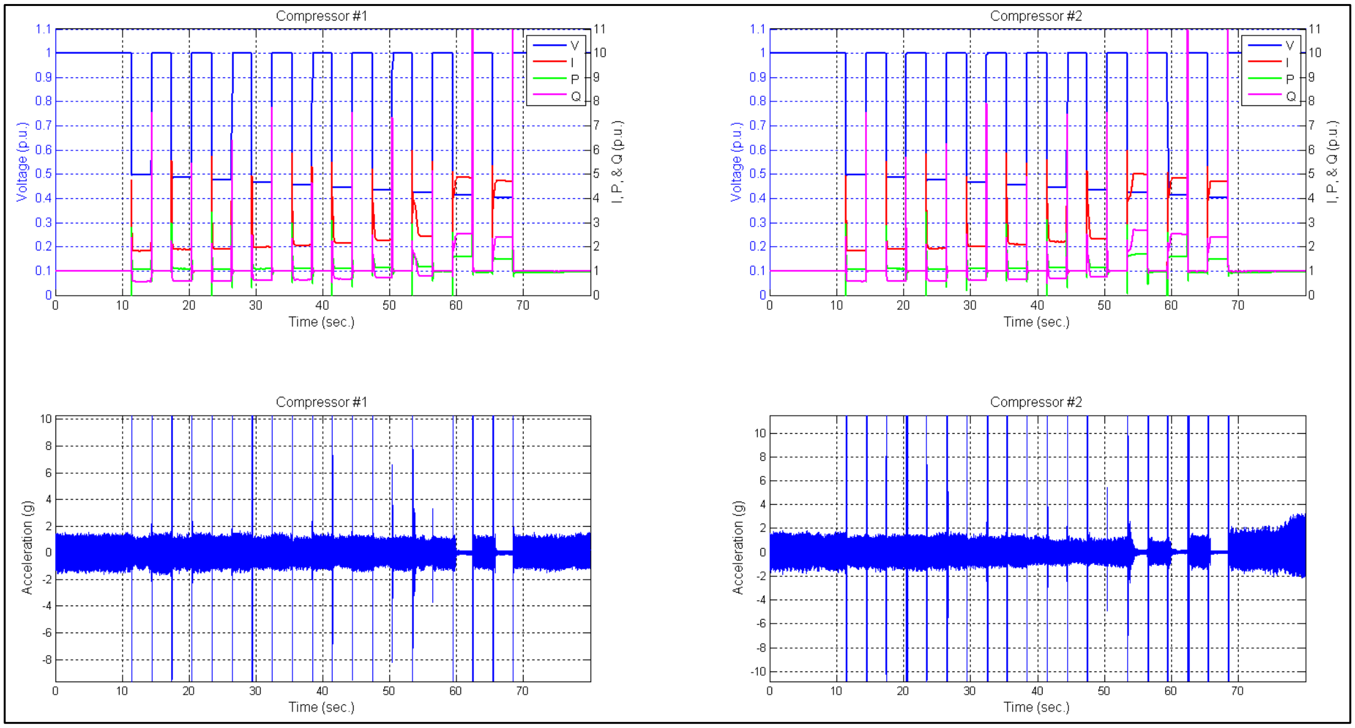

Figure 9.13.1 A/C #7 Compressor Stalling During Under-voltages (50% to 41% voltage)

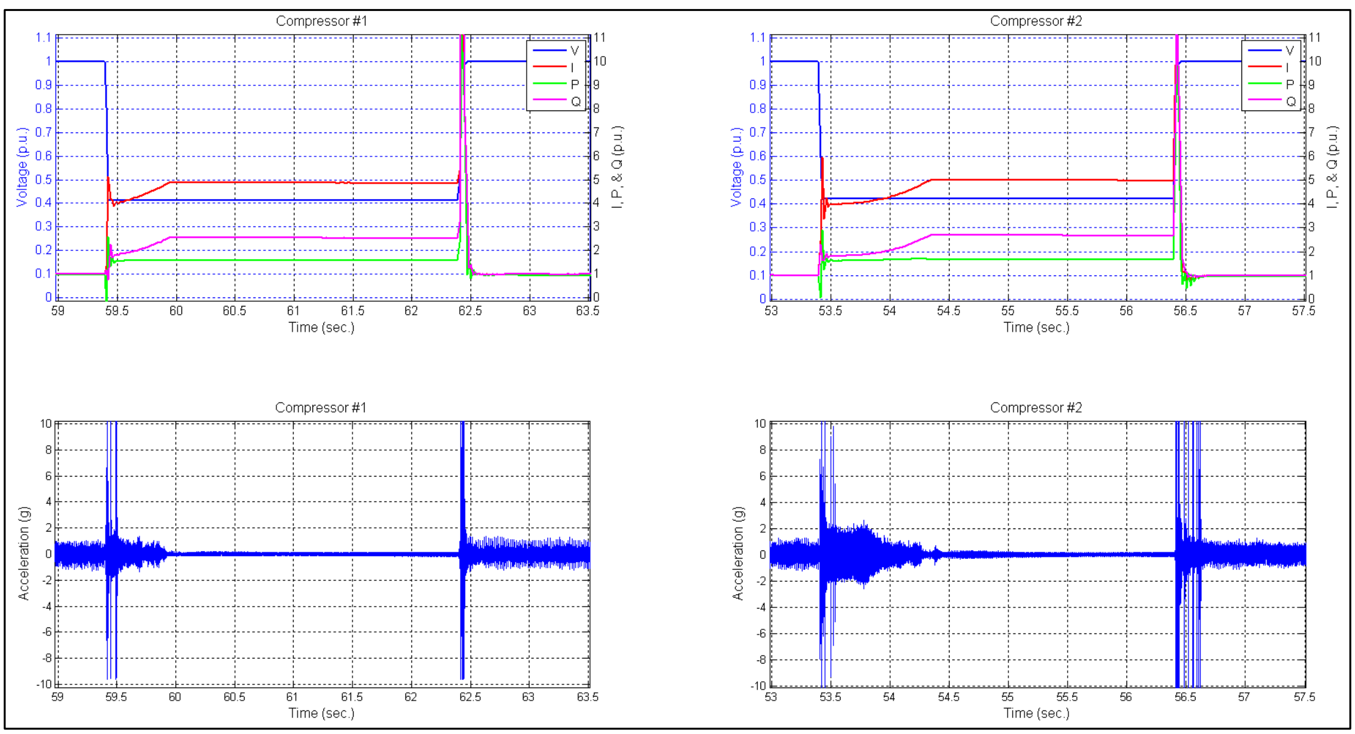

Figure 9.13.2 A/C #7 Compressor Stalling During Under-voltage (42% and 43% voltage)

Additionally, a voltage ramp test was performed to capture the dual compressor's current, real power, and reactive power consumption at different voltage levels as shown in the figure below. The stalling point for compressor #1 current, real power, and reactive power reached 4.4 pu, 1.4 pu, and 2.2 pu while the restarting points for the same parameters increased to as large as 6.1 pu, 2.8 pu, and 3.8 pu. The stalling point for compressor #2 current, real power, and reactive power reached 4.5 pu, 1.4 pu, and 2.2 pu while the restarting points for the same parameters increased to as large as 5.6 pu, 2.3 pu, and 3.3 pu.

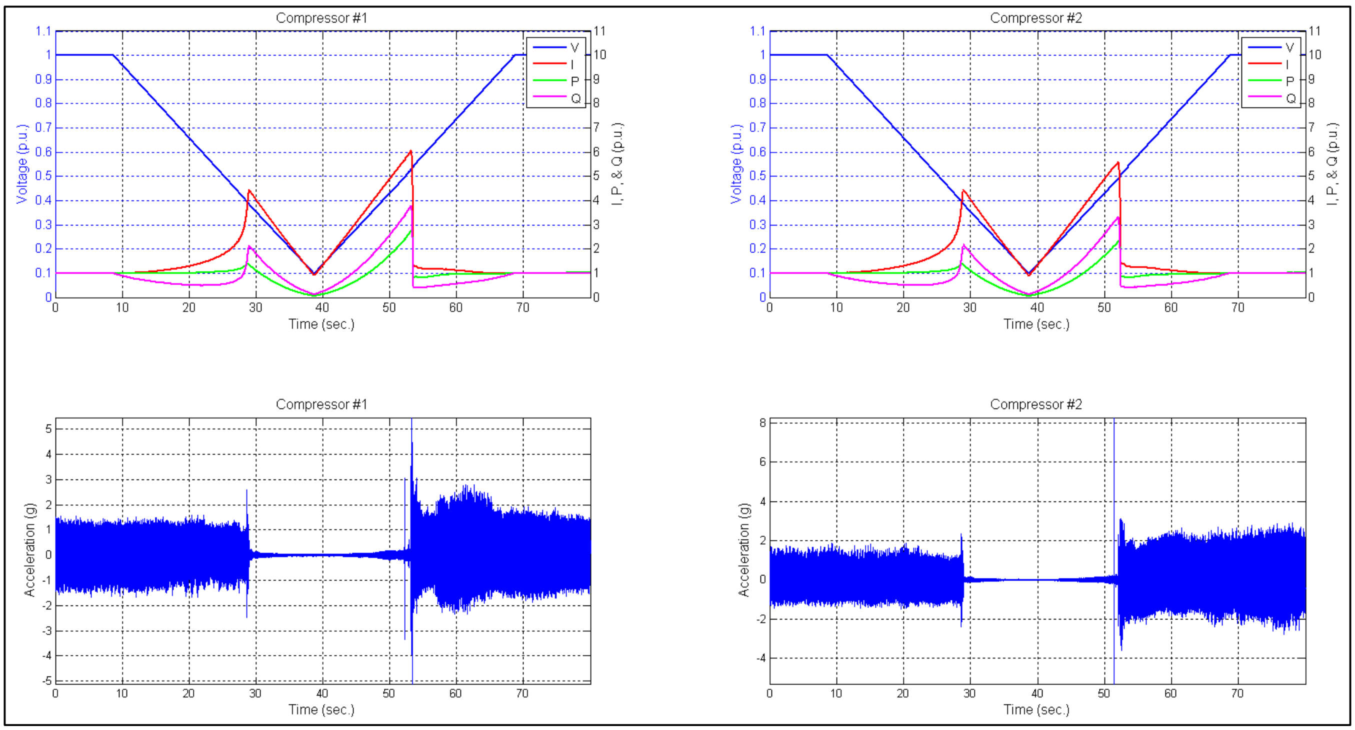

Figure 9.13.3 A/C #7 Compressor Stalling During Voltage Ramp