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ASSESSMENT OF INCOMPATIBILITY OF HVAC EQUIPMENT AND GROUND FAULT CIRCUIT INTERRUPTER (GFCI) BREAKERS

Phase I Report

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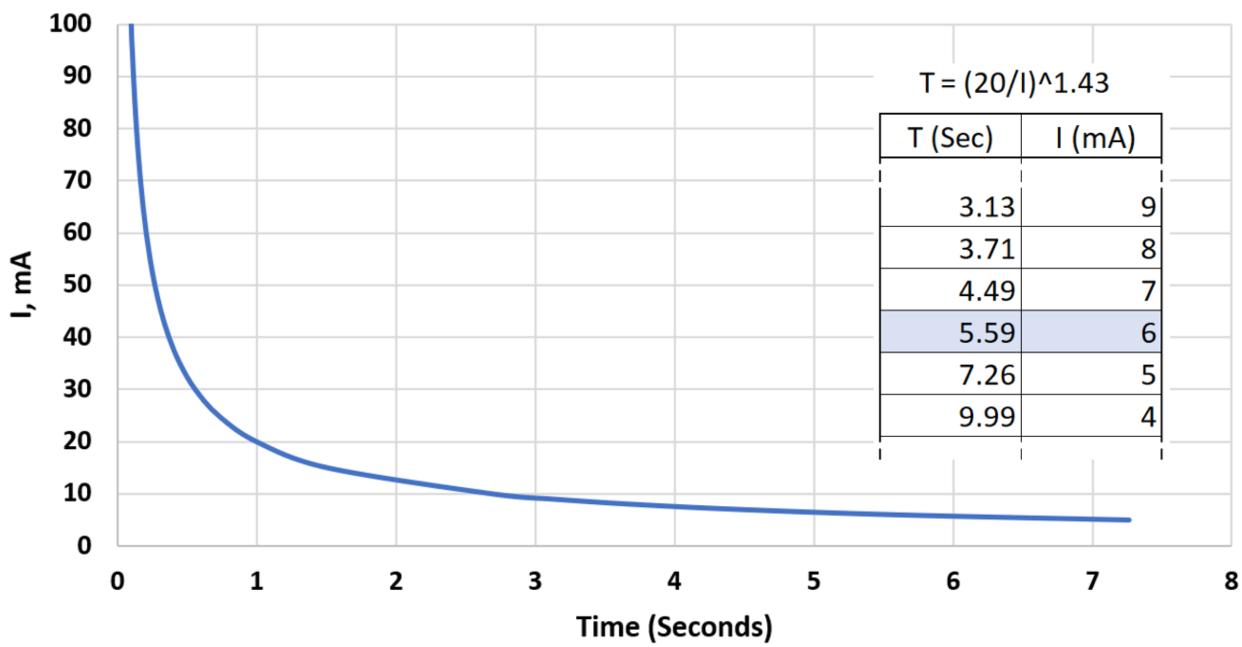
EXECUTIVE SUMMARY

The National Electric Code (NEC) 2020 requirement of ground fault circuit interrupt (GFCI) devices on HVAC "outlets" (outdoor part of an HVAC unit), revealed an incompatibility between HVAC units and the GFCIs: the apparent unnecessary operation of the GFCI during normal HVAC operation. The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) and EPRI examined two HVAC units (one with adjustable speed drive, or ASD control, and one—a single-stage unit—without ASD control) and two GFCI devices to discover and identify the conditions behind this apparent incompatibility. The HVAC-GFCI implementations were tested in EPRI's laboratory located in Knoxville, TN where temperature and humidity could be controlled while the HVAC units were subjected to various start-up and operating scenarios under various temperature and humidity conditions. GFCI operation is triggered by a measured difference of not less than 4 milliamps but must trip at 6 milliamps and larger between the current entering the HVAC power input terminals and that returning to the input power source.

UL 943 provides an equation involving current and time as shown in Figure ES-1: $T = (20/I)^{1.43}$, where T represents seconds while I represents milliamps (mA). Basically, time durations and measured current levels falling within the boundary (below and to the left) defined by this equation should not trip the GFCI while those exceeding the boundary should trip the GFCI. For the trip current level of 6 mA, therefore, the trip time is 5.59 seconds.



T (Sec)	I (mA)
3.13	9
3.71	8
4.49	7
5.59	6
7.26	5
9.99	4

Figure ES-1
Time vs. Current Plot – UL 943

Leakage current was investigated specifically. One manufacturer has studied leakage current from different components of its HVAC systems with measurements varying from negligible to 119 milliamps depending on how the HVAC unit received power.

Two HVAC units, Unit 1 and Unit 6, were tested in EPRI's laboratory in Knoxville, TN. The purpose of the testing was to identify conditions that may cause GFCI circuit breakers to trip when powered by these types of loads. The topologies of these two types of HVAC systems tested in the ERPRI's laboratory were very different, Unit 1 was a single-stage HVAC system that energized its outdoor unit by applying power through a direct-on-line (DOL) starter, and Unit 6 controlled the compressor through a power electronic controller called a variable frequency drive (VFD). Seven tests attempted to replicate conditions that resulted in the tripping of GFCIs.

The HVAC-GFCI laboratory tests were performed in conditions of controlled temperature and humidity in which, per the testing protocol, start-up tests and operational tests were conducted on the two HVAC units that had been configured such that leakage current measurements could be made on the individual components of each unit. Possible paths for the leakage current included the input power conductors to the HVAC unit, ground circuits that were isolated and measured individually during HVAC unit operation, and other points within the HVAC unit.

UNIT 1 Test Results Summary

Note that no GFCI trips occurred for Unit 1 tests. This may be due to the manufacturer recommended GFCI unit used in testing which may have accounted only for leakage current related to the fundamental frequency, or the GFCI used may have been faulty. Future tests will be refined to check the health of the GFCI unit between test regimes to rule out possible faulty GFCI.

Testing used three environmental test conditions: Condition 1, Condition 2, and Condition 3 as defined below.

Table ES -1
Environmental test conditions

Test Condition Designation	Outdoor Air Temp (db*)	Indoor Air Temp (db)	Test Simulation
1	75° F	75° F	Nominal Base Line (75 degrees)
2	95° F (Nominal + 20° F)	75° F	Full Nominal Cooling Conditions
3	47 °F (Nominal - 28° F)	75° F	Full Nominal Heating Conditions

Multiple current transformers (CTs) were involved with test measurement points at multiple locations. Since Z-CT measured the differential current between L1 and L2, it was used as the standard of measure. All other CTs measure the leakage current at the ground wire for each subcomponent and the total current through the main grounding conductor. The CTs used in the project were all brand new and factory calibrated. The list of CTs is shown in Table ES-2 below.

Table ES-2
Current transformers

Manufacturer	Model	Serial Number	Measurement	Measurement Description
AEMC	2620	104315WBS	Z-CT	CT Installed around outdoor L1 and L2 input wiring
Hioki	CT6700	211230270	HFT-GND	Total Ground Current Outdoor Unit: High Frequency Response CT
AEMC	K110	156921WGDV	Comp-GND	Compressor Ground Connection
AEMC	K110	156925WGDV	LFT-GND	Total Ground Current Outdoor Unit: Low Frequency CT
AEMC	K110	156920WGDV	Fan	Condenser Fan Ground
AEMC	K110	153156WCDV	Cap-GND	Capacitor Ground Current
AEMC	SR661	09L29347DV	L1 Current	Total Current
AEMC	SR661	120172HDV	L2 Current	Total Current

Unit 1 TEST 0—Power Applied

Conditions 1&3: All RMS current measured by the Z-CT were within the UL 943 time/current curve. A significant difference was observed between the current measured by the Z-CT and that measured by the high-frequency (HF) and low-frequency (LF) ground CTs. During the nominal running time period, the compressor leakage current measured by the HF and LF CTs was greater than that measured by the Z-CT. This may be injected electrical noise from another device in the thermal chamber, or differences in the frequency response of the two CTs.

Condition 2: RMS current measured by the Z-CT during the application of power and the compressor start phase of this test were within the UL 943 time/current curve limits. The Z-CT measured 7.0 mA during the nominal running phase which is slightly above the maximum limits dictated in UL 943. The compressor leakage current was above the total leakage current measured by the Z-CT.

Thoughts: The GFCI did not trip during any of the testing, and leakage current measured by the Z-CT did not exceed the limits in UL 943. The results of this test indicate that this phenomenon may not contribute enough leakage current to cause a GFCI to trip. The majority of the leakage current measurements during these tests did not exceed the time/current limits within UL 943; however, an FFT analysis was conducted on one of the waveforms and it shows the RMS current is spread across a wide frequency spectrum. Therefore, the leakage current measured at the fundamental frequency of 60 Hz was lower than the total RMS current measured by the Z-CT.

Unit 1 TEST 1—Power Applied

Condition 1: Leakage current measurements taken during the time when power was applied, and when the compressor started were within the limits of the UL 943 time/current curve.

Condition 2: All RMS current measured by the Z-CT were within UL 943 time/current curve. However, a significant difference was observed between the current measured by the Z-CT measurements and the HF and LF ground CTs.

Condition 3: RMS current measured by the Z-CT during the application of power and the compressor start phases of this test were within UL 943 time/current curve. The Z-CT measured above the allowable limits of UL 943 during the 0-degree and 45-degree point-on-wave test. The leakage current measured during these times may have been due to the point-on-wave when the compressor started; however, this was not associated with the point-on-wave when power was applied due to a 5-minute delay from the time power is applied to the circuit and the point in time when the compressor started.

Thoughts: The test was conducted in all three temperature conditions. The test results indicated that a greater amount of leakage current may have been created when the compressor started with temperature conditions in the full nominal heating condition (condition 3).

Unit 1 TEST 2- HVAC Running Test

Conditions 1 through 3: All leakage current measurements were slightly above the limits shown in UL 943; however, the FFT shows the RMS current is spread across a wide frequency spectrum. Leakage current measured by the Z-CT was very close to the allowable limits of UL 943.

Thoughts: This test was conducted while the thermal chambers were configured to operate in the nominal baseline condition. Leakage current may have been higher were the thermal conditions set to the full nominal heating condition as learned from the analysis of data from the Power Applied Test.

Unit 1 TEST 3- Thermostat Cycling Test

Conditions 2 and 3: The highest leakage current was measured during the Outdoor Running Timeframe of the testing. The Z-CT measured between 7.2 mA and 7.4 mA during these times.

Thoughts: ***Of the tests executed, this one may have been the closest to tripping a GFCI***. A longer running time may have eventually tripped the circuit breaker as this was the case for the manufacturer. The difference in EPRI's testing versus that of the manufacturer may be that EPRI used an amplifier voltage source, and the manufacturer was connected to the utility supply. Possible reasons for the GFCI tripping in the manufacturer's circuit and not in EPRI's setup may be that their source impedance may have been lower and PQ events such as voltage sags may have resulted in higher leakage current during conditions that required higher current such as during voltage sags or when the compressor started. The high-resolution metering equipment created very large file sized during long runtime tests. The metering equipment may be configured to auto stop/start files so the file sizes are smaller making this testing more palatable.

Unit 1 TEST 4—Defrost Cycle Test

Condition 3: Condition 3 was the only thermal condition employed for this test. Test 4 did not yield significant leakage current.

Thoughts: The leakage current during the defrost cycle was 0.3 mA above the UL 943 allowable limits. However, taking into account measurement error, that the current measurements were taken at the outdoor unit, that the GFCI was located around thirty feet away from the outdoor unit, then current levels above the fundamental frequency may have contributed to the GFCI's not tripping if it only reacted to the fundamental current spectrum.

Unit 1 TEST 5—Voltage Interruption Test

Conditions 2 & 3: Conditions 2 and 3 were tested. While the restarting of the HVAC unit after the interruption of voltage tests (high and low impedance did not produce measured current in excess of UL 943 limits, the running measurement time period afterward produced leakage current above the allowable limits of UL 943. Therefore, this test may not be valuable as the running leakage current levels are not the result of these types of voltage interruptions. The leakage current was similar during the running portion of the Thermostat Running Test which might be a better way to reproduce the leakage current as it is more cyclical.

Unit 1 TEST 6—High/Low Voltage Range Test

Condition 2: Only thermal condition 2 was used for this test.

Leakage current as measured by Z-CT was always above the limits of UL 943 during this testing. The highest leakage current was measured when the input voltage was between 95% and 90% of nominal.

A longer dwell time at these voltage levels may be a good representative test.

UNIT 6 Test Results Summary

The same test equipment and test conditions used for Unit 1 testing were used for Unit 6 testing.

Unit 6 TEST 0 - Power Applied, Extended time off

Test chamber temperature conditions did not appear to affect the magnitude of measured leakage current. However, humidity may have been a factor in the measured leakage current magnitude for Unit 6 when power was applied:

- Condition 1 and 3 leakage current was 47 mA when chamber humidity was 45% and 54%
- Condition 2 leakage current was 21 mA when chamber humidity was 29%

The original GFCI (shown in Figure 7-3) tripped occasionally when power was applied, and the compressor enabled. This GFCI was replaced with another unit, tests were repeated, and data collected with the latter GFCI connected to Unit 6. According to the data, maximum leakage current occurred when the application of power or when the compressor was enabled coincided with the positive or negative peak of the input voltage to the HVAC. Thus, installing an SCR on the front end of the power feed and enabling power at the zero crossing of the voltage as well as enabling the compressor at the zero crossing of the voltage may limit the leakage current during these operational periods.

Note: An anomaly observed during Test 0 and other tests was that the measured leakage current might exceed the UL 943 limit of 6 mA, yet the GFCI did not trip: the Z-CT measured around 14 mA during all Unit 6 test while the equipment under test (EUT) was operating nominally (cooling or heating). This is above the limits of UL 943. However, the measured current, as shown in **Error! Reference source not found.**, breaks down as:

- An FFT (fast Fourier transform) shows that the 60-Hz current was 4 mA (below the maximum limits in UL 943)
- The FFT also shows that the 5.9-kHZ current was 8.5 mA which may be above the measurement limits of the GFCI.

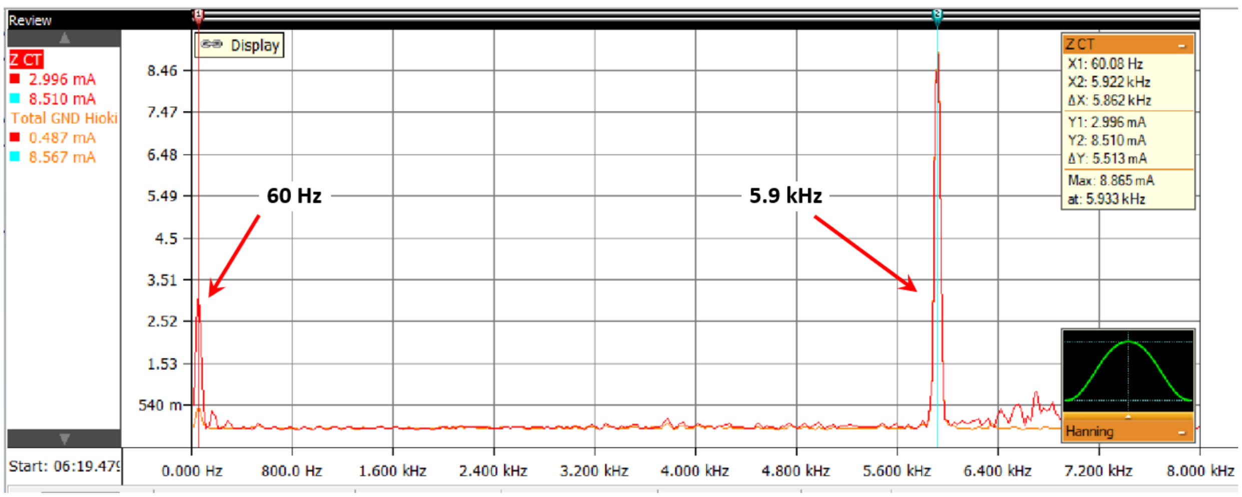


Figure ES-2
FFT Showing the values of the Z-CT and Total Ground HF CT

Unit 6 Test 1- Power Applied

Results were the same as those for Test 0 - Power Applied, Extended time off.

Unit 6 Test 2- HVAC Running

The maximum leakage current appeared to occur when the compressor was enabled, or when an apparent step change in loading occurred—that is, when the nominal current increased or decreased, the measured leakage current increased significantly for a few cycles and then followed the nominal current as it increased or decreased.

Unit 6 Test 3- Thermostat Cycling

The maximum was observed when the DC Bus was enabled, or the compressor experienced a step change in loading. Although the leakage current was greater than 6 milliamps during these time periods, the leakage current was an acceptable level as per the time/current curve of UL 943. During the EUT running time period the Z-CT measured RMS current levels above 6 milliamps, which is above the allowable limits in UL 943. The GFCI did not trip during this condition. An FFT analysis of the RMS current during the nominal running time period showed the majority of the leakage current lies in the 6kHz range while the leakage current at 60Hz is only about 4ma which is within the limits of UL 943. If the GFCI does not react on high frequency current this may explain why it did not trip.

Unit 6 Test 4- Defrost Cycling Test

Maximum leakage current was observed both when power was applied to the EUT and when the compressor enabled, but not during the defrost cycles.

Unit 6 Test 5- Voltage Interruption

Maximum Leakage current was observed when power was restored to the EUT.

Unit 6 Test 6-High/Low Voltage Test

The maximum leakage current appeared to occur when the compressor was enabled, or when an apparent step change in loading occurred—that is, when the nominal current increased or decreased, the measured leakage current increased significantly for a few cycles and then followed the nominal current as it increased or decreased.

Distortion power factor suddenly and significantly increased when transitioning from 90% voltage to 100% voltage and from 86% voltage to 100% voltage.

Test X- Ad hoc Voltage Sag Test

This test was not part of original regimen.

Distortion power factor was observed to worsen significantly during a 30-cycle, 80% voltage sag.

The original GFCI was in the circuit for this test early in the test regimen. This GFCI tripped during some preliminary testing. Testing conducted at the same time as Test 0 used the original GFCI (prone to tripping) that was changed to another GFCI (less prone to tripping). Time for additional testing expired before this test could be conducted with the replacement circuit breaker that was used for all the required tests. Voltage sag testing should be part of future investigations.

The next phase of this project may consider testing several GFCI circuit breaker manufacturer's products to determine the mechanisms that cause them to trip. Another important regime of tests for phase two may be to add tests that apply real world power quality events such as voltage sags and capacitor switching transients to the HVAC/GFCI combinations to investigate if they may result in the tripping of GFCIs.

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1 INTRODUCTION AND TEST SUMMARY

Recently, the 2020 edition of the National Electric Code (NEC) was revised with additional requirements for Ground Fault Circuit-Interrupters (GFCIs). Section 210.8(F) specifically addresses GFCI protection related to dwelling unit outdoor 'outlets' 1. As states began to adopt the new 2020 NEC, contractors began to install GFCI breakers per Section 210.8(F). However, there were no requirements within the appliance safety standard tests to ensure that GFCI and HVAC appliances could work harmoniously together. As a result, soon thereafter many of these new installations were completed, a plethora of reports emerged concerning issues with the of GFCIs and the HVAC units: many GFCIs were tripping multiple times per day.

Equipment affected by the GFCI devices tripping includes single-, two- and variable-speed air-conditioners, heat pumps and heat pump pool heaters. As of May 2023, 34 states have adopted the 2020 NEC. Because of the issues created by this new Section 210.8(F) with regards to HVAC equipment, nine states have deleted 210.8(F), seventeen states have delayed adopting 210.8(F) until 9/1/2026 for HVAC equipment, seven states have modified 210.8(F) so that it does not affect HVAC equipment, and one state has adopted the 2020 NEC without addressing 210.8(F).

NFPA issued TIA 20-19 for the 2020 NEC which adds an Exception No. 2 to 210.8(F) stating "Ground-fault circuit-interrupter protection shall not be required for listed HVAC equipment. This exception shall expire September 1, 2026." This is referenced by all the states who have implemented a delay in adopting 210.8(F) until 9/1/2026.

NFPA also issued TIA 23-3 which does exactly the same thing for 210.8(F) in the 2023 NEC. As of Why the NEC included GFCIs on outdoor "outlets."

The NEC was revised to include GFCI installation for outdoor HVAC 'outlets. The NEC had no such requirement until the 2020 revision.

UL 943 lists GFCIs as Class A devices rated for AC 240 volts and AC 120 volts only. GFCI circuit breakers are designed to trip when they measure a difference between the source and return path of greater than 6 milliamps; the 6-mA trip level does not prove to be applicable to industrial environments. [2][3]

A conflict of electromagnetic compatibility soon became apparent with the adoption of the GFCI requirement: the GFCIs intended to prevent the accidental electrocution of persons coming into contact with the outdoor HVAC 'outlet' also interfered with the operation of the HVAC system. Some GFCIs tripped whenever the HVAC unit began cooling. Was the GFCI too sensitive?

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[1] Per NEC Article 100, an "Outlet" is not a plug or receptacle as one might traditionally think, but a point in the wiring system where the current is taken from supply equipment to branch off to outdoor equipment such as an air conditioning or heat pump condenser unit [1]

What was the source and path for the current? What might be done to improve system electromagnetic compatibility.

Test Summary

Two HVAC units were tested in EPRI's laboratory in Knoxville, TN. The purpose of the testing was to identify conditions that may cause GFCI circuit breakers to trip when powered by these types of loads. The topologies of these two types of HVAC systems tested in the EPRI's laboratory were very different, as one unit controlled the compressor through a power electronic controller called a variable frequency drive (VFD[2]), while the second unit, a single-stage HVAC system, energized its outdoor unit by applying power through a direct-on-line (DOL) starter. A test regime of seven tests were chosen from an offering of eleven tests to try and replicate conditions that results in the tripping of GFCIs when they supply power to these types of loads. The body of the document shows the reaction of these systems during the conducted tests. At a high level, the test results show that the two distinctly different unit topologies demonstrated distinctly different test results. Each HVAC manufacturer requested that their unit be tested with a specific make and model of GFCI breaker as a combined system. No direct system-to-system response to the same breaker was conducted.

High Level VFD HVAC Unit Summary:

- The VFD controlled unit created larger magnitude leakage currents, as high as 1,986 milliamps for 35 microseconds when power was applied after being turned off for greater than 12 hours.
- The GFCI chosen by the HVAC manufacturer tripped randomly when power was applied after the unit was turned off for more than 12 hours *and* when the DC bus of the VFD was enabled. The circuit breaker tripped on several occasions; therefore, it was decided to change the GFCI circuit breaker to a more robust one to identify the conditions where maximum leakage current was achieved. The test results for the VFD controlled HVAC system seemed to indicate the highest magnitude leakage current was achieved when power was applied at the peak of the voltage sine wave (90-degrees point-on-wave (POW)).

High Level Single-Stage HVAC Unit Summary:

This HVAC model and GFCI breaker manufacturer generated multiple reports from the field on nuisance GFCI tripping. Therefore, these devices were chosen to be tested.

- The HVAC system with the single-stage compressor produced significant leakage current for the longest duration, 90 milliamps for around 200 milliseconds. The

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[2] Power-electronically controlled motor drives may be called adjustable speed drives (ASDs), variable frequency drives (VFDs), variable speed drives (VSDs), and other terms.

leakage current in this case was observed anytime the outdoor unit was energized – regardless of extended off time or normal cycling.

- The GFCI chosen by the manufacturer of the single-stage HVAC system did not trip for any of the tests. The thermostat cycling test was run by this unit's OEM in their facility for days and found to eventually trip the GFCI. The protocol used in this effort called for one hour of 5-minute, on-off cycling – which may explain why a trip was not recorded.

There were several occasions during the testing where more than 6-milliamps of current was measured and the GFCI did not trip. The circuit breakers may not have tripped for several reasons. The manufacturer may have chosen to follow Dalziel's curve, decided to allow the circuit breaker trip based on the fundamental frequency current, or the sum of the fundamental frequency and the harmonic currents.

2 PROJECT EVOLUTION

The Air Conditioning, Heating, and Refrigeration Institute (AHRI), desiring to promote collaboration between the HVAC and GFCI industries, to identify the specific reasons for the electrical characteristics related to the incompatibility, determine the root cause, and develop solutions to address this issue, contacted EPRI to investigate all the above. As several parties connected to HVAC systems and GFCI devices were involved with finding a workable solution to the HVAC-GFCI issue, EPRI, a neutral 3rd party, was asked to help investigate the problem and identify possible actions to resolve it.

Develop GFCI undesirable tripping theories and conduct root cause analysis

Task 1.1 Examine electrical characteristics of equipment/components and their energy levels that might be causing GFCI tripping.

Working closely with HVAC OEMs, examine startup, switching, and operational modes of equipment components, and assess potential impact on the GFCI trip detection thresholds. How might non-standard operating conditions (power quality phenomena such as voltage sags, transients, or elevated voltage distortion) impact GFCI performance?

Research high-frequency (HF) coupling within the appliance, its components, or its internal and external conductors. System and component analysis might include:

- High frequencies coupling within the appliance, its components, or its internal and external conductors.
- The effects of low voltage between indoor and outdoor units passing to the ground
    - Refrigerant and lubricant impact on HF coupling and/or voltage leakage for submersed motors.
- Effects of refrigerant levels such as that following a period of rest after a cooling cycle
- High-frequency coupling due to power electronic switching in the HVAC unit
    - Potential voltage distortion from adjacent loads in the dwelling that could lead to high- frequency, non-linear currents through the outdoor-located HVAC equipment.
    - Leakage current and resulting motor bearing current issues are a known problem with specific ASD applications—due to the high-frequency components seen by the motor.

Task 1.2 Evaluate the manner in which GFCI devices, their internal algorithms, or other means used to detect leakage currents could lead to nuisance tripping when no hazardous voltage exists.

Working closely with GFCI OEMs, examine the GFCI algorithms, trip thresholds, and timing characteristics. EPRI disassembled some of the GFCIs; however, the specific code/algorithm used is proprietary to the OEM. Investigate whether a high-frequency hazard may exist without an accompanying low-frequency hazard.

- Of issue is the high frequency switching signatures and related sidebands coupling via potential ground paths such as through HVAC components or through a grounded individual touching the equipment.
- While low-frequency, higher-voltage, 50/60 Hz components may be expected to pose the most hazard, an examination of the energy available at higher frequency, lower magnitude components will be studied also.
    - The work of electrical safety research teams concerning electrical hazards related to stray voltages, fundamental voltages, and higher-frequency components will inform this effort.

Investigate and possibly test effects of transient voltage surge suppression, power conditioning, and line reactors.

Background

Ground Path & Ground Bonds

The earth serves as a return path back to the voltage source which is the utility. This return flow requires a grounding electrode such as a grounding rod (driven into the earth and normally at 0 volts) typically at the utility service entrance. A grounding conductor creates this connection to earth for electrical equipment and for the neutral conductor (called a grounded conductor) in a facility or residence. These serve as the ground path for a facility or residence.

Unpowered metallic surfaces such as electrical cabinets and equipment enclosures or cases are connected to the ground path through bonds—metallic connections that allow electrical connectivity and continuity. These connections are called equipment bonding jumpers.

Normally, electric current flows from the utility, through the main panel, through protective circuit breakers, through conductors to the electrical load, back to the main panel over the neutral conductor which is connected to the grounding conductor at the main panel through the main bonding jumper.

Ground Faults

However, an unintentional connection may develop between otherwise unpowered metallic surfaces and the current carrying conductor (known as a “short circuit” or “ground fault”). The bonded path to ground allows a low-resistance circuit for the resulting unintentional current. This unintentional current rapidly increases (only limited by the low-resistance of the ground path) until it exceeds the rating of the circuit breaker (selected to protect the conductor insulation and to prevent fires) which opens to stop the flow of current through the shorted conductor-to-ground path. This is the purpose of the ground path and equipment bonds. [1]

Leakage Current

A difference in voltage potential between two surfaces—even if they are insulated from one another—may allow some flow of current between them. This is because no perfect insulator exists. This leakage current typically is small; however, it may be large enough to result in adverse effects to humans or animals. [19]

What is leakage current? In a single-phase system, two conductors may connect to the load—one to supply current at some voltage and one to return current at 0 volts. Ideally, all of the current flowing to the load through the “hot” conductor (typically black in the US for 120-volt systems) returns through the neutral conductor (typically white in the US for 120-volt systems). Should these two measured values not be the same, then the difference has flowed somewhere else. This difference may be the result of wire insulation breakdown, may not be sufficient to trip a panel circuit breaker, and is known as leakage current. Stray capacitance along the length of a conductor may also create a path to ground for leakage current. Should a grounding conductor (the safety ground) accompany the current-carrying conductors, this leakage current might be flowing through it. Since this current is flowing to the facility ground, it should pose no safety issue to persons nearby (although a panel circuit breaker may ultimately trip). However, should the difference in current flow through some other path to ground, it may pose an electrical hazard to persons or animals nearby. Indeed, should the insulation breakdown allow a metallic surface to become energized, a person contacting the surface may experience touch current—perhaps only limited by the body’s resistance from touch point to ground. Touch current is the electric current through a human body or through an animal body when it touches one or more accessible parts of an installation or of equipment[3].

Any electrical system has leakage current. The main concern is the amount of leakage current. While it may be insignificant compared to the normal load current, it may be enough to cause harm or even death to animals or humans. As noted above, to prevent this leakage current from becoming a hazard, GFCIs were developed and are explained in more detail later in this report.

[3] [IEC 60050-195, 195-05-21] These definitions appear in 3.208DV of the 4th Edition of UL 60335-2-40.

Another term, residual current, appears not to be well defined but is used to describe a type of circuit breaker, the residual current circuit breaker (RCCB). Like the GFCI, this circuit breaker measures the incoming current and outgoing current. Any difference indicates that some current (the residual current in this context) is taking another path to ground.

Resistance of the Human Body

Some design methods may model the human body as an equivalent resistance to establish the possible current flow through the body. However, the resistance of the human body depends on the path through the body, the moisture on the skin, or the presence of wounds. This resistance may vary by the individual. Several charts identify the resistance from the hand to the foot—a likely path for current flow—as 400 or 500 ohms. Assuming a 110-volt source, this resistance would result in a current of between 220 and 275 milliamps—far beyond the let-go threshold of 10.5 to 16 milliamps identified in Dalziel's study. Dry skin may have resistance between 100,000 and 600,000 ohms while wet skin may have 1,000 ohms of resistance. The former might allow 0.18 to 1.1 milliamps (very minor) while the latter might allow 110 milliamps (possibly lethal). Relying on an assumed level of resistance that will itself prevent lethal levels of short- circuit current in the event of the human-to-ground path seems inadvisable.

The resistance of the human body varies from individual to individual and from one area of the body to another. The resistance of a dry, calloused hand may exceed 100,000 ohms while the resistance inside the human body might be around 300 ohms. A potential at or above 500 volts can break down the resistance of the outer layer of skin. [20]

Touch Current

Should a human body (or a model of a human body) become a pathway, then touch current exists--according to IEC 60990. Normally, energized parts of electrical equipment are not accessible [21] (reference is IEC 60479-1). However, in fault situations, conductive parts may suddenly become energized.

The Ground Fault Circuit Interrupter (GFCI)

Should a human body (or a model of a human body) become a pathway, then touch current exists--according to IEC 60990. Normally, energized parts of electrical equipment are not accessible [21]. However, in fault situations, conductive parts may suddenly become energized.

GFCI Considerations/Relevant Standards

As mentioned earlier, Dalziel developed the first GFCI design. His design involved a magnetic circuit along with a semiconductor device—only just developed at that time. His device performed safely and reliably. Such magnetic circuits appear to have been replaced in more modern designs. Some manufacturers of GFCIs have tried to match this curve as the trip point for their products. EPRI engineers have spoken with several individuals knowledgeable about GFCI construction. Anecdotally, one individual observed that one GFCI model—that claimed to match the Dalziel curve—when connected to one HVAC system, tripped six times in eight days.

Another older model used to protect the same system simply ignored frequencies above 200 Hz—tripping once in two years. Yet, this robustness to higher-frequency currents may not protect humans from injury or death due to those currents.

Curiously, a 6-milliamp trip level for GFCIs is required by UL 943 in North America, but a 30-milliamp trip setting appears to be the personnel trip level adopted by Australia, Europe, and the Marine industry—a level beyond the “let-go” threshold identified by Dalziel as the point at which someone cannot make their hand let go of the source of the electric shock. This individual so affected requires the aid of another individual putting themselves perhaps in the same peril by rendering aid.

UL 943 defines several classes of GFCIs and their applicability:

- Class A—150 volts or less and must protect against let-go and ventricular fibrillation: 6 mA rating.
- Class C—150 volts up to 300 volts, grounded or double-insulated, must protect against ventricular fibrillation (let-go optional): 20 mA rating.
- Class D—greater than 300 volts, grounded or double-insulated, must protect against ventricular fibrillation, shall have oversized equipment grounding conductor: 20 mA rating—low-impedance path to ground required.
- Class E—greater than 300 volts, grounded or double-insulated, must protect against ventricular fibrillation with standard grounding or double insulation with high-speed tripping: 20 mA rating—high-speed tripping required.

UL 943 provides an equation involving current and time: $T = (20/I)1.43$, where T represents seconds while I represents milliamps. Basically, time durations and measured current levels falling within the boundary defined by this equation should not trip the GFCI while those exceeding the boundary should trip the GFCI. For the trip current level of 6 mA, therefore, the trip time is 5.59 seconds as shown in Figure 2-1. Accordingly, a level of current briefly exceeding 6 mA may not trip the GFCI for time durations of less than 5.59 seconds as shown in the figure.

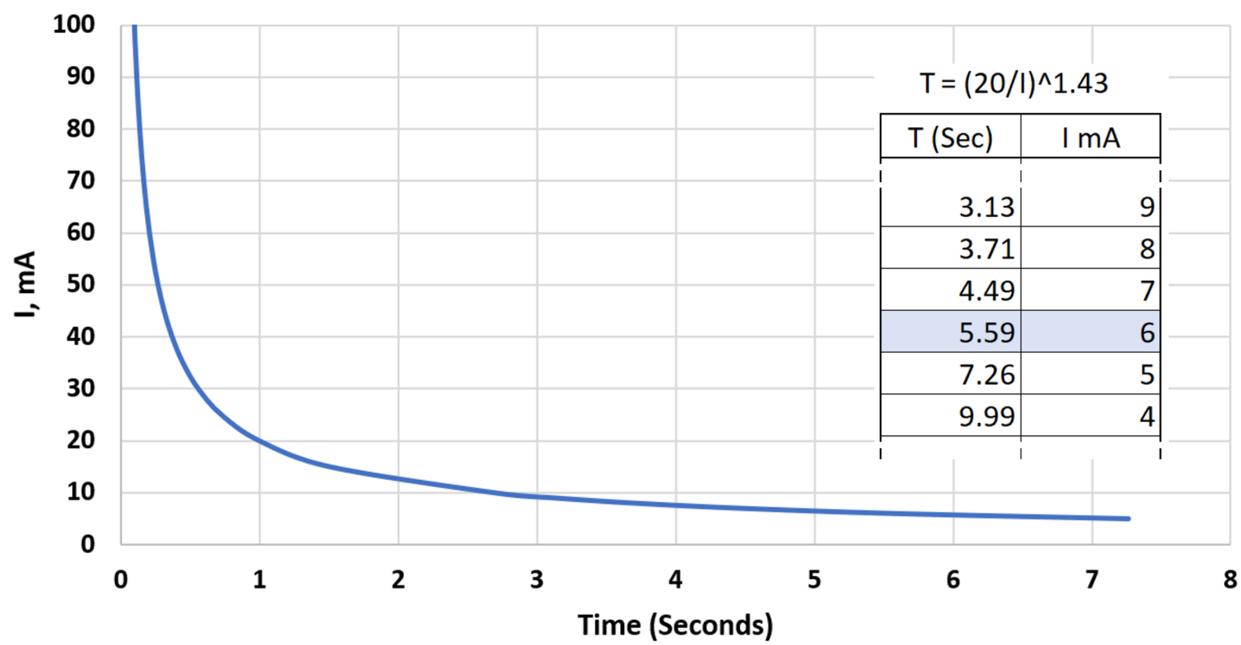


Figure 2-1
GFCI Time Limits by Current Flow and Voltage at GFCI terminals

Four types of residual current devices (RCDs) appear currently to be in use in Europe and elsewhere. While the 30-mA rating alluded to earlier appears in the device specifications, other requirements may apply. Some RCDs appeared first in an IEC Standard:

- Type AC – for detecting residual sinusoidal currents—serves fixed equipment only with no DC components in load current. While suitable for general use, this device may not trip for 30 mA of leakage current related to ASDs. [6] [7]
- Type A – for detecting residual sinusoidal currents and pulsating DC current—single-phase class1 electronic loads specifically. [7]
- Type F – combines Type A capability along with currents resulting from ASD operation along with 10 mA of direct current; also withstands surge current (see IEC 62423 and IEC 60755) [7]
- Type B – combines capabilities of AC, A, & F, and is designed for newer loads such as ASDs, photovoltaic inverters, EV chargers, and types of medical equipment. Annex B of IEC 60755 suggests the types of RCDs most suitable for various electronic load architectures. [7]

These different types of RCDs may be coordinated in different ways using a cascading series of trip values—at the top level, for instance, a 1,000 mA, time- delayed RCD may supply a 300 mA, selective RCD at the next level. This RCD in turn may supply the next level consisting of two instantaneous, 100 mA or 30 mA RCDs. [7] While the 30-mA rating greatly exceeds the 6-mA rating determined by UL 943 and exceeds the 'let-go' threshold of 10 milliamps to 16 milliamps from the Dalziel tests, the instantaneous trip time may be only a few cycles—thus, while painful—the human-leakage current interaction may not be lethal within those few cycles of duration.

Some countries may have their own requirements. In Britain, the BS7671: 2018 + Amendment 2: 2022 provides some emphasis on protecting a final circuit with a residual current operated circuit breaker (RCBO)—which may be similar to the GFCI. To avoid unwanted tripping, clause 531.3.2.(iii) places a 30% limit on the accumulated PE currents as measured downstream of the RCD (that is, 30% of the RCD's 30 mA rating). Thus, for a 30 mA RCD, the accumulation of PE currents should be 9 mA.[8] How this current might be limited to 9 mA is not clear (the article points out the importance of understanding the leakage contribution of each load); however, testing after final installation in these cases may assess conformance to clause 531.3.2.(iii).

The UL 60335-2-40 / CAN/CSA-C22.2 No. 60335-2-40 (UL/CSA 60335-2-40), 4th edition, references leakage current and touch current. Materials found on internet sites (concerning Clause 13.2DV.1 D1, Part 2), indicate that touch current shall not exceed 3.5 milliamps for equipment accessible to the general public.

Further, this touch current must be equal to or less than 2 milliamps per the rated power output in kilowatts. The absolute maximum for such measured current is 5 milliamps regardless of the rated power. Testing by methods established in UL/CSA 60335-2-40 determines compliance with these requirements.

Touch current references the human capacity of perception and response to electrical current. PN-EN 60990 establishes a current test probe with 2 kΩ resistance to measure touch current. As described earlier, the actual resistance of the human body depends on the path through the body—and may not be 2 kΩ in all cases.

Trip Current Levels Explored

The immediate question concerning trip levels for GFCIs concerns this potentially lethal current level—how much is too much? The answer to this question—as well as the origin of the first functional and marketed GFCI—came from the same individual: Charles F. Dalziel.

A study by Charles F. Dalziel from University of California at Berkeley—from just before and after World War II—entitled "Effects of Electric Shock on Man" [5] established a range of sensitivities to AC and DC electric current for both men and women (presumably, the potentially lethal levels were carried out on animals). His study revealed that individuals sustained a range of tolerance for electric current. The averages of these measurements are reproduced in **Error! Reference source not found.** below:

Table 2-1
Dalziel Study Data (adapted from [5])

		Milliamperes (thousandths of an ampere)					
				Alternating Current			
				RMS Values			
		Direct Current		60 Cycle		10,000 Cycles	
Effect		Men	Women	Men	Women	Men	Women
No Sensation on hand		1	0.6	0.4	0.3	7	5
Slight Tingling, Perception threshold		5.2	3.5	1.1	0.7	12	8
Shock—not painful and muscular control not lost		9	6	1.8	1.2	17	11
Painful shock—painful but muscular control not lost		62	41	9	6	55	37
Painful shock—let-go threshold		76	51	16	10.5	75	50
Painful and severe shock—muscular contractions, breathing difficult		90	60	23	15	94	63
Possible ventricular fibrillation from short shocks							
Shock duration 0.03 sec.		1300	1300	1000	1000	1100	1100
Shock duration 3.0 sec.		500	500	100	100	500	500
Ventricular fibrillation—certain death		Multiply values immediately above by 2.75. To be lethal, short shocks must occur during susceptible phase of heart cycle					

Note that the point at which muscular control is not lost for 60-cycle current is 9 milliamps for men and 6 milliamps for women.

Dalziel's work produced a curve shown below in Figure 2-2.

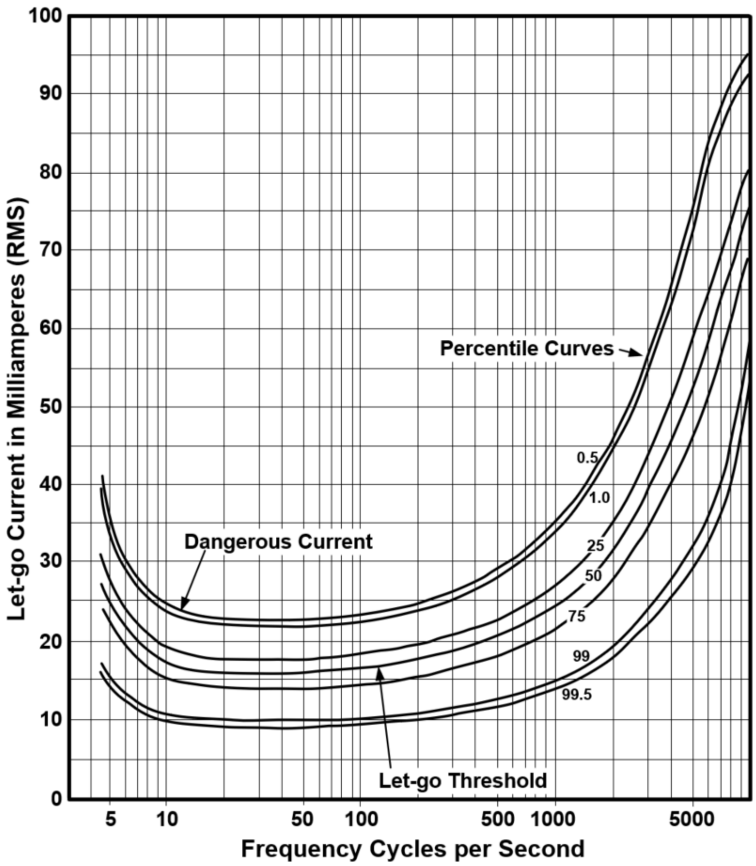


Figure 2-2
Let-go curves as RMS Milliamps vs Hz (adapted from [5])

Nearly all test subjects could let go of the charged object according to the bottom-most curve (around 9 mA at 50 Hz) while very few could do so according to the top-most curve (around 23 mA at 50 Hz).

Time Dependence:[4] On the issue of tolerable body current limits, the standard IEC 60479-1 provides a current threshold for a current path from hand to feet resulting in ventricular fibrillation as shown Figure 2-3. This standard considers the possibility of ventricular fibrillation to be a function of current flow *duration*—an issue within Zone AC-4 and specifically involving the c1, c2, and c3 boundaries. These zones are associated with specific outcomes involving current magnitudes and durations:

- Zone AC-1, the affected individual might detect a prickling sensation (but no harm) for current magnitudes and durations up to line a

[4] https://elek.com/wp-content/uploads/2019/10/Safety-Limit-Calculations-to-IEEE-and-IEC-Standards.pdf

- Zone AC-2 (between lines a and b), the affected individual might experience involuntary muscle contraction (usually not harmful)
- Zone AC-3 (beyond line b), the affected individual might experience strong involuntary muscle contraction (usually no organic damage), and disturbances to heart impulses that are reversible.
- Zone AC-4 (above and beyond curve c3), breathing arrest, cardiac arrest, burns.

The significance of these last curves (c1, c2, c3): no known incidents of human electrocution appear to have occurred below the c1 curve. The other two curves, c2 and c3, along with c1 represent the probability of ventricular fibrillation occurring due to the magnitudes and durations of current levels:

- c1 to c2: up to 5% probability of ventricular fibrillation
- c2 to c3: up to 50% probability of ventricular fibrillation
- Beyond c3: greater than 50% probability of ventricular fibrillation

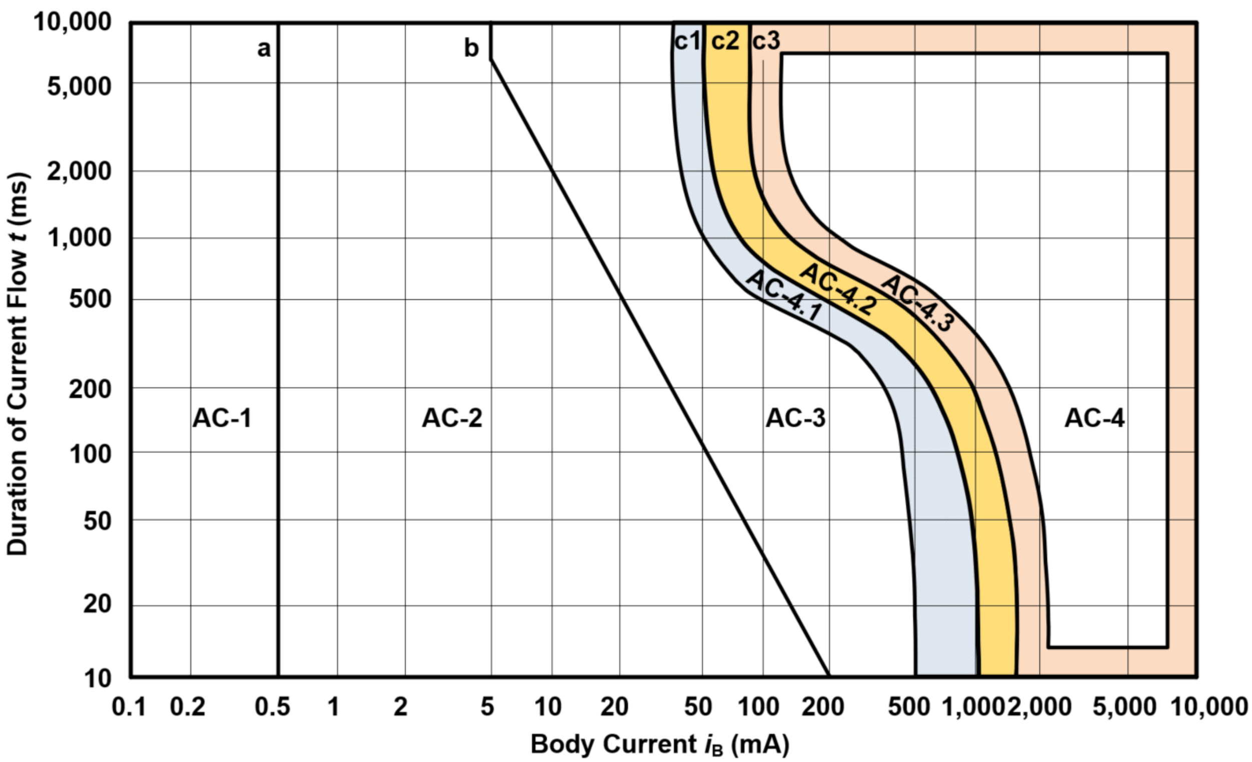


Figure 2-3
Adapted from https://elek.com/wp-content/uploads/2019/10/Safety-Limit-Calculations-to-IEEE-and-IEC-Standards.

Importantly, IEEE Std 80 *IEEE Guide for Safety in AC Substation Grounding*, uses the Dalziel data rather than a duration plot—pointing out that at points on a graph comparing Dalziel's limits compared to the time duration limits of another researcher, Biegelmeier,[5] Dalziel's limits are more conservative (smaller in current magnitude) in the region of time corresponding to the human heartbeat (0.6 and 0.7 seconds). Both are examined in Figure 2-4. Note that the left-hand equation in the figure is for a 50 kg (110 lb.) body weight while the right-hand equation is for a 70 kg (155 lb.) body weight.

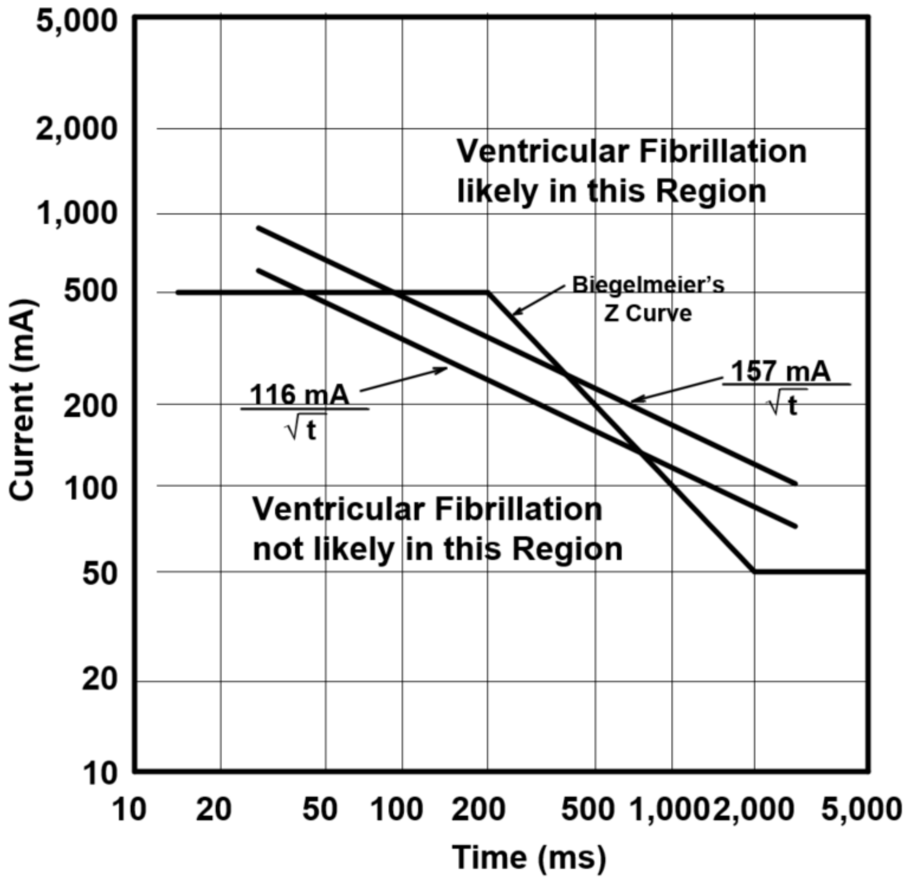


Figure 2-4
Biegelmeier's and Dalziel's findings Compared

[5] Biegelmeier, U. G., and Lee, W. R., "New considerations on the threshold of ventricular fibrillation for AC shocks at 50–60 Hz," *Proceedings of the IEEE,* vol. 127, pp. 103–110, 1980.

3 THEORIES OF GFCI NUISANCE TRIPPING

With project Phase 1A, EPRI was tasked with investigating this issue, devising theories about the source of the problem, developing a testing protocol, and using that protocol to test several HVAC units along with GFCI devices. This effort involved examining the HVAC types known to be affected. Likewise, the GFCI types known to trip were examined.

GFCI Sensitivity

EPRI evaluated the manner in which GFCI devices, their internal algorithms, or other means used to detect leakage currents could lead to nuisance tripping when no hazardous voltage exists.

To begin, GFCIs can be differentiated by class: Class A (B is obsolete), C, D, and E. Class A includes residential GFCIs (single-phase units) whereas Classes C through E are for industrial environments (typically three-phase units). Different standards may be involved depending on the class as shown in Table 3-1. Article 100 of the NEC states that a Class A GFCI trips for a value of 4 to 6 mA of current flowing to ground according to UL 943. [9]

UL 943 provides an equation involving current and time: $T = (20/I)^{1.43}$, where T represents seconds while I represents milliamps. Basically, time durations and measured current levels falling within the boundary defined by this equation should not trip the GFCI while those exceeding the boundary should trip the GFCI. According to the equation provided, the trip current level of 6 mA corresponds to the trip time of 5.59 seconds as shown in **Error! Reference source not found.**.

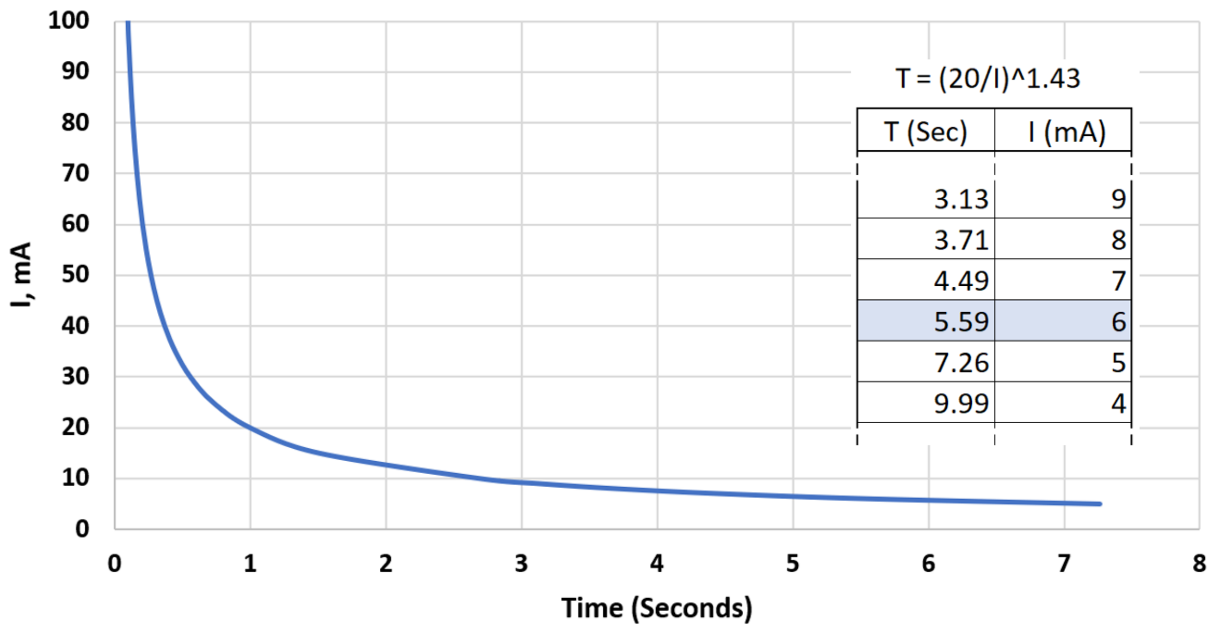


Figure 3-1
GFCI Time Limits by Current Flow and Voltage at GFCI Terminals

Table 3-1
Residential vs. Industrial GFCIs

60 Hz Voltage	UL Standard		GFCI Class							
			Residential		Industrial					
			A		C[a]		D[b]		E[c]	
120, 120/240, 208Y/120, 127, 220Y,127	UL943	Trip Current	X	6 mA	--	--	--	--	--	--
Up to 600	UL943C	Trip Current	--	--	X	20 mA for up to 1 second	X	20 mA for up to 1 second	X	20 mA for up to 1 second

a – up to 300 V to ground per conductor with double insulation or reliable equipment grounding
b – over 300V to ground per conductor with specially sized, reliable grounding to limiting fault voltage across human to 150 volts
c – over 300V to ground per conductor with conventional equipment grounding

The GFCI units of concern happen to be for a residential environment. One example schematic for a single-phase residential GFCI is illustrated in Figure 3-2. The typical GFCI circuit breaker design uses a current transformer and comparator to measure the difference between the supply and return conductors from the load equipment. Should the differential between the supply and return exceed the trip threshold (5 or 6 milliamps for example), the comparator triggers an SCR which in turn triggers a relay to disconnect the line from the load. Response times of GFCIs can be less than 1/10 of a second. The schematic below represents one possible design for a GFCI--several may exist. This design suggests several paths whereby high-frequency currents might cause the GFCI to trip.

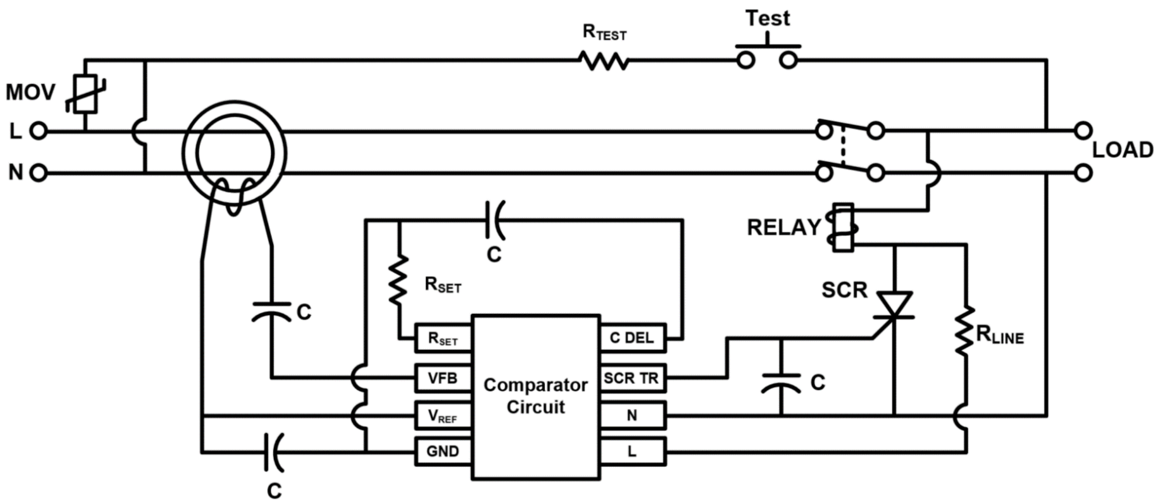


Figure 3-2
Example GFCI Schematic

Possible trip methods for above schematic (one or more at once):

- High-frequency currents along with the power frequency of 60 Hz may be measured at the GFCI input. The High-frequency currents may discharge to ground within the GFCI circuitry; the current differential may exceed 5 or 6 mA and thus trigger the GFCI to disconnect.
- High-frequency currents travel in both line and neutral conductors; the HF currents in neutral conductor cross the capacitor between SCR TR and N and trigger the SCR which causes the disconnect.
- High-frequency currents travel in both line and neutral conductors; the RLINE resistor dissipates some of the HF on the Line conductor and the difference exceeds 5 to 6 mA between line and neutral conductors and thus triggers the GFCI to disconnect.
- High-frequency currents travel in both line and neutral conductors; HF signals interfere with the comparator circuit.

One of the GFCI units was removed from its casing by EPRI engineers as shown below in Figure 3-3. This unit had two circuit transformers (CTs) whereas the schematic shown above has only one CT.

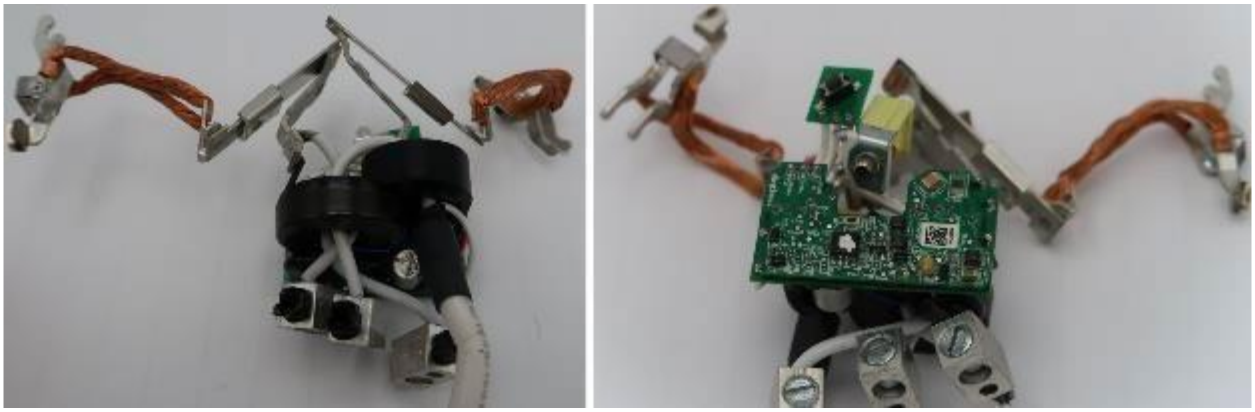


Figure 3-3
GFCI Internal Components

EPRI engineers have identified four comparator chips so far: AFE3010 by Texas Instruments, AFE3010 by Fairchild Semiconductor, the FM 2140 by Fudan Microelectronics, and NCS37010 by Semiconductor Components Industries, LLC. The comparator chip may be programmable such that firmware updates may be possible. Other GFCI designs may have other possible paths for high-frequency current interactions that may cause unwanted tripping.

The GFCI units available for Phase 1 testing are listed in **Error! Reference source not found.**.

Table 3-2
GFCIs for Laboratory Testing

Sample Number	Details
1	Prior to firmware revision
2	After Firmware revision
3	N/A
4	N/A
5	N/A

The two HVAC units listed in Table 3-3 were tested for this Phase 1 testing sequence: Units 1 and 6.

Table 3-3
HVAC Units Tested

Details	Unit 1	Unit 6
Unit Type	Split	Multi-split
OD Unit Nominal Capacity	4 Ton	4 Ton
OD Unit Rated Voltage/Ph:	208/230vac-single	208/230-60-1
OD Unit Rated Current Draw (RLA):	19.6	28.15
Compressor Type (VS, 1S)	1S	VS
OD Fan Motor Type (PSC,ECM)	PSC	ECM
ID Fan Motor Type (PSC, ECM)	ECM	ECM
ID Unit Rated Current Draw (RLA):	8	0.53

Key:
OD- Outdoor
ID - Indoor
PSC – Permanent Split Capacitor Motor
ECM – Electronically Commutated Motor
RLA – Rated Load Amps
VS- Variable Speed
1S- Single Speed

The two units available in the lab for this initial phase of testing include Unit 1 and Unit 6 — shown below in **Error! Reference source not found.**.

Figure 3-4
Tested Units 1 and 6

4 THEORIES OF HVAC TRIPPING AND ROOT CAUSE ANALYSIS

Root Cause Analysis

To summarize the problem: HVAC systems are tripping offline. The tripping appears to occur coincidentally with the newly mandated GFCI requirement in the NEC. The GFCI trips because it detects a difference in supply current in the "hot" conductor and return current in the neutral conductor. This difference may be a smaller value of return current—which may indicate some current flowing to ground (Figure 4-5).

The initial suspect in this investigation might well be high-frequency currents resulting from the operation of ASDs to drive fans and/or compressors. Figure 4-1 below illustrates an ASD with an active diode rectifier at the front end and an inverter at the back end driving the motor. Each has a switching speed which generates harmonic distortion. An example of a leakage current mechanism within power electronics systems is the current that exists due to the stray capacitance between the power electronic switch and the heat sink upon which it is mounted.[10] Additional leakage current can be generated in the capacitive paths between the motor bearings. Other reasons for leakage currents within drives include either built-in filters or external filters.

Because capacitive path impedance reduces at high frequencies (HF), the leakage currents may increase with frequency— eventually appearing as a short circuit at higher frequencies.

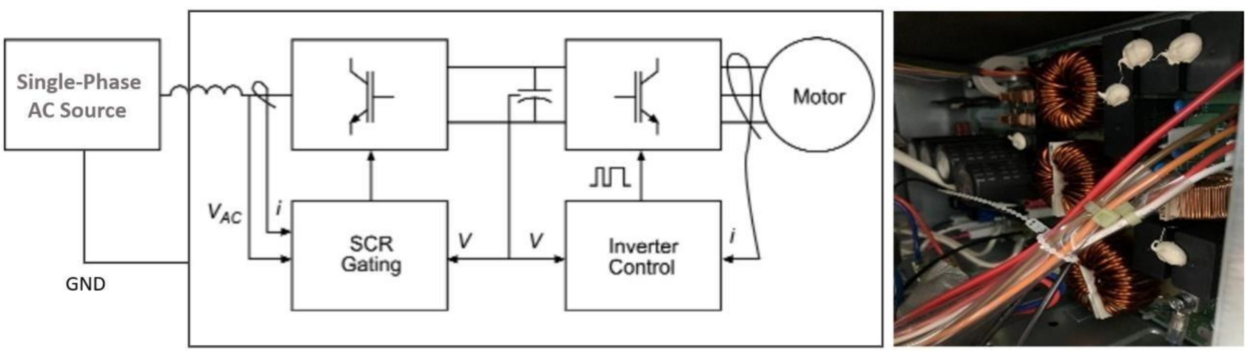


Figure 4-1
Example Schematic of ASD controlled Motor

Anecdotal references to high leakage current identified hundreds of milliamps to as high as 9 amps. Therefore, laboratory measurement and verification of leakage current in all models tested carries some importance.

Variable frequency drive leakage current

A GFCI may operate unintentionally due to the leakage current between grounds as was alluded to earlier. The trace shown in Figure 4-2 illustrates the high-frequency voltage pulses of an ASD. These high-frequency pulses may travel through the motor shaft, through the shaft bearing and bearing traces and ultimately through the motor base to ground as illustrated in Figure 4-3. The arcing resulting from these pulses may cause the fluting on the bearing race shown in Figure 4-4.

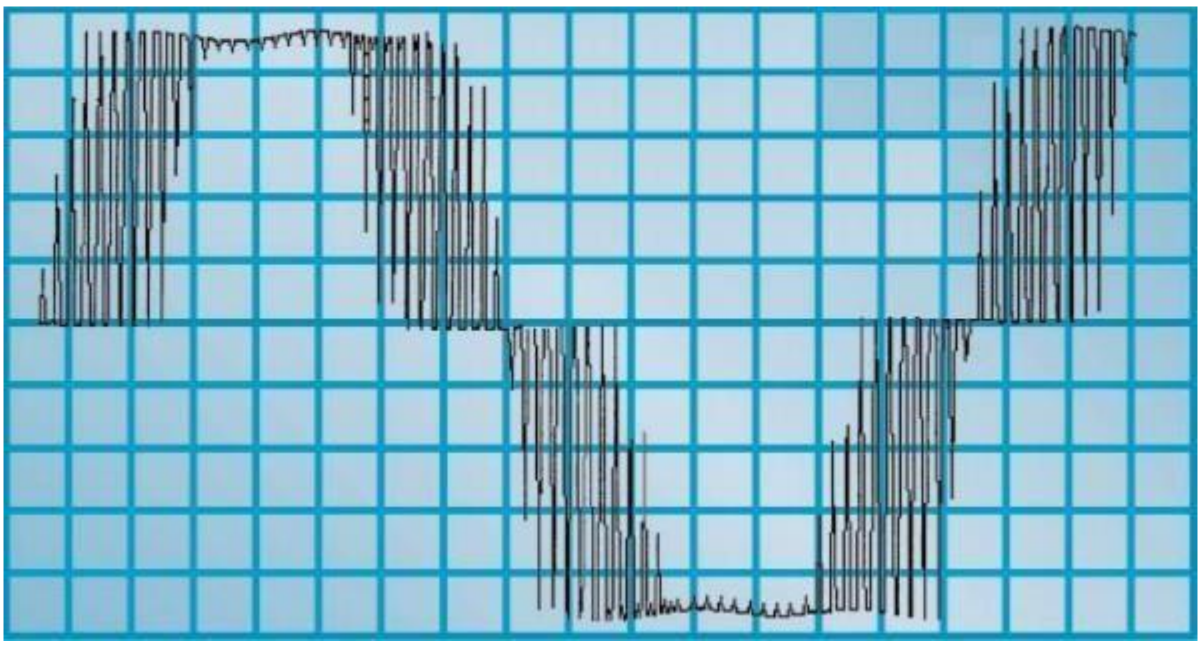


Figure 4-2
Example Pulsed Waveform of ASD to Motor

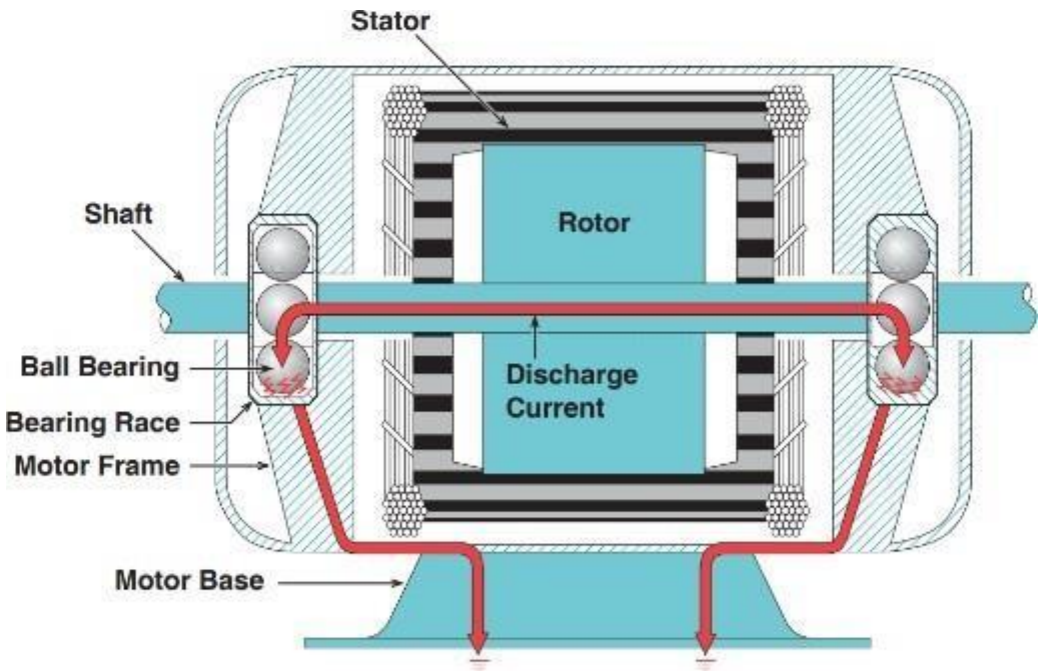


Figure 4-3
Path-to-ground Discharge Current due to ASD Switching Frequencies

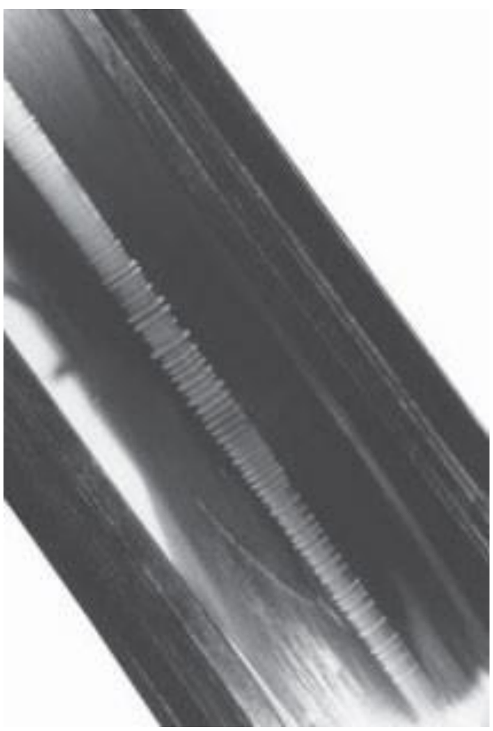


Figure 4-4
Fluted Etching on Bearing Race made by Discharge Currents

A schematic of an ASD circuit shown in Figure 4-5 might illustrate possible paths of high-frequency leakage current. Here, the leakage current might have several paths to follow—some of which have the current flowing up through the ground connection and into Leakage Breaker 2. In this case, the leakage current might cause Leakage Breaker 2—also known as a residual current circuit breaker (RCB)—to trip.

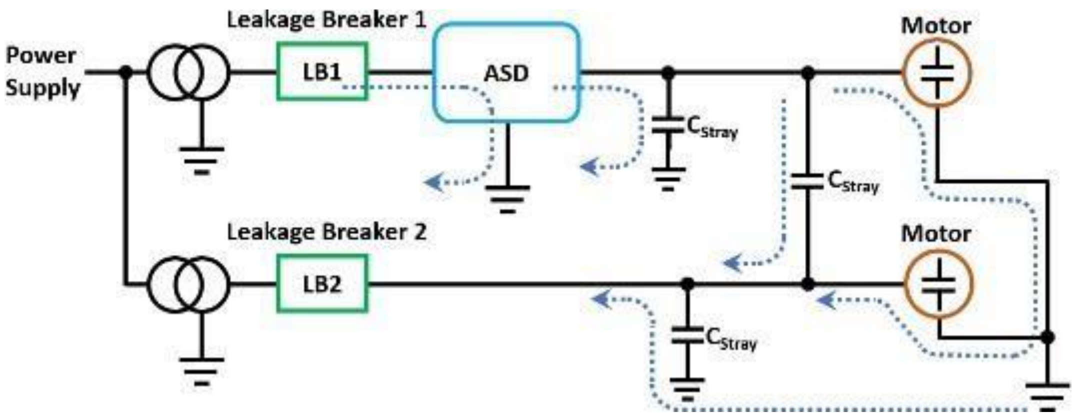


Figure 4-5
Possible Paths of High Frequency Leakage Current (adapted from [11])

HVAC Leakage Current

Some appliances might have what is known as "leakage current"—alternating current that might find a path through stray capacitive reactance. Since this current might typically involve high frequencies, those frequencies associated with ASDs might be relevant. One article about leakage current [12] examined undesirable tripping of residual current circuit breakers associated with ASD operation. In this case, the residual current contained high- frequency leakage currents from ASD operation as well—illustrated in Figure 4-6. Not being capable of distinguishing between residual current (described earlier in section on leakage current) and leakage current, such a circuit breaker may open once the trip setting was exceeded due possibly to the leakage current or the combination of residual and leakage current.

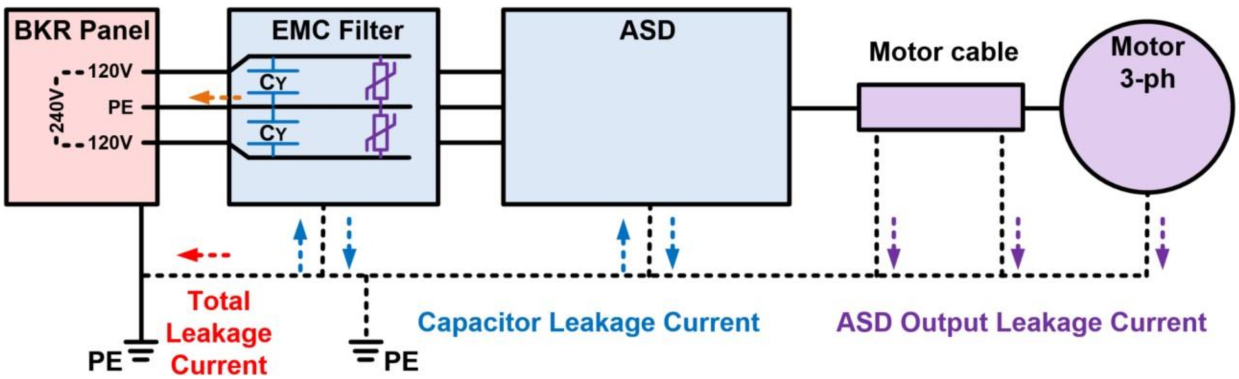


Figure 4-6
Leakage Currents Due to ASD Operation (240-volt split-phase residential) Adapted from [12]

VFDs normally have both Y-capacitors (to reduce EMI noise) and MOVs (to absorb grid transients) in the EMI filter and input circuits. The currents flowing through these two components may count as leakage current and may trip the GFCI. This additional leakage current (orange arrow) may originate from Y-capacitor and MOV paths in the filter during any grid transients or voltage unbalance.

The recent adoption of ASDs into HVAC equipment along with the recent GFCI requirement might suggest a correlation; therefore, high-frequency leakage current might be causing undesirable GFCI tripping.

However, HVAC units without ASDs, also affected by the GFCI requirement, have tripped offline as well. These issues require measurement and analysis to identify the presence and level of leakage current present in HVAC systems with and without ASDs. Since the high-frequency currents may originate from ASDs, or other power electronics associated with equipment near the HVAC system (itself without or with an ASD), measuring in situ for some situations may be necessary to better understand the cause of GFCI tripping.

Part of the examination involves determining what components might be the source of the leakage current. This leakage current may come from conductors, transformers, motors, inverters, and filters. Inverters and filters each might contain capacitors which themselves might contribute high-frequency currents to the leakage current problem. It may be possible that the refrigerant and lubrication fluids—even the copper tubes between the indoor and outdoor units play a part.

Conductors

Conductor leakage current varies by the type and thickness of its insulation along with its proximity to a grounding source. The worst case involves direct contact of the insulation with ground. This insulation has a resistance value and capacitance value. For instance, the resistance value of the insulation (vinyl-insulated) of an 8 mm2 wire size may allow 0.009 mA of leakage current per 1 km of length while the capacitance may allow 99.6 mA for the same length.[13] Longer conductors potentially have more leakage current due to the increased capacitance. For one meter of conductor, this leakage current might be only 0.099609 or 0.1 mA. This value is much below 4 to 6 mA and is not likely to add significantly to the total leakage current of the system.

UL 60335-2-40-2022, 4th Edition, allows the option of installing a second ground conductor or a larger ground conductor—perhaps to provide a lower-impedance path to ground and reduce leakage current.

Capacitors

Capacitors are basically parallel plates separated by an insulating material. This insulator is not perfect—some current passes through. The amount of current is dependent on the temperature of the capacitor, applied voltage, charging period, and type of capacitor such as aluminum electrolytic, foil, ceramic, or plastic film capacitors. Leakage current for the aluminum electrolytic capacitor type is greater than that for the others.[14]

DC leakage current (DCL) may be expressed as I DCL = V / R Insulation (Ohms Law), meaning that it may increase with increasing voltage or decreasing resistance of the insulation. When voltage is first applied to a capacitor, leakage current may be at its greatest and may fall as the capacitor charges according to its time constant as illustrated in Figure 4-7. While time and temperature along with component age may decrease the effectiveness of the insulating material, newly installed units have tripped—too soon for the aging effect to take place.

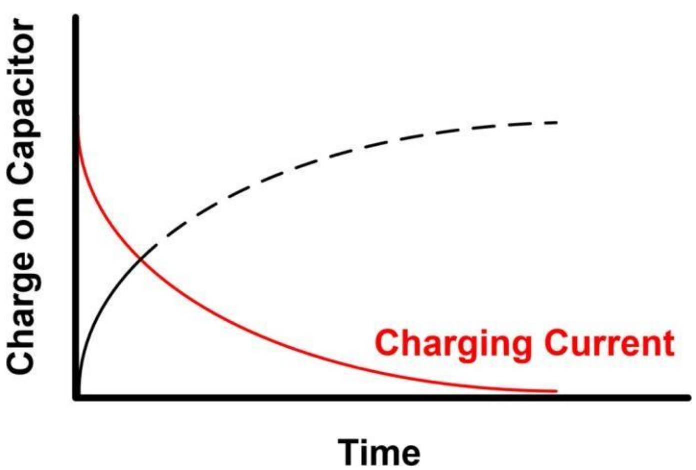


Figure 4-7
Example capacitor charging time constant (adapted from [14])

Various insulating materials such as polymer, ceramic, paper, polyester film, and polyphenylenesulfide film have their own resistance characteristics as shown in Figure 4-8.

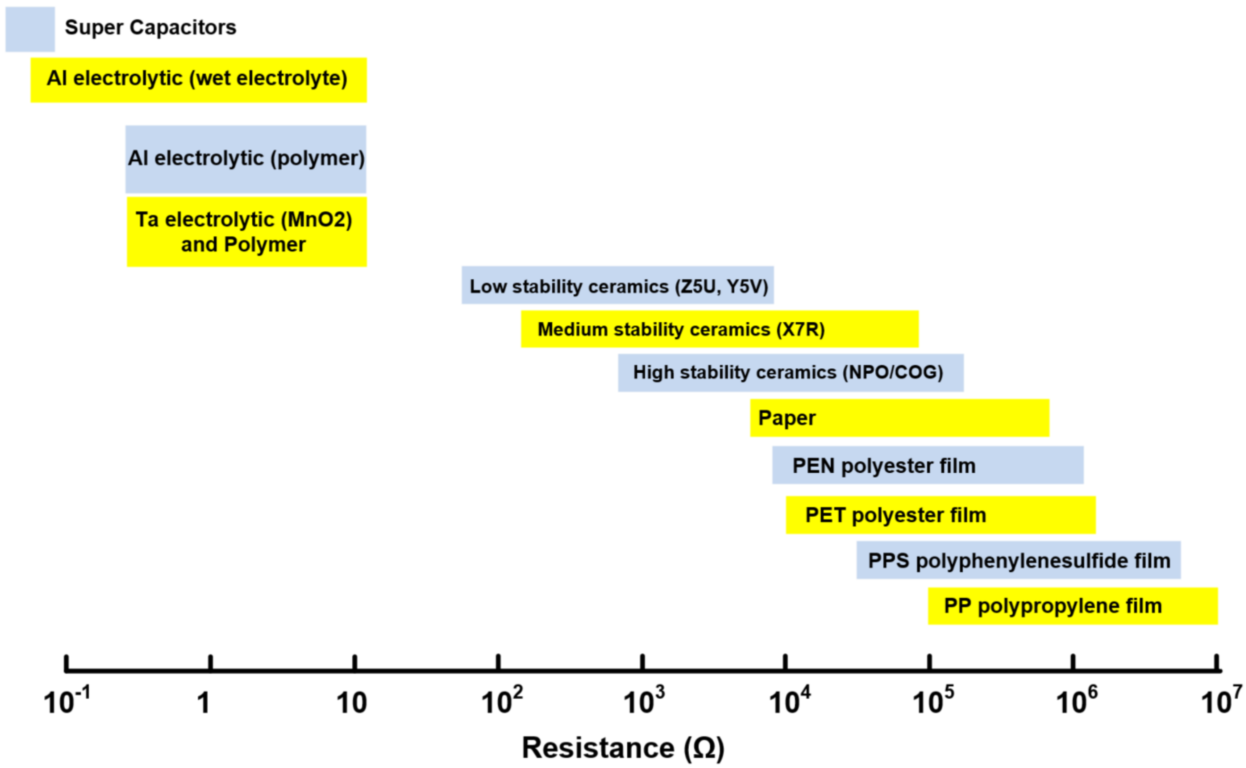


Figure 4-8
Resistance of various capacitor film insulation (adapted from [14])

Transformers

One path for leakage current for the transformer involves leakage flux as illustrated in Figure 4-9. Eliminating this leakage flux may be impossible although it may be minimized by effective placement of the primary and secondary windings.

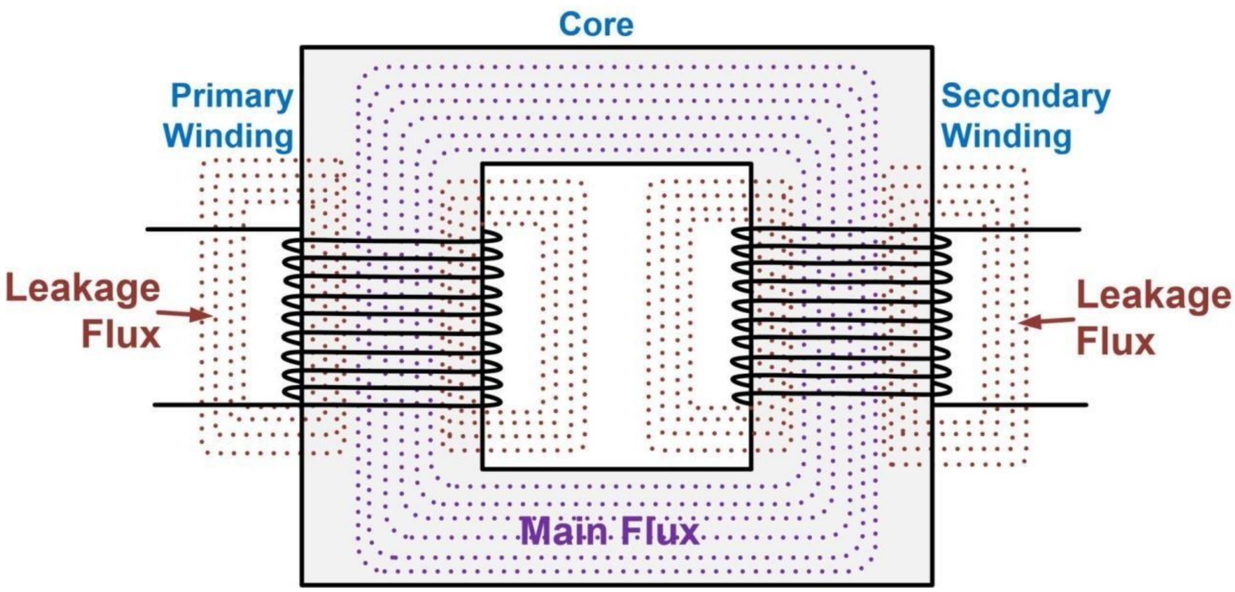


Figure 4-9
Leakage flux may occur at both primary and secondary windings (adapted from [15])

The transformers likely to be used in HVAC equipment are small—probably less than 500 VA. The quality of the transformers used is not known. While medical devices are required to have a very low value of leakage current—in the microamp range, the requirements for non-medical use transformers may be less stringent. Even so, the leakage current value for these may be less than 4 to 6 mA. At the same time, this leakage current may add to other sources to exceed 6 mA; therefore, it may be necessary to monitor any transformer used in the HVAC systems tested for leakage current.

Electric Motors

The electric motors used in HVAC systems may be single-phase or, with the use of inverters, three-phase designs. Single-phase motors may be split-phase, capacitor-start, two-value capacitor, permanent-split capacitor (PSC), and shaded pole all shown in Figure 4-10. While all might be used in HVAC systems, the motors with capacitors might drive the compressor while the split-phase and shaded-pole motors might likely drive fans. It is worth noting that, for one of the two HVAC units tested, the capacitor casing is directly connected to the frame of the unit—forming a path to ground through the grounded metal frame.

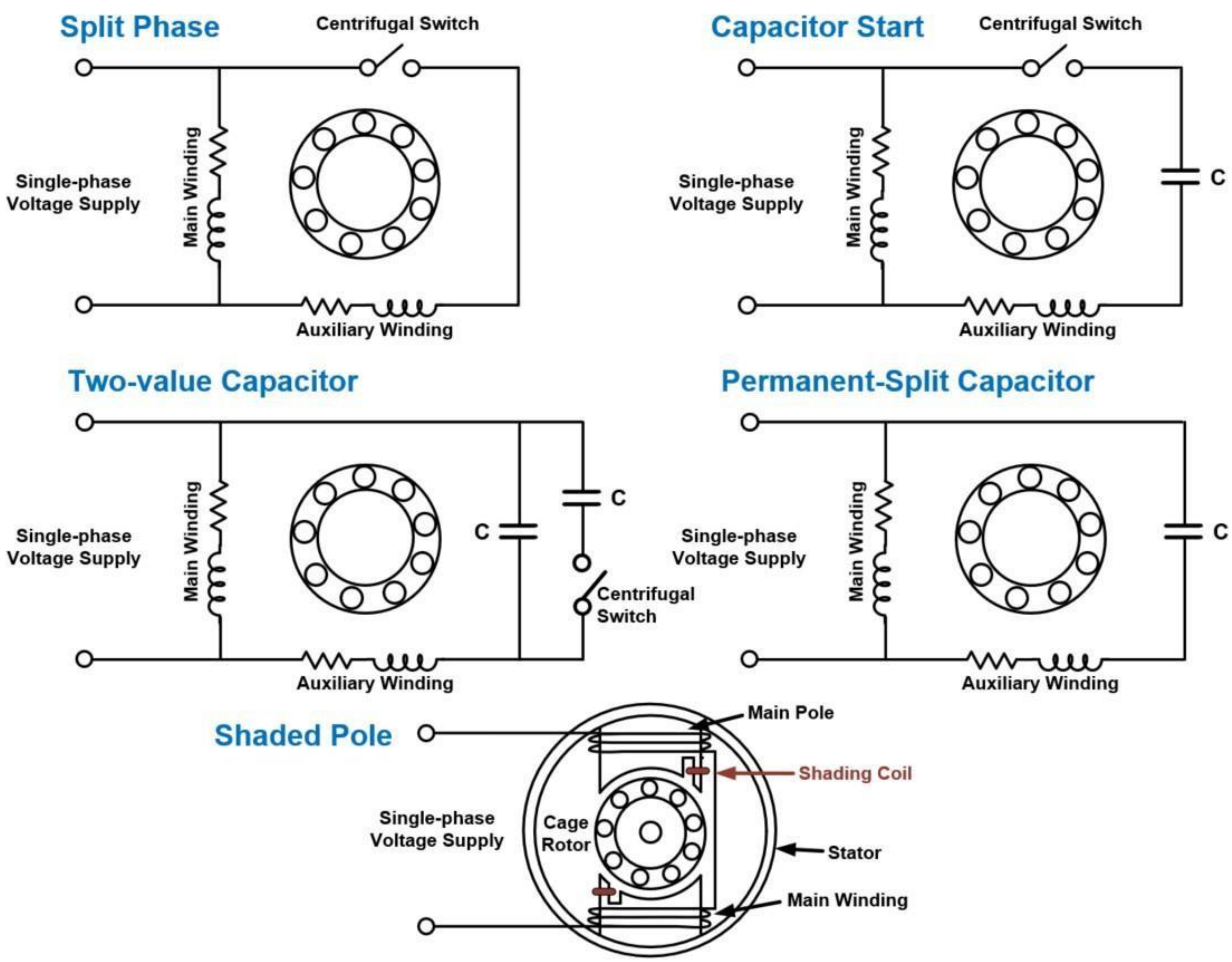


Figure 4-10
Types of single-phase motors

The PSC motor's leakage current has a dominant line-frequency component. Such currents flow through parasitic capacitances to ground. As such the motors' leakage current can be predictable. A simplified induction motor schematic may be seen in Figure 4-11. The stator and rotor have inductive windings.

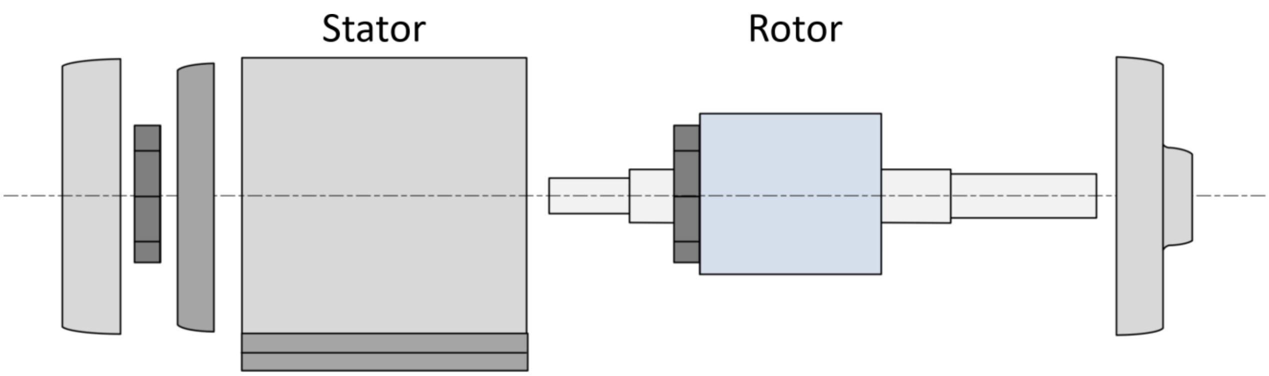


Figure 4-11
Induction motor simplified schematic

A newer motor design is the electronically commutated motor (ECM). This motor has a permanent magnet instead of inductive rotor windings. A simplified schematic may be seen in Figure 4-12. This motor type has onboard electronics (an inverter). The ECM has more paths for leakage current than the PSC such as parasitic capacitances between the power switching devices and the ground. [16] The parasitic capacitances of the windings to the ground and the parasitic capacitances of the power switching devices to the ground may be large contributors to the leakage current. One of the test units—that otherwise did not appear to have an inverter—has an ECM. Therefore, some single-stage units experiencing tripping—that did not appear to have power electronics—may actually have these present in the ECM.

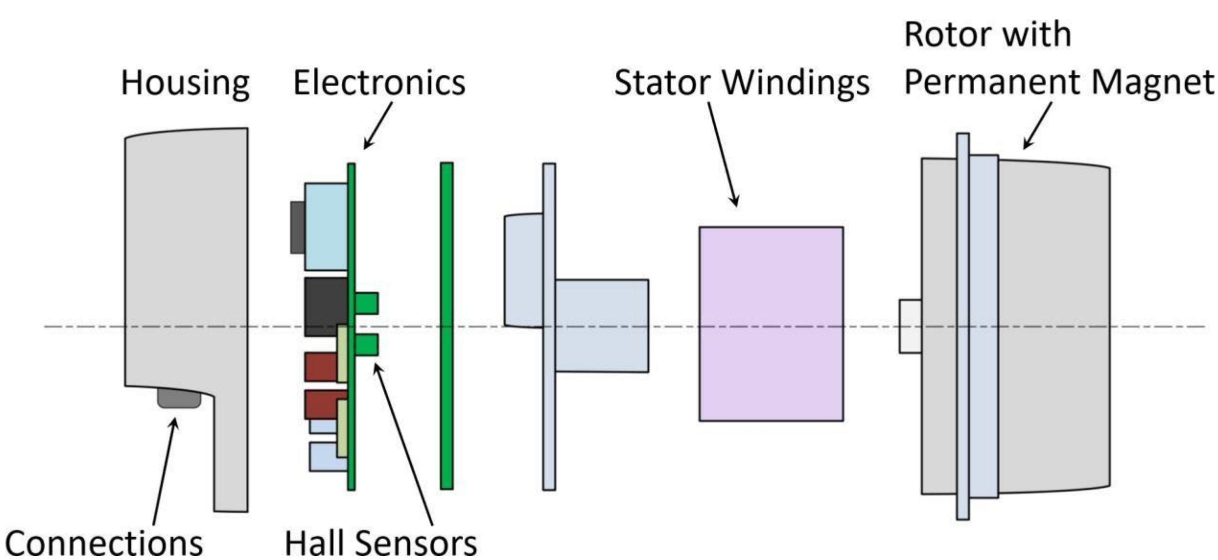


Figure 4-12
Electronically commutated motor (ECM) simplified schematic.

Inverters

Inverters, also called adjustable speed drive (ASDs) and several other terms, use high-frequency power-electronic switching to create pulses that drive the motor and control its speed. These high frequency pulses can find paths to ground and contribute to leakage currents.

Compressors, HVAC Fluids and Copper Tubing

The motor and compressor have been combined in a sealed, hermetic system. The sealed container, called the shell, holds both the motor and pumping components along with some fluid. The orientation of the motor and components may affect how much the motor is in contact with the fluid. For instance, one manufacturer's scroll compressor has the motor placed at the bottom of the shell allowing it to be submerged at times—such as at startup after a long period of inactivity. This scroll compressor is known to have greater measured leakage current than those with the motor located at the top of the shell.[17]

The oils and refrigerants used in refrigeration systems have changed over the years due to the move away from chlorofluorocarbon-based refrigerants. CFCs may have been compatible with mineral oil used as a lubricant which may not be compatible with those refrigerants in use today. The fluid combinations used to provide effective cooling and lubrication simultaneously have been determined already by the manufacturers as have the electrical insulation properties of these fluids. As the fluids age, however, the resistance may decrease—thus allowing more leakage current.

This resistance may be measured to assess the condition of the oil-refrigerant fluid using an insulation resistance tester that supplies DC voltages to the windings and insulation points of a motor to measure the current leakage rate (so-called "non-destructive" testing). For instance, a submersed motor such as with the hermetically sealed compressor might measure 600,000 ohms with an applied voltage of 500 volts corresponds to a leakage rate of 0.000833 amps or 833 microamps.[18] A reading of 60,000 ohms at the same voltage, however, might indicate a leakage current rate of 0.00833 amps or 8.33 milliamps. DC voltage testing can determine if the HVAC fluids have broken down enough to cause leakage current.

The copper tubes, being excellent conductors of electricity, might provide a path to ground through stray capacitances or their own connections to the HVAC hardware. It is possible that the breakdown of the HVAC fluids could allow the leakage current to flow to ground via the copper tubes carrying the fluids. It is also possible that the tubes—being attached to the compressor—may carry the leakage current directly.

Miscellaneous Sources of Leakage Current

A crankcase heater may be a possible leakage current path, and once the equipment is installed, a possible leakage current path to ground may be enabled in water/high humidity conditions combined with the presence of ionic contaminants that are deposited on contactors, connectors etc.

Manufacturer Testing of Leakage Current

Toshiba tested several components (a schematic of their testing setup is shown in Figure 4-13)— most likely to be used in HVAC systems—for leakage current.[13] Among them, motors of various sizes. Tested units 1 and 6 are both 4-ton units. The compressor motors are rated at approximately 3 kW and 5 kW, respectively. Interpolating from the Toshiba document, the 3-kW size of motor might have 0.26 mA of leakage current in operation with 1.27 mA during startup. The 5-kW motor might have 0.29 mA of leakage current in operation with 1.28 mA at startup.

Again, while these values may be too small to trip a GFCI, the leakage current from motors may add to other sources to exceed 4 to 6 mA.

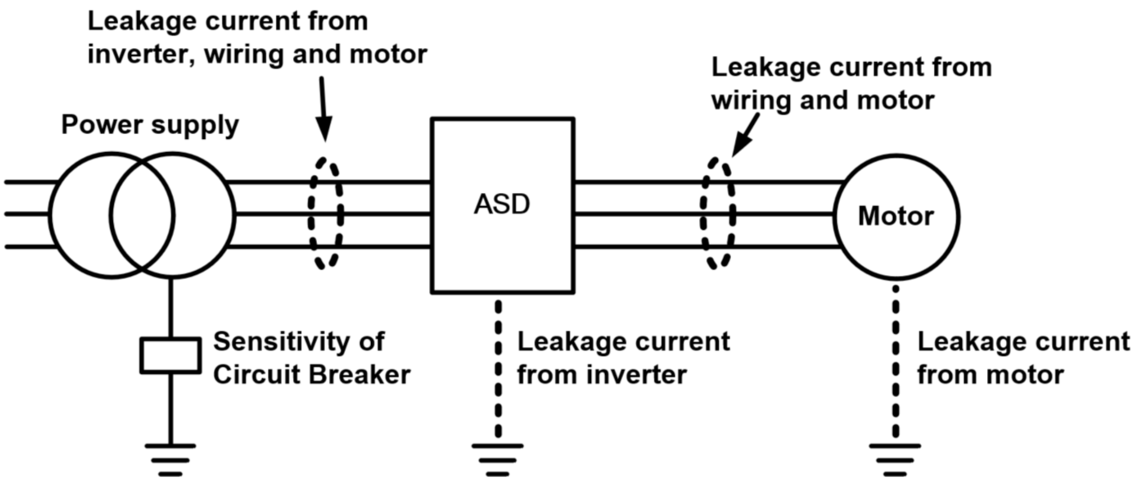


Figure 4-13
Toshiba monitoring test setup

Inverters

Toshiba also tested inverters (also called ASDs) using the power configurations shown in Figure 4-14 at left with lower voltage (120-volt level), single-phase units supplied through the configurations at right. For the inverters and filters, the type of power supply configuration greatly affected the amount of leakage current. Typically, those supplied through Power system A had less measured leakage current than those supplied by Power system B.

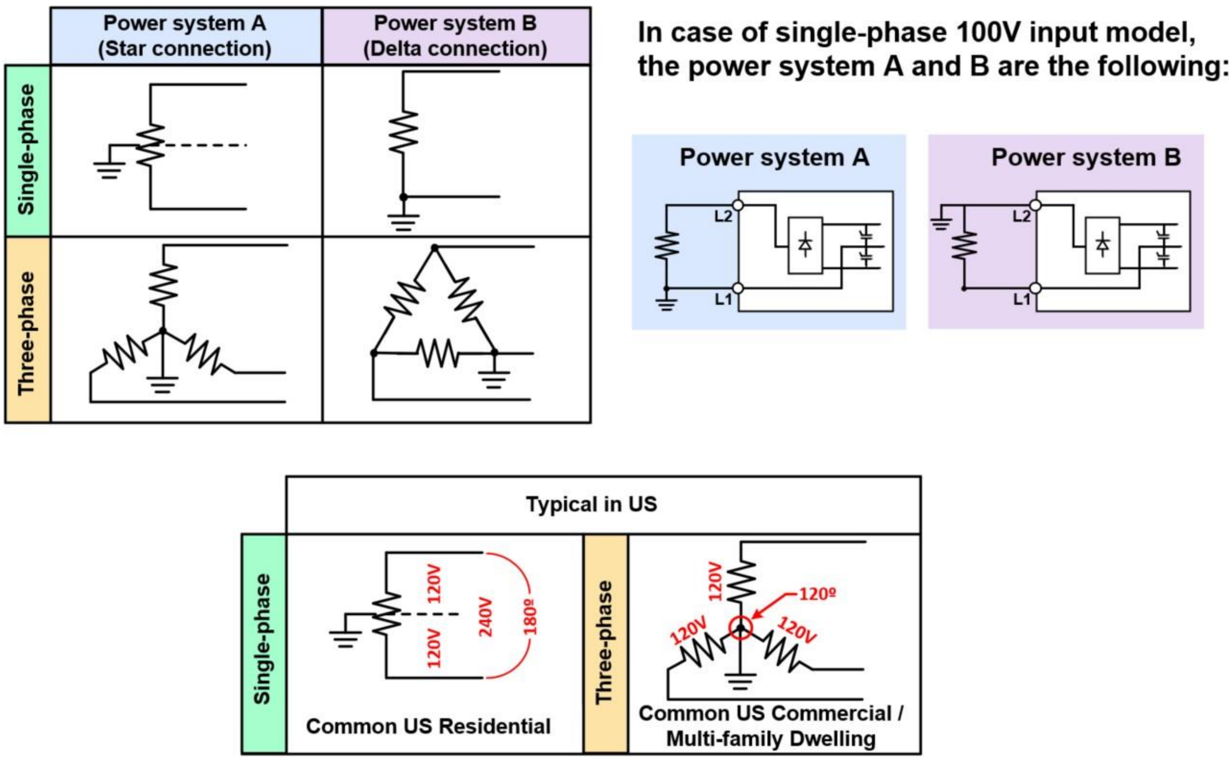


Figure 4-14
Power supply configurations used in the Toshiba tests.

Should an inverter be used to control the motor, the power supply system may affect the leakage current: Power system A (whether three-phase or single-phase) produced the least amount of leakage current while Power system B often produced significantly more leakage current.

The leakage current may vary by inverter model and size—with wide variation by model. One powered by the single-phase, split-phase configuration shown in Power supply A—a 2.2 kW (3 HP) model, had 0.1 mA of leakage current while another different unit of the same size and powered the same way had 8.1 mA of leakage current—which might immediately trip a GFCI. Another unit of similar size powered using the Power supply A configuration might have 0.9 mA of leakage current; however, powered from the Power supply B configuration, that same unit 7.6 mA of leakage current. Others powered through the latter configuration had over 40 mA of leakage current. Thus, the amount of leakage current for inverters may depend on the model as well as its power supply configuration.

Filters

Inverters with filters incorporated into the assembly may have high levels of leakage current from the filter—likely due to the capacitors. Figure 4-15 examines the leakage current measured with some filter models at left and with corresponding inverter models at right. The leakage current for the single-phase inverter models indicated at right (see red rectangle) seems relatively low for both power system configurations at 0.85 and 1.88 mA respectively. The corresponding filter model indicated at left (red rectangle at left), however, shows a leakage current of 54 mA.

Filter Type-form	Inverter type-form VF-nC3	Inverter type-form VF-nC1	Approx. Leakage Current (mA)
EMFAS2011Z	VFnC3S-1001P~1004P	VFnC1S-1001P~1004P	54
EMFAS2025Z	VFnC3S-1007P	VFnC1S-1007P	18
EMFAS2011Z	VFnC3S-2001~2007P	VFnC1S-2002~2007P	112
EMFAS2025Z	VFnC3S-2015, 2022P	VFnC1S-2015, 2022P	37
EMFA2006Z	VFnC3-2001~2007P	VFnC1-2001~2007P	117
EMFA2015Z	VFnC3-2015, 2022P	VFnC1-2015, 2022P	117
EMFS11-4025CZ	VFnC3-2037P	-	125

Inverter type-form	Approximate leakage current [mA]			
	Standard		Small capacitors	
	Power system A	Power system B	Power system A	Power system B
VFNC3S-1001P	0.85	1.88	-	-
VFNC3S-1002P	0.85	1.88	-	-
VFNC3S-1004P	0.85	1.88	-	-
VFNC3S-1007P	0.26	0.26	-	-
VFNC3S-2001PL	1.63	9.77	0.89	2.64
VFNC3S-2002PL	1.63	9.77	0.89	2.64

Figure 4-15
Inverter and corresponding filter leakage current measurements

By far, the most leakage current might emerge from a filter applied to the inverter. As with the inverter in the Toshiba study, these varied by the power supply connection—the least for the Power supply A systems and the most for the Power Supply B systems. In Figure 4-16 below, a filter for a 3 HP inverter measured 23 mA when connected to Power supply A compared to 119 mA when connected to Power supply B.

Clearly, the inverter and filter together could provide enough leakage current to exceed a GFCI's 6 mA trip level.

Filter Type-form	Inverter type-form VF-MB-2	Leakage Current (mA)	
		Power System A	Power System B
EMF4S-2010A	VFMB1S-2002～2007PL	10	54
EMF4S-2018B	VFMB1S-2015PL	10	54
EMF4S-2024C	VFMB1S-2022PL	23	119
EMF4-4015B	VFMB1-4004～4037PL	17	125
EMF4-4047D	VFMB1-4055～4075PL	52	383
EMF4-4049E	VFMB1-4110～4150PL	52	383

Figure 4-16
Leakage current by filter type and power supply

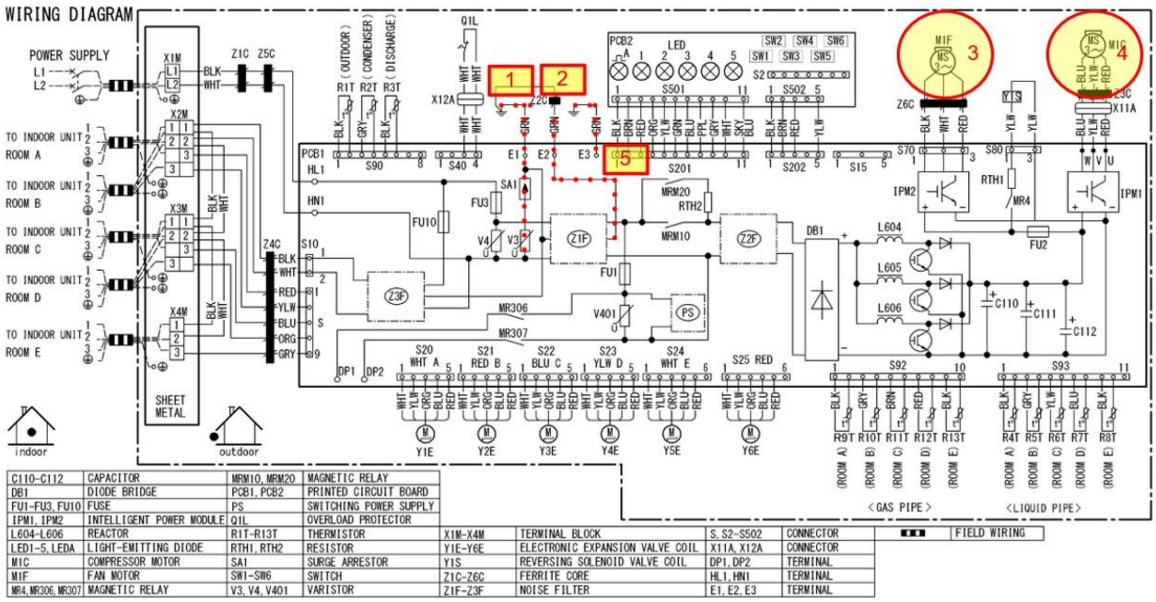
The above analysis shows that leakage current may vary greatly for power supply configuration, by model of inverter, and the corresponding filter for the inverter.

The Variable-speed and Single-speed Model Analyses

Analysis of the schematics for Unit 6, as shown in Figure 4-17 and Figure 4-18, reveal possible paths for leakage current from the inverter and the motors. For the outdoor unit:

1. V3 is a MOV referenced Line-to-ground. If the MOV conducts, enough ground current could be produced to trip the breaker.

2. If Z1F filtered undesirable frequencies to ground, this could result in tripping the GFCI.
3. Leakage current from the drive output through the bearings of the motor to ground.
4. Leakage current from capacitors through heat sink to ground.



1 — V3 is a MOV referenced L-G. If the MOV conducts enough ground current could be produced to trip the breaker

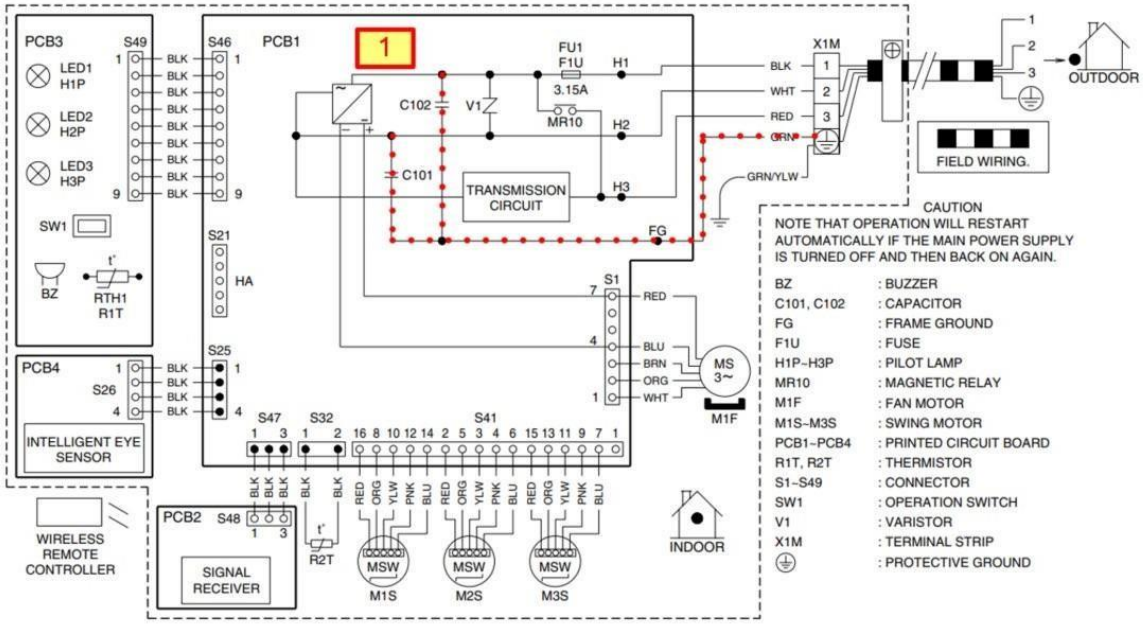
2 — If Z1F filtered undesirable frequencies to ground could result in tripping the GFCI

3&4 — Leakage current from the drive output through the bearings of the motor to ground

5 — DC power supply and heat sink ground

Figure 4-17
Variable speed model (Unit 6), Outdoor unit analysis

For the indoor unit shown in Figure 4-18, C101 and C102 form a path to ground for currents higher than the fundamental frequency.



1 C101 and C102 is a path to ground for currents higher than the fundamental frequency.

Figure 4-18
Variable-speed model (Unit 6), indoor unit analysis

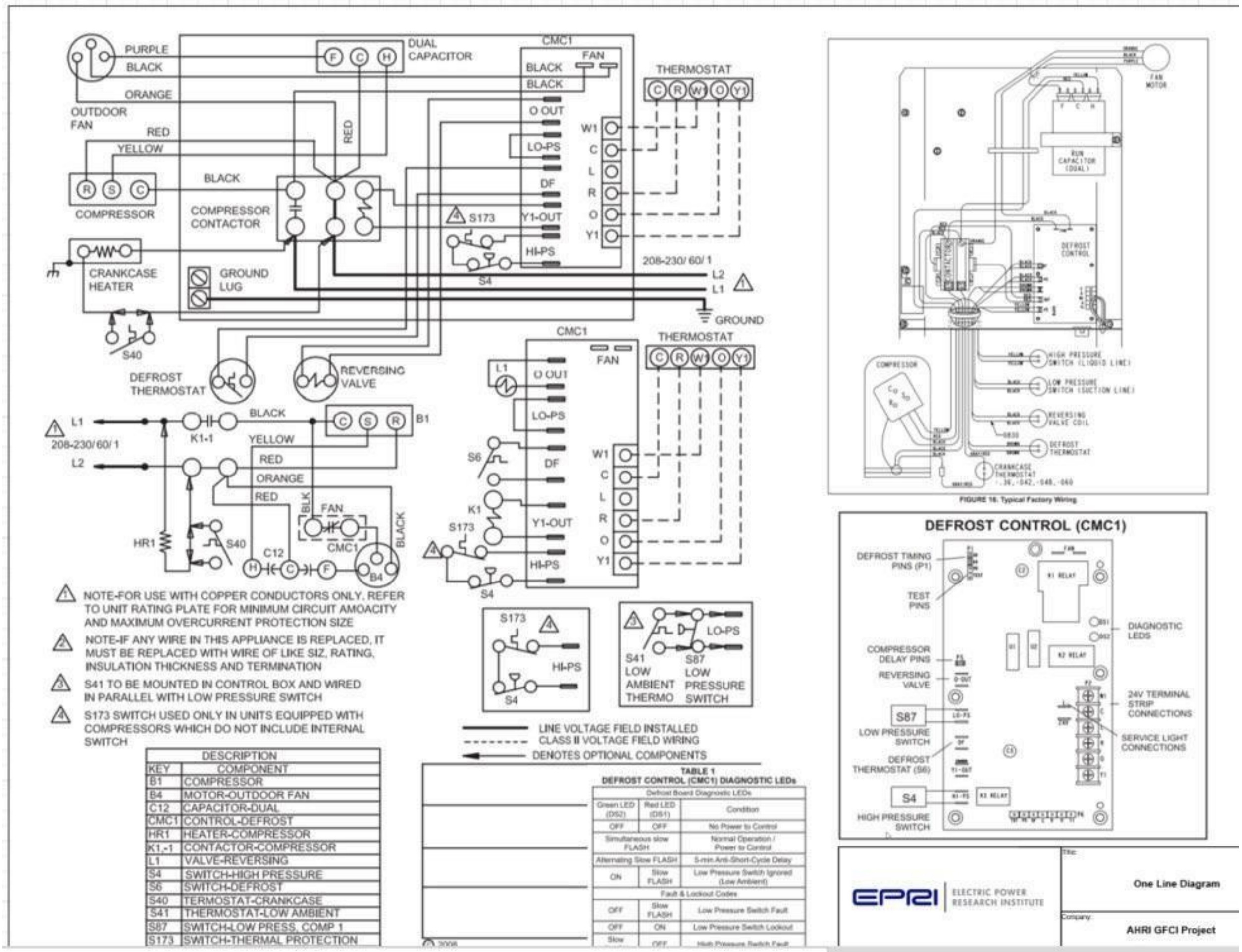


Figure 4-19
Single-speed model outdoor unit analysis

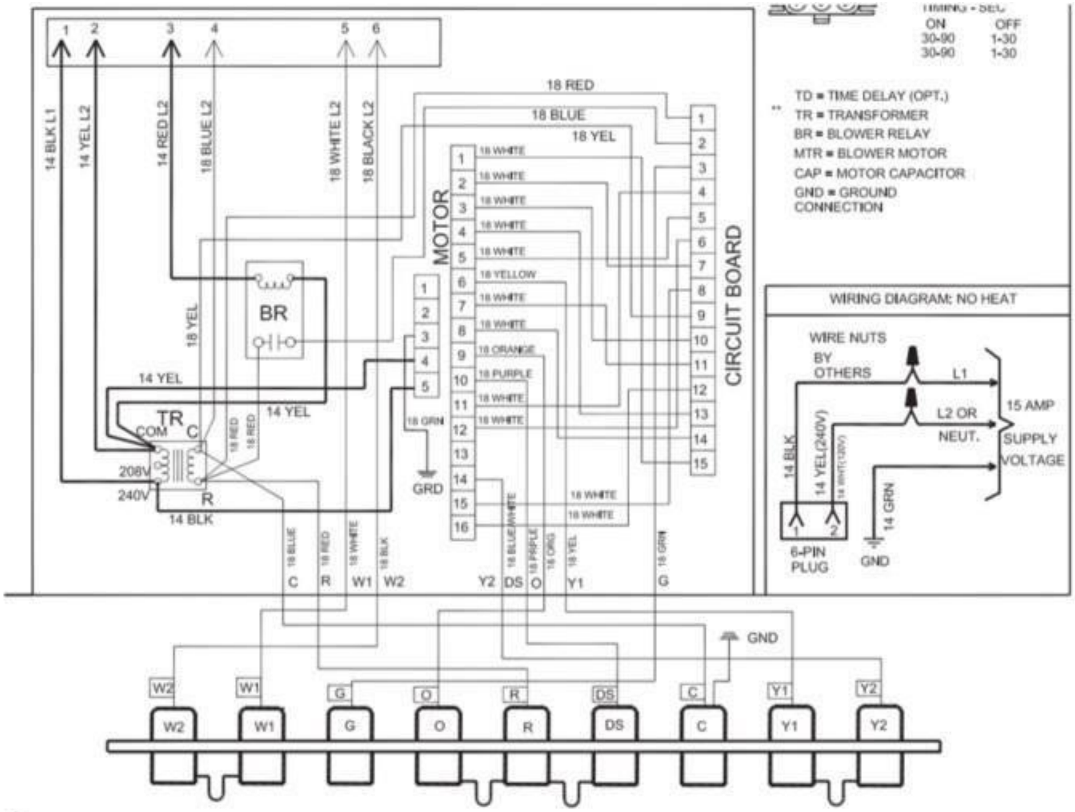


Figure 4-20
Single-speed model, indoor unit analysis

Since the indoor unit is not powered by the outdoor unit, there is no inference that the indoor unit leakage current could contribute to the outdoor unit leakage current resulting in a nuisance trip.

5 SUMMARY AND RECOMMENDATIONS FOR TEST SCENARIOS

The 2020 edition of the National Electric Code (NEC) was revised with additional requirements for GFCIs regarding HVAC 'outlets.' However, the installation of GFCIs with these designs has revealed a situation of incompatibility between the HVAC units—single-, two- and variable-speed air-conditioners—and the GFCIs. Nuisance tripping of the GFCIs has become all too common.

This study examined materials and standards related to circuit breaker and GFCI sensitivity, leakage current from possible 120-volt to 240-volt HVAC system components, and the sources of various levels of electric current for the Class A GFCI to trip.
While the 30-mA trip limit for European RCDs is above the 'let-go' threshold according to Dalziel's study, an instantaneous trip time of a few cycles may prevent a fatal interaction—although, it may be painful. Standards from specific countries may establish a different 'touch current' limit.

One manufacturer, Toshiba, measured the leakage current of several components that may likely appear in 120-volt to 240-volt HVAC units—including ASDs and filters. Depending on the component, the component model, and the configuration of power supply, this leakage current varied between insignificant values to values much greater than 6 mA. Indeed, some measured leakage current—specifically for ASDs and filters—was more than enough to trip a GFCI conforming to the 6-mA limit—or even the 30-mA trip limit for RCDs. As high-frequency currents emanating from these components may be involved in nuisance tripping of GFCIs, these high-frequency currents should be measured.

To identify a method of addressing this incompatibility between HVAC units and GFCIs, testing occurred to characterize the source(s) magnitude(s) and frequencies of leakage current measured from two test HVAC units along with the trip characteristics of two designs of GFCIs. As the nuisance tripping might also coincide with power quality events in the voltage supply, these HVAC units and GFCIs were tested in the presence of voltage sags, transients, and other events.

Potential Solutions Investigated

Decrease the carrier frequency of the VFD.

Higher-frequency pulses (higher than 60 Hz) from ASDs produce higher-frequency voltage and current pulses that are more prone to find extraneous paths to ground—such as through the motor bearings. The single-phase, two-pulse ASDs used in residential applications might allow the reduction of the carrier frequency; this action may depend on the manufacturer. However, this may increase the audible noise level.

Ramping up VFD in steps

Leakage current resulting from ASD acceleration of motors during startup might be minimized by allowing a more gradual process of this acceleration.

Placement of GFCI

Long conductors (long lead length) between the GFCI and its source can allow the stray capacitance of the conductor to create high-frequency paths to ground that may cause the GFCI to trip.

OV protection from voltage spikes

Overvoltage spikes may occur from lightning strikes or capacitor switching transients. Protecting circuits from direct lightning strikes may be difficult; however, mitigation in stages may be possible for strikes occurring elsewhere on a distribution circuit.

Chokes and Filters

Inductive chokes (also called line reactors) and harmonic filters can greatly reduce high-frequency pulses in electrical systems. The possible point or points of application with respect to the GFCI may require testing. The choke may reduce any high-frequency component (that is, greater than 60 Hz).

Lower the stray capacitances between grounds via use of cables and wires with lower insulation permittivity. This might deny the high-frequency components a path via the wires' stray capacitance.

Install leakage breakers designed for the harmonics and surge suppression to the variable frequency drive's own system and other systems.

6 UNIT 1 TEST RESULTS

Background for testing HVAC Unit Number 1

As related in Chapter 1, GFCI circuit breakers have tripped when powered by HVAC units of various topologies. This chapter will describe the testing of a single-stage HVAC system—*the equipment under test*, or EUT. This HVAC design turns the compressor and condenser fan on and off through the use of contactors and relays. Therefore, the compressor is either in a digital state of “on” or “off” unlike the compressors powered by adjustable speed drives.

Test Objectives

The test objective was to discover test conditions that created the highest leakage current. Early in the project, eleven possible tests were proposed that might determine conditions that may create enough leakage current to cause a GFCI to trip. Budget constraints caused the team to reduce the number of tests to seven as shown in **Error! Reference source not found.**. The r esults of these tests are described in the following sections. The remaining tests may be conducted in Phase 2 of this project.

Test Setup

This section will describe the test setup for the Unit 1 testing. Figure 6-1 is a collage of photos from the Unit 1 test setup. The test setup contained HVAC test unit 1, a 45-kVA power amplifier from California Instruments, the 200-amp voltage sag generator, and metering and measurement devices including the HMB Gen 3i waveform recorder and a Hikoi 3198 power analyzer.

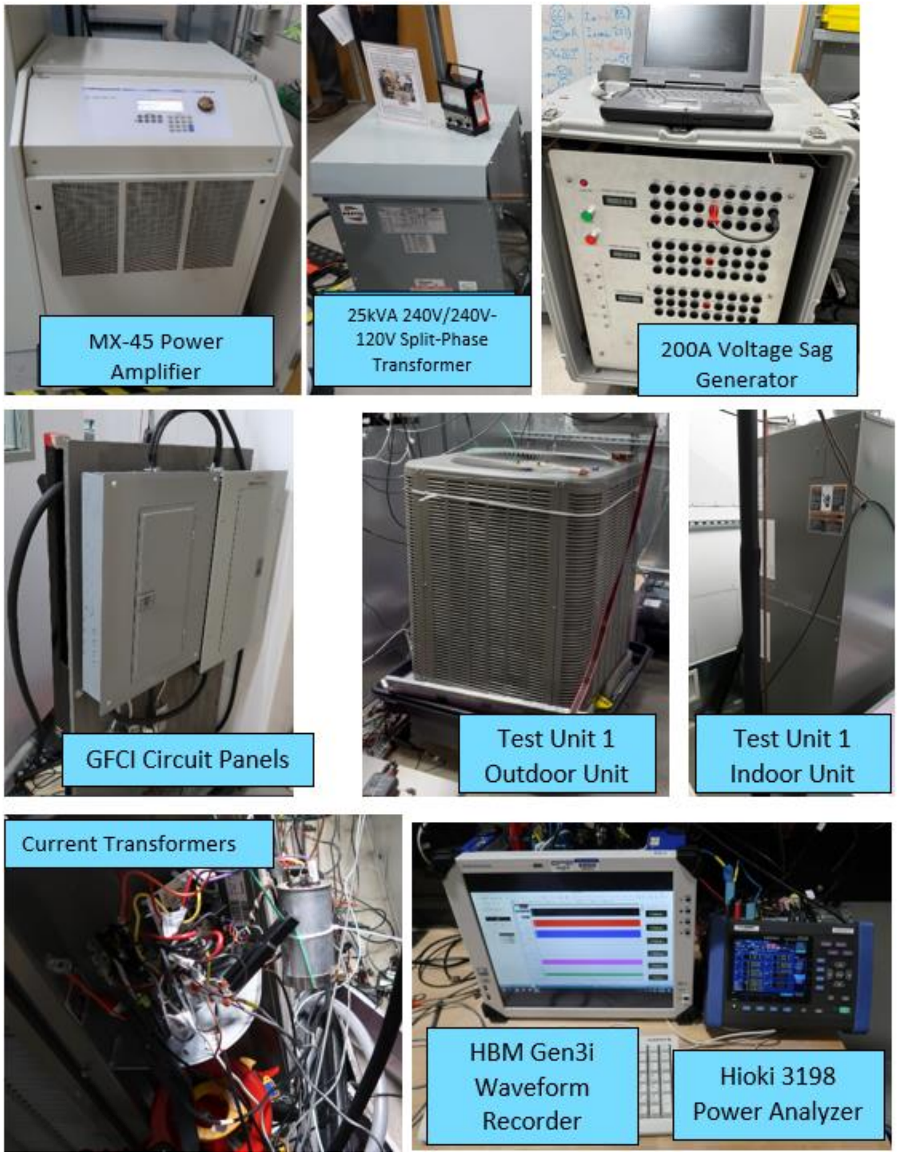


Figure 6-1
AHRI Test Setup for Test Unit 1

Testing was conducted to determine what may be causing the GFCIs to trip when connected upstream of HVAC systems. The test objective was to discover conditions that created the highest leakage current. Figure 6-2 contains a block diagram of the test setup. Numbers 1, 2a, 2b, 3, and 4 are placed in Figure 6-2 to note the location where CTs were placed in the circuit The numbers are associated to the CTs shown in **Error! Reference source not found.**.

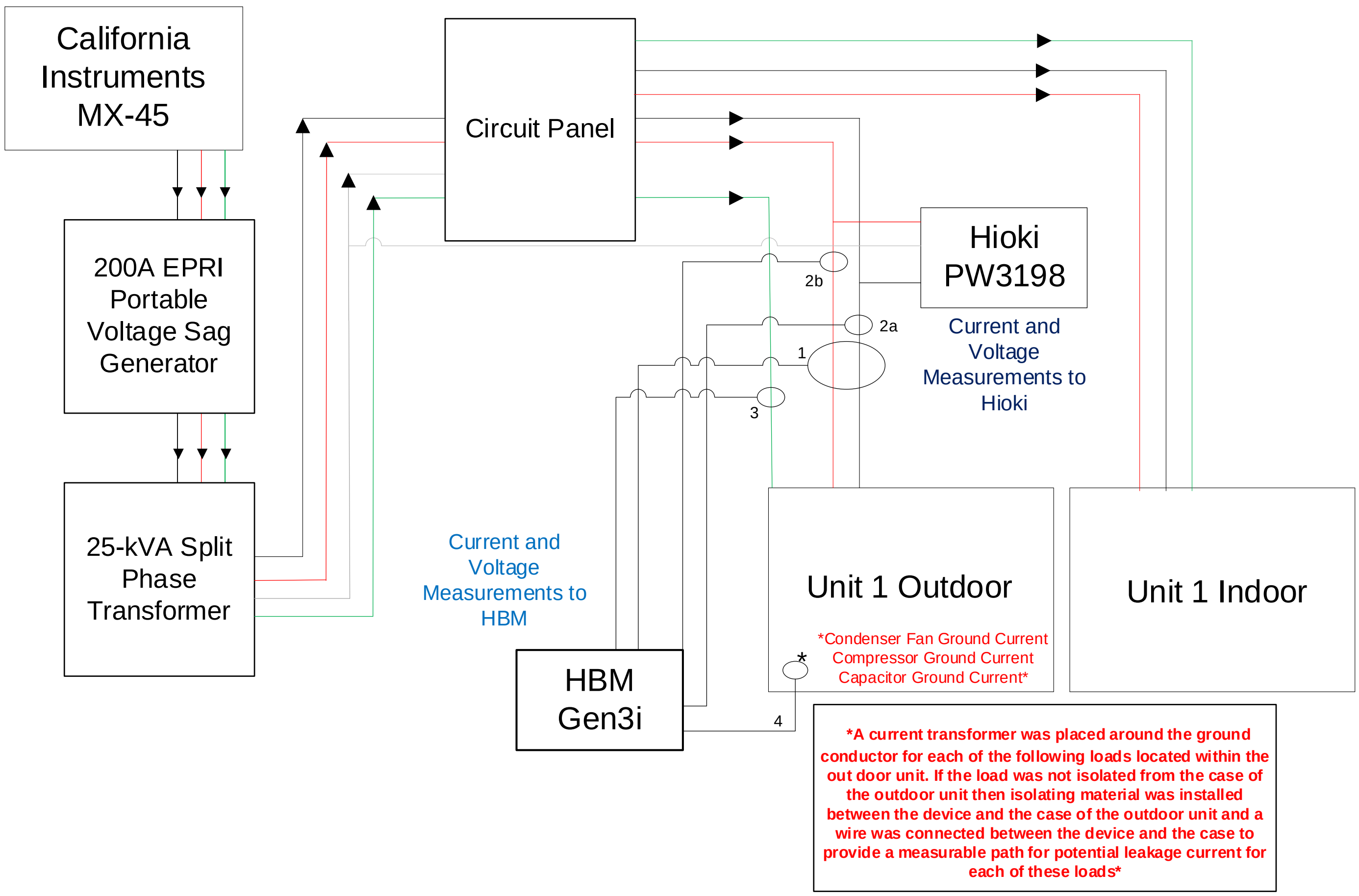


Figure 6-2
Test Setup Diagram

Error! Reference source not found. associates the current transformers to the monitoring l ocations.

Table 6-1
Current Transformer Data

Manufacturer	Model	Serial Number	Measurement	Measurement Description	Location in Circuit Figure 6-2
AEMC	2620	104315WBS	Z-CT	CT Installed around outdoor L1 and L2 input wiring	1
Hioki	CT6700	211230270	HFT-GND	Total Ground Current Outdoor Unit: High Frequency Response CT	3
Hioki	3272	220139616	CT6700 Supply	DC Power Supply for Hioki CT	N/A
AEMC	K110	156921WGDV	Comp-GND	Compressor Ground Connection	4
AEMC	K110	156925WGDV	LFT-GND	Total Ground Current Outdoor Unit: Low Frequency CT	3
AEMC	K110	156920WGDV	Fan	Condenser Fan Ground	4
AEMC	K110	153156WCDV	Cap-GND	Capacitor Ground Current	4
AEMC	SR661	09L29347DV	L1 Current	Total Current	2a
AEMC	SR661	120172HDV	L2 Current	Total Current	2b

Note: Current through the ground conductor of the outdoor unit was measured using a high-frequency Hioki CT6700 current probe as well as a low-frequency AEMC K110 current probe. These current probes measured leakage current values that were well above the operational limits of the GFCI. The AEMC 2620 current probe installed around the L1 and L2 conductors measured much lower current flow than the current flowing though the ground conductor. The AEMC 2620 was temporarily relocated to measure the leakage current through the high- and low- pressure refrigerant lines, and these higher currents confirmed the measurement of the current probes installed around the ground conductor. An investigation was conducted to identify the source of these ground currents; however, the test schedule did not provide time to identify the source of these currents. Future testing may consider adding another AEMC 2620 leakage current probe to measure leakage current that may be flowing through the refrigerant or copper refrigerant lines between the outdoor and the indoor units of the EUT.

A GFCI reacts on the difference between the L1 and L2 current and not the actual measured current of the ground conductor; therefore, this may be the reason the GFCI did not trip during any of the tests. The AEMC 2620 leakage current probe was returned to measure the difference between the L1 and L2 conductors and testing of Unit 1 began. The AEMC 2620 was used as the primary measurement for total leakage current of the outdoor unit.

Unit 1 Testing

This section will detail the 7 tests that were conducted. The tests shown in **Error! Reference s ource not found.** were conducted in one or more of the indoor and outdoor chamber conditions shown in **Error! Reference source not found.**.

Table 6-2
Test Matrix

Test No.	Test	Procedure	Purpose
0	Power Applied: Extended Off Time	Power down HVAC system overnight, start in the morning to mimic extended off time.	Refrigerants and oils may settle in the compressor. The settling may contribute to additional leakage current – causing GFCI to trip during start-up sequence.
1	Power Applied	Apply power to the compressor at 0-degrees, 45-degrees, and 90-degrees point-on-wave.	To determine if where power is applied on the 60-hertz voltage wave may affect the magnitude of the leakage current.
2	HVAC Running	Monitor the output voltages and current and any suspected leakage current paths while the HVAC is bringing the indoor chamber to the set temperature from a starting temperature to a setpoint.	The purpose of this test is to observe the HVAC unit operating for one hour to see if it trips a GFCI.
3	Thermostat Cycling	Monitor the output voltages and current and any suspected leakage current paths while the HVAC unit is cycled in a 5-minute ON/ 5-minute OFF test pattern for one hour.	Determine if the GFCI trips while the HVAC unit cycles.
4	Defrost Cycling Test	Monitor the output voltages and current and any suspected leakage current paths with the HVAC operating in thermal condition 3 shown in **Error! Reference source not f ound.**.	The purpose of this test is to monitor the leakage current paths while the HVAC unit is operating in defrost cycling mode.
5	Voltage Interruption	Inject voltage interruptions into the EUT. Observe and document the performance of the EUT. Perform the test with all tap jumpers of the voltage sag generator on the 0% tap and again with the voltage tap jumpers removed.	Determine if the response of the HVAC system may cause the GFCI to trip for high- impedance voltage interruptions (open circuit) and low-impedance voltage interruptions (tap transformer set to 0%).
6	High/Low Voltage Range Test (C84.1)	Using a power amplifier, increase the nominal voltage to the maximum and minimum in three-volt increments until the EUT trips or the C84.1 Range B limits are reached. If the minimum/maximum voltage level is achieved, allow the unit to operate for two, 5-minute on/off cycles as described in the thermostat cycling test.	Investigate the response of the EUT when operating at the minimum and maximum "acceptable" voltage levels provided in the ANSI C84.1 standard.

Table 6-3
Test Chamber Temperature Conditions

Test Condition Designation	Outdoor Air Temp (db*)	Indoor Air Temp (db)	Test Simulation
1	75° F	75° F	Nominal Base Line (75 degrees)
2	95° F (Nominal + 20° F)	75° F	Full Nominal Cooling Conditions
3	47 °F (Nominal - 28° F)	75° F	Full Nominal Heating Conditions

*Dry bulb

The manufacturer requested that testing be conducted with a specific manufacturer's circuit breaker. That circuit breaker was to be manufactured prior to the year 2021, week 43, day 4. According to the manufacturer, the firmware was updated after this date. The circuit breaker that was used during the testing is shown in **Error! Reference source not found.**. The circuit b reaker was manufactured in 2021 on the 28th week, on the 4th day of the week. The circuit breaker did not trip for any of the tests that were conducted.

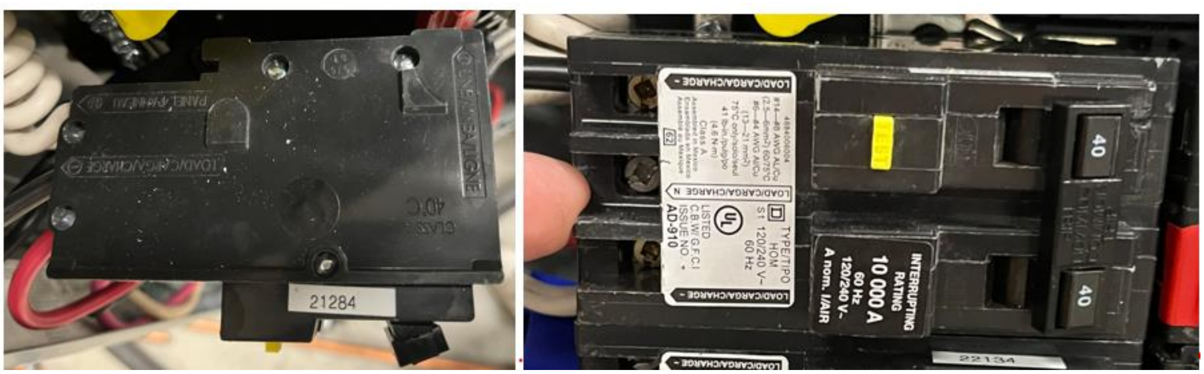


Figure 6-3
GFCI Circuit Braker Used for all Testing

Test 0 Power Applied: Extended Time Off

The purpose of the Extended Off Power Applied test is to determine if refrigerants and oils settling in the compressor during extended periods of no operation may cause an increase in the leakage current at startup. The hypothesis is the leakage current created during startup may result in GFCI tripping. This test was conducted once at each thermal condition shown in **Error! Reference source not found.**.

The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** s hows the maximum and minimum leakage current recorded during each test, the relative humidity of the temperature chamber during the test, and some general observation notes. The

RMS Current for each measurement point was documented at the time when power was applied (approximately 4 ms), when the compressor started (approximately 300 ms), and during the remaining time the HVAC system was running (approximately 25 minutes). **Error! Reference source not found.** shows the measurement periods that produced the maximum and minimum leakage current as well as the RMS current value that was recorded by the Z-CT. The table also shows whether the current level was within the trip current/time limit shown in UL 943. The relative humidity of the temperature chamber during the test is included in the table as well.

Table 6-4
Extended Time Off Test Tabular Data

Chamber Temperature Condition	Lowest Measured Z-CT RMS Current	Highest Measured Z-CT RMS Current	Within UL 943 Current/Time Limits?	GFCI Trip?	Outdoor Humidity
1	3.8 mA During Compressor Running Measurement Period	32.2 mA During Compressor Start Measurement Period	Yes	No	21%
2	4.5 mA During Application of Power Measurement Period	43.6 mA During Compressor Start Measurement Period	Yes	No	17%
3	5.4 mA During Compressor Running Measurement Period	27.4 mA During Compressor Start Measurement Period	Yes	No	39%

Thermal Condition 1 Testing

Error! Reference source not found. shows that the maximum leakage current was measured d uring the compressor start measurement period with the system operating in chamber condition 2. The lowest leakage current measured by the Z-CT was observed during the compressor running time period when the system was operating in chamber condition 1. Figure 6-4 through Figure 6-15 show the oscillography of each test and highlights the maximum current, minimum current, and RMS current of every location where leakage current was measured. **Error! Reference source not found.** through **Error! Reference source not found.** sh ow the RMS currents from all the current sensor measurements during the three temperature conditions and all three measurement time frames. No GFCI trips occurred during these tests.

Figure 6-4 shows the oscillography captured by the waveform data logger with the system operating in Chamber Temperature Condition 1. The test was conducted for at least 30 minutes as per the test protocol. The test was initiated by applying power via a knife switch with power supplied for the 30-minute duration. Figure 6-4 shows the three timeframes—application of power, compressor start, and nominal running—where RMS leakage currents are shown in the following figures and tables. The 240-volt supply voltage, both phase currents that supply the outdoor unit, and current flow through the grounding conductor were measured with high-frequency and low-frequency response CTs. The difference in the line current was measured though an AEMC 2620 leakage current probe (Z-CT), while the compressor leakage current was monitored with an AMEC K110 low-frequency current probe. GFCI's react on differential current; therefore, the Z-CT was used as the standard to compare against the other current measurement devices. *Note: in all the charts, a value appears at left under the name of the leakage current being measured. This is an artifact showing the value registered at the location of the red cursor which may or may not be visible in the chart. This value has no relevance to the measurements of concern.*

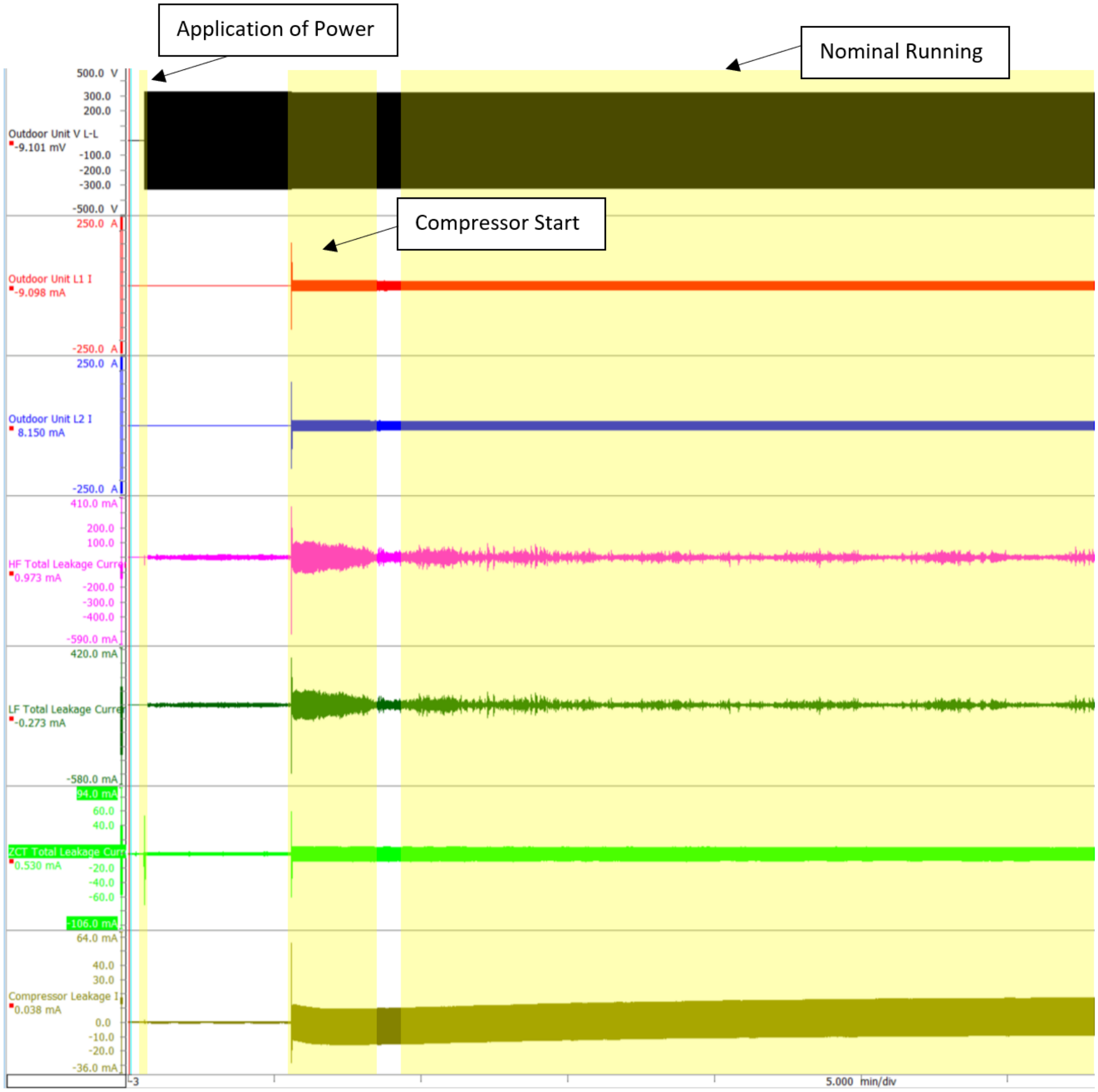


Figure 6-4
Test 0 Condition 1 Monitoring File 57

Figure 6-5 shows a ‘zoomed-in’ view of the time when the knife switch was closed, and power was applied as well as the RMS leakage currents that resulted. The current probes measured a very short burst of current when the switch was closed. The RMS values during this short time period were below the time current requirements of UL 943 and a detailed chart may be seen in Figure 6-5 below.

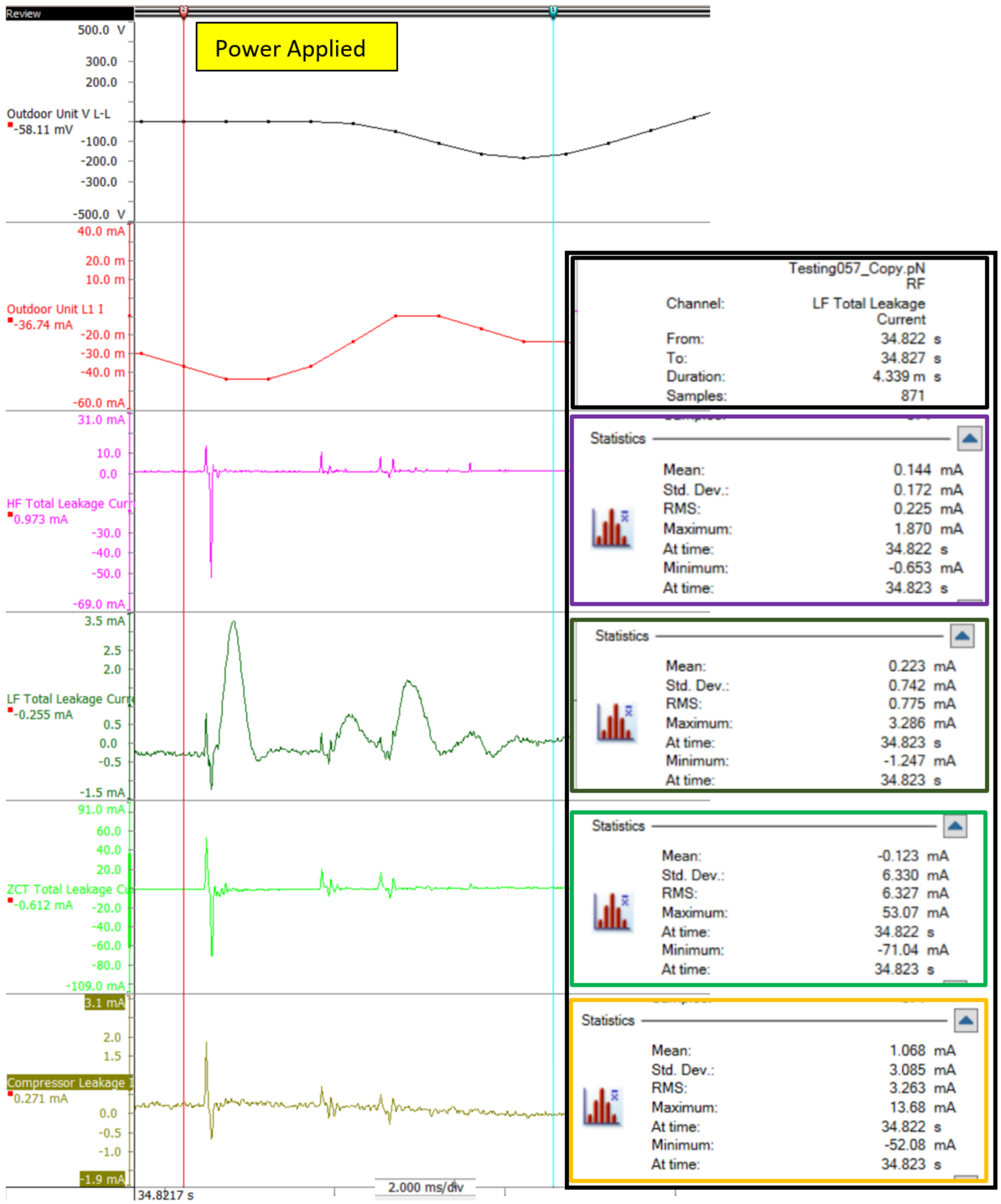


Figure 6-5
Power Applied Leakage Current Measurements

Figure 6-6 is a ‘zoomed-in’ view of when the compressor started as well as the RMS leakage currents that resulted. This was the time during the test when the leakage current was the highest; however, the current measured by the Z-CT was within the operational limits of the time current curve shown in UL 943. These values may be seen in **Error! Reference source not found.**.

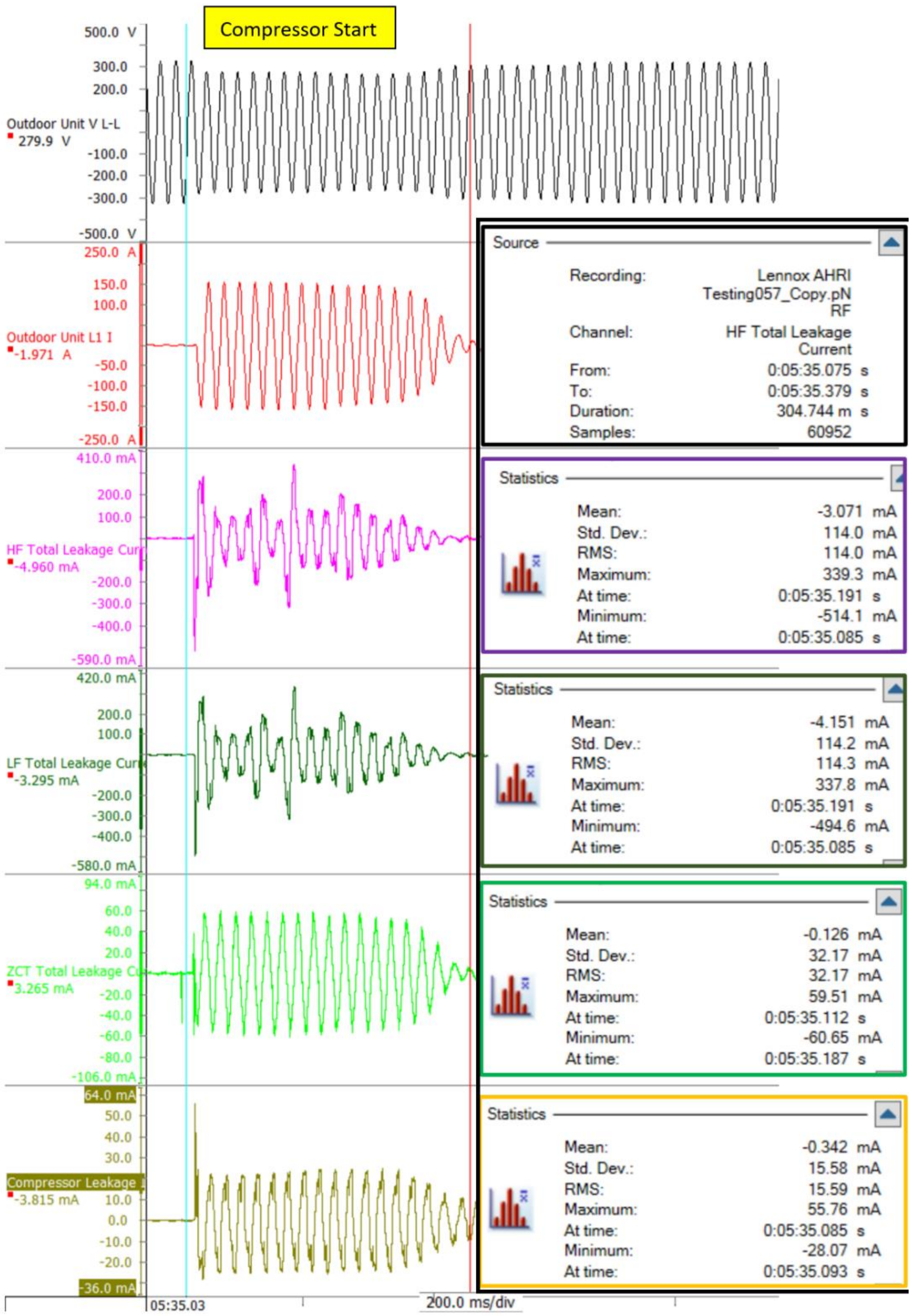


Figure 6-6
Compressor Start Leakage Current Measurements

Figure 6-7 is a 'zoomed-in' view of the remaining time power was applied to the system (approximately 27 minutes) and the RMS leakage currents that resulted. The oscillography shows the currents during normal operation as the outdoor unit operates. The Z-CT measured values within the operational RMS current limits as per UL 943. The compressor leakage current probe measured RMS current greater than the Z-CT as did the HF and LF leakage current probes. The reason for the higher measurement is not known; however, there may be another load in the system whose leakage current may be shifted in phase. Thus, a summation of the currents may have created the lower value reported by the Z-CT.

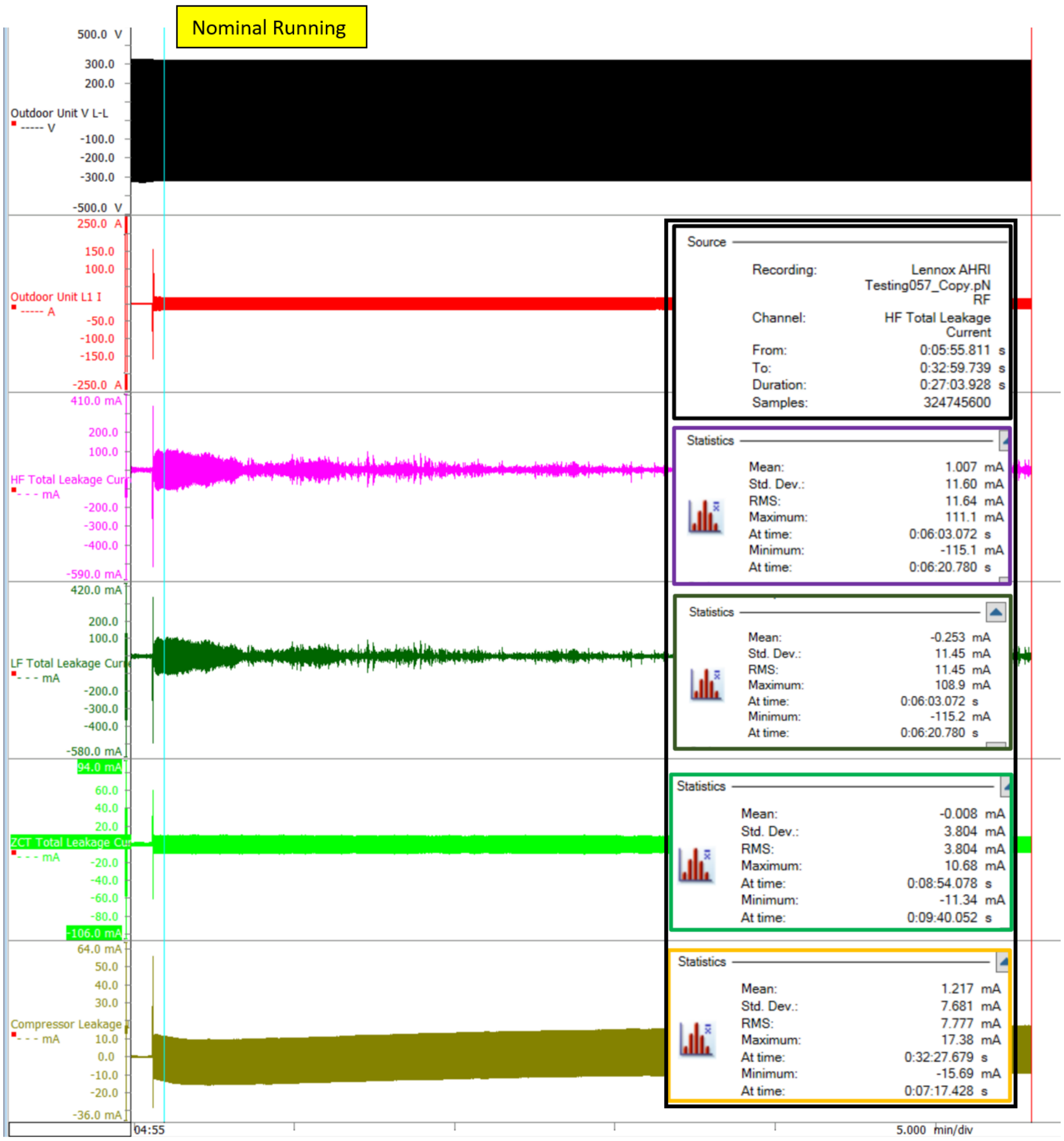


Figure 6-7
Nominal Running Leakage Current Measurements

Error! Reference source not found. shows the RMS current values during the time that power was applied to the circuit, the compressor started, and the remaining time the compressor was running. The data shows the circuit breaker did not trip at any time during the test and the Z-CT, the standard of measure, never exceeded the time/current limits in UL 943. The Compressor leakage current level was below the levels measured by the Z-CT during the application of power and when the compressor started; however, compressor leakage current measured above the Z-CT during the compressor running time period of the test. The HF and LF CTs connected to the ground conductor measured almost no current during the application of power; however, these always measured significantly higher current levels than the Z-CT during conditions when the compressor started or ran. The current levels measured by the HF and LF CTs agree within a few tenths of an amp. The reason for this phenomenon is not known; however, a GFCI does not act upon current flowing through the ground conductor but rather the *differential* current between the conductors that supply current to the load. Therefore, the Z-CT is the trusted measurement.

Table 6-5
Condition 1 Extended Time Off Critical Time Measurements

Note: All measurements are represented as RMS	**Application of Power**		**Compressor Start**		**Compressor Running**		
Measurement Time Base	2 ms/div		200 ms/div		5000 ms/div		
RMS Measurement Time	4.3 ms		305 ms		27 min 4 sec		
UL 943 Limit	**903 mA**	**Within UL 943 Current/Time Limits?**	**46 mA**	**Within UL 943 Current/Time Limits?**	**6 mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	6.3 mA	Yes	32.2 mA	Yes	3.8 mA	Yes	No
Compressor Leakage	3.3 mA	Yes	15.6 mA	Yes	7.8 mA	No	No
HF Probe Ground Conductor	0.2 mA	Yes	114.0 mA	No	11.6 mA	No	No
LF Probe Ground Conductor	0.8 mA	Yes	114.3 mA	No	11.5 mA	No	No

Thermal Condition 2 Testing

Figure 6-8 shows the oscillography captured by the waveform data logger with the system operating in Chamber Temperature Condition 2. The leakage current of the start capacitor and the condenser fan were added to the data acquisition system prior to beginning Chamber Temperature Condition 2 testing. The test was conducted for at least 30 minutes as per the test protocol. The test was conducted by applying power via a knife switch with power supplied for the 30-minute duration. Figure 6-8 shows the three timeframes—application of power, compressor start, and nominal running—where RMS leakage currents are shown in the following figures and tables. The 240-volt supply voltage, both phase currents that supply the outdoor unit, and current flow through the grounding conductor were measured with high-frequency and low-frequency response CTs. The difference in the line current was measured though a AEMC 2620 leakage current probe (Z-CT), while the compressor leakage current, condenser leakage current, and the start capacitor leakage current were monitored with AMEC K110 low-frequency current probes. GFCI's react on differential current; therefore, the Z-CT was used as the standard to compare against the other current measurement devices. Note: in all the charts, a value appears at left under the name of the leakage current being measured. This is an artifact showing the value registered at the location of the red cursor which may or may not be visible in the chart. This value has no relevance to the measurements of concern.

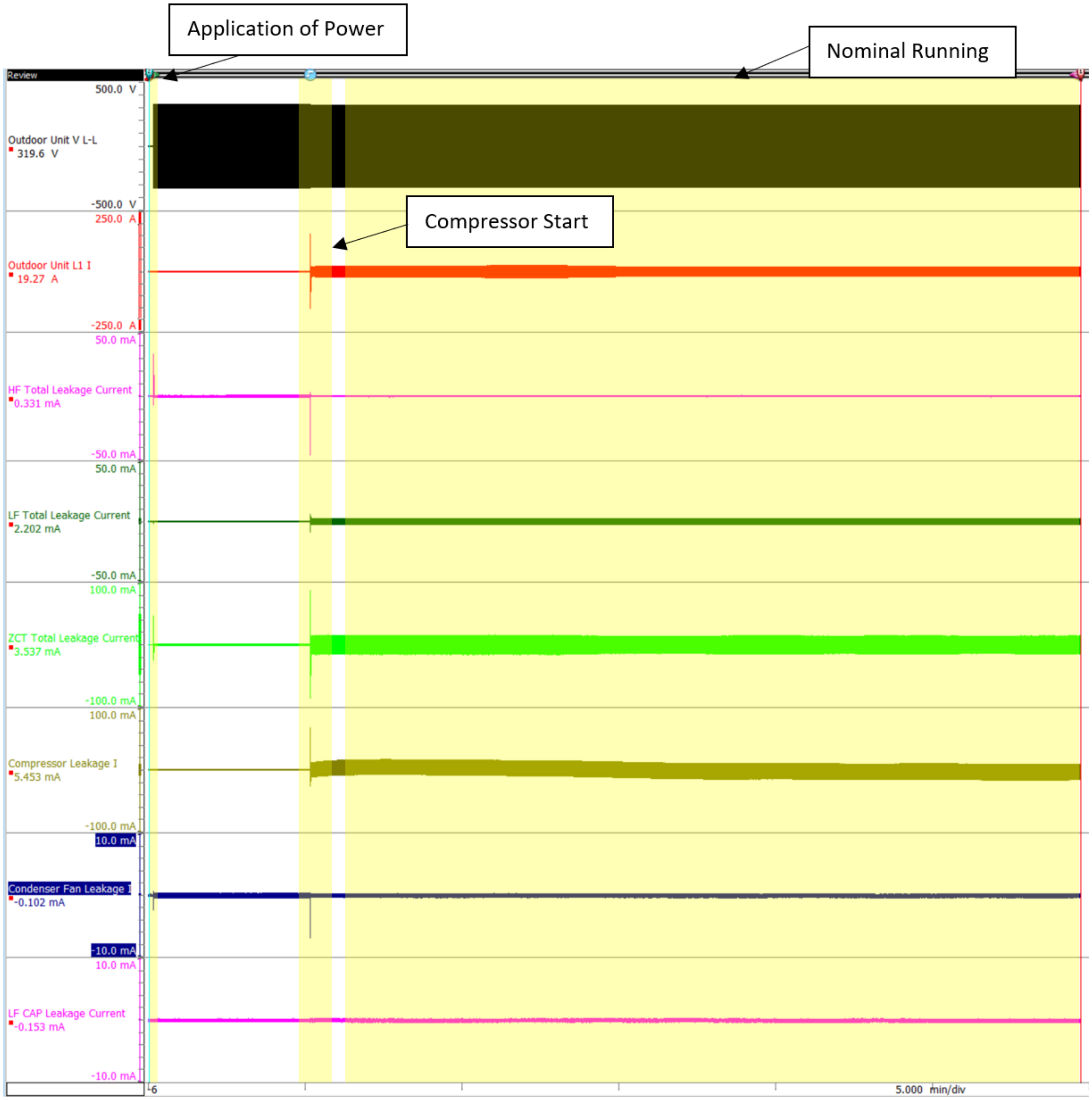


Figure 6-8
Test 0 Condition 2 Monitoring File 82

Figure 6-9 shows a ‘zoomed-in’ view of the time when the knife switch was closed, and power was applied as well as the RMS leakage currents that resulted. The current probes measured a very short burst of current when the switch was closed. The RMS values during this short time period were below the time current requirements of UL 943 and a detailed chart may be seen in Figure 6-9 below.

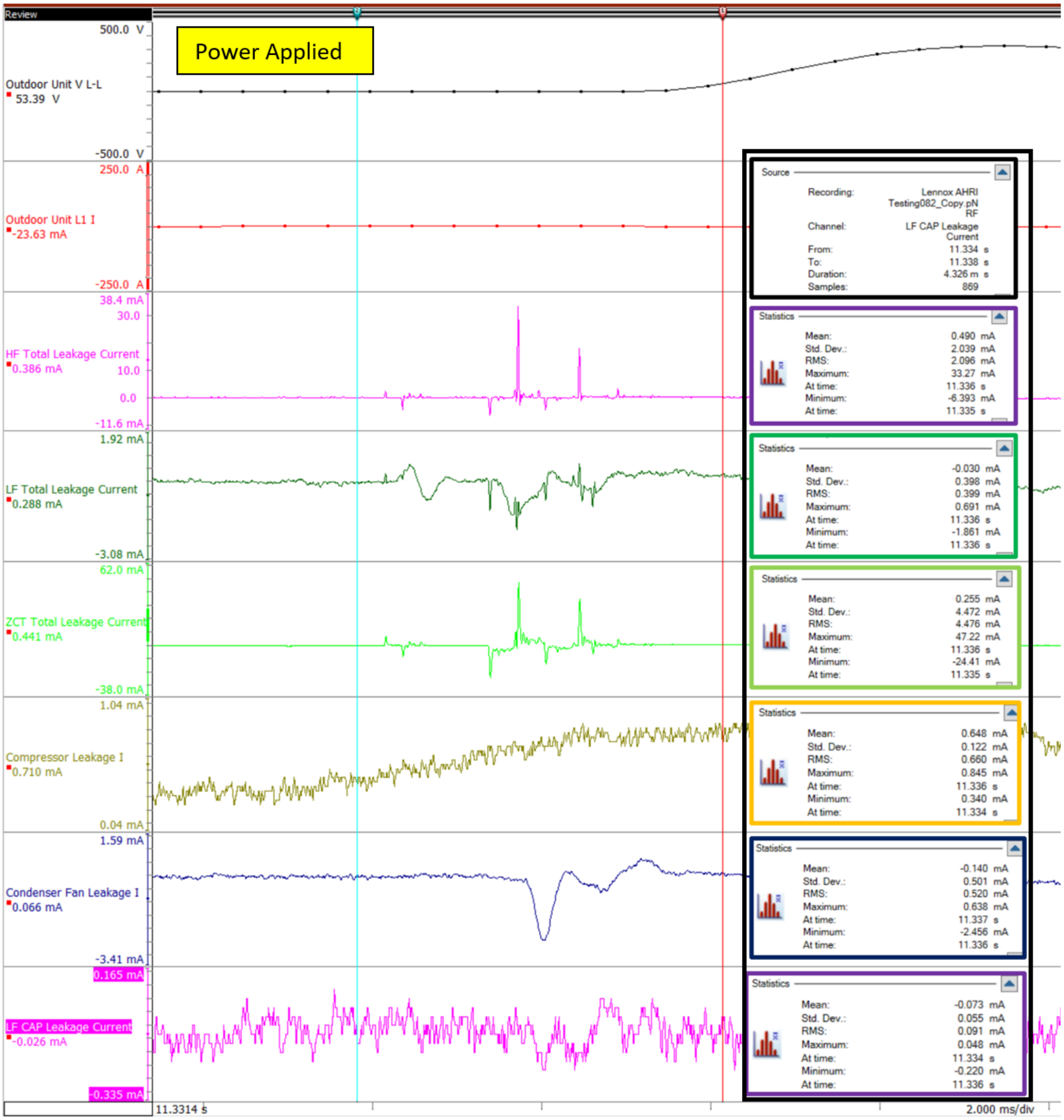


Figure 6-9
Power Applied Leakage Current Measurements

Figure 6-10 is a ‘zoomed-in’ view of when the compressor started as well as the RMS leakage currents that resulted. This was the time during the test when the leakage current was the highest; however, the current measured by the Z-CT was within the operational limits of the time current curve shown in UL 943. These values may be seen in **Error! Reference source not found.** below.

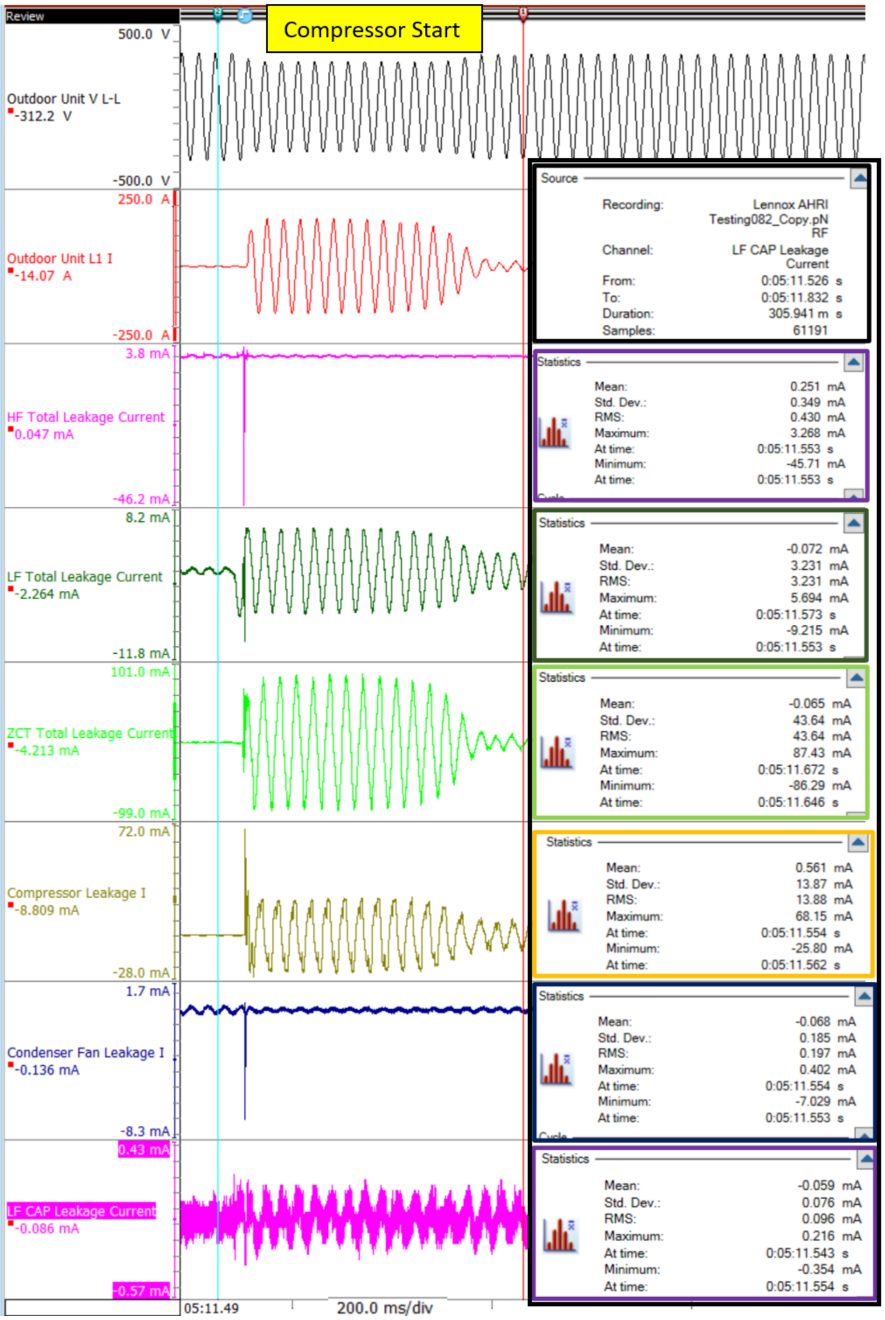


Figure 6-10
Compressor Start Leakage Current Measurements

Figure 6-11 is a view of the remaining time power was applied to the system (approximately 24.5 minutes) and the RMS leakage currents that resulted. The oscillography shows the currents during normal operation as the outdoor unit operates. The Z-CT measured 7 milliamps during this test period which is above the operational RMS current limits as per UL 943. An explanation why the current was higher than the allowable limits but did not trip the GFCI is provided after Figure 6-11.

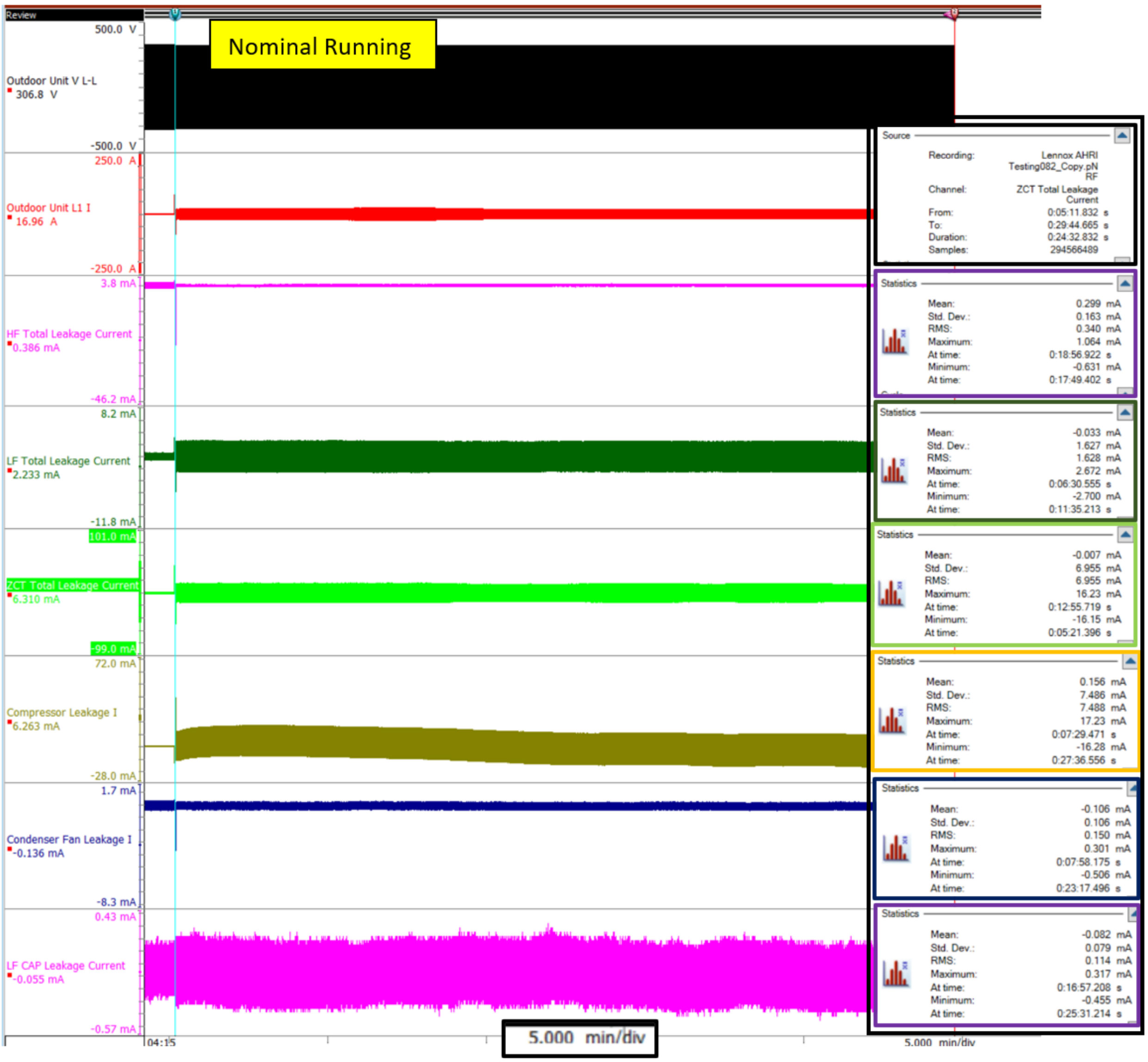


Figure 6-11
Nominal Running Leakage Current Measurements

The reason for the higher than allowable current measurement is not known; however, the Z-CT measures the current at the input terminals to the outdoor unit, and the GFCI circuit breaker was installed in the "service panel." A length of conductors—2 conductors @ 40ft each—lay between the panel and the outdoor unit during the test. The long length of wire may have dampened the leakage current at the panel enough that the leakage current may have been within acceptable limits at the GFCI. Figure 6-12 shows an FFT of the time during the compressor running cycle when the RMS current shown in **Error! Reference source not found.** was above the limits of the GFCI circuit breaker. Another reason the GFCI may not have tripped is the circuit breaker may only react to fundamental 60-Hz current and not the sum of all frequencies. The FFT in Figure 6-12 shows the majority of the peak current measured by the Z-CT was 60-Hz fundamental current; however, the Z-CT also measured current out to at least 2 kHz. The RMS current was only 1 mA above the limit; therefore, if the GFCI reacts only on fundamental current, then there may have been enough higher-order frequency current mixed in the total RMS current measurement to allow the GFCI to continue to operate. The Blue cursor in Figure 6-12 shows the *peak current* was 9.147 mA. The 60-Hz current may have been very close to 6 mA.

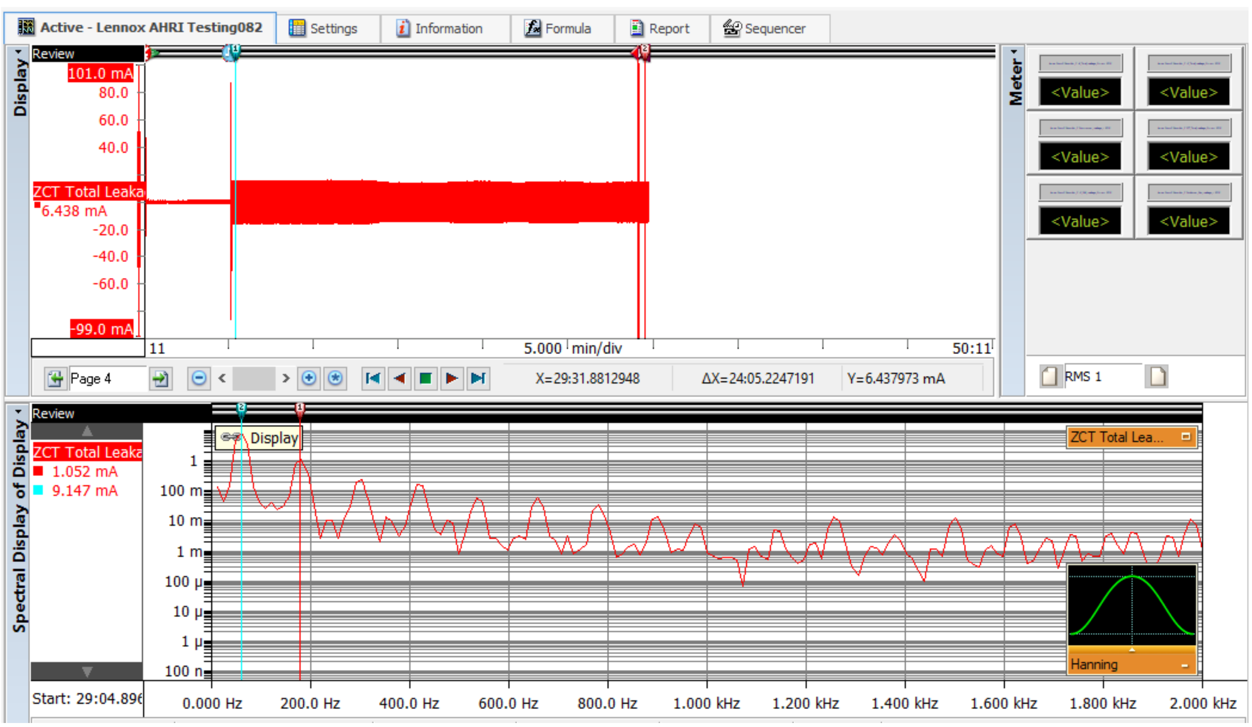


Figure 6-12
FFT during Compressor Running Measurement Period

Error! Reference source not found. shows the RMS current values during the time that power w as applied to the circuit, the compressor started, and the remaining time the compressor was running. The data shows the circuit breaker did not trip at any time during the test and the Z-CT, the standard of measure, did not exceed the maximum current limits during the Application of Power or the Compressor Start measurement intervals as per UL 943. However, the Z-CT measured 7 mA, 1 mA above the must trip level, during the Compressor running time interval. The Compressor leakage current level was below the levels measured by the Z-CT during the application of power and when the compressor started; however, compressor leakage current measured above the Z-CT during the compressor running time period of the test. The HF and LF CTs connected to the ground conductor measured almost no current during the application of power; however, these always measured lower current levels than the Z-CT during conditions when the compressor started or running. The current levels measured by the HF and LF CTs did not agree during any of the testing which was counter to the results shown during the Thermal Chamber 1 testing.

Table 6-6
Condition 2 Extended Time Off Critical Time Measurements

Note: All measurements are represented as RMS	**Application of Power**		**Compressor Start**		**Compressor Running**		
Measurement Time Base	2 ms/div		200 ms/div		5000 ms/div		
MS Measurement Time	4.3 ms		305 ms		24 min 33 sec		
UL 943 Limit	**903 mA**	**Within UL 943 Current/Time Limits?**	**46 mA**	**Within UL 943 Current/Time Limits?**	**6 mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	4.5 mA	Yes	43.6 mA	Yes	7.0 mA	No	No
Compressor Leakage	0.6 mA	Yes	13.9 mA	Yes	7.5 mA	No	No
Condenser Fan Leakage	0.5 mA	Yes	0.2 mA	Yes	0.3 mA	Yes	No
Capacitor Leakage	0.1 mA	Yes	0.1 mA	Yes	0.1 mA	Yes	No
HF Probe Ground Conductor	2.1 mA	Yes	0.4 mA	Yes	0.3 mA	Yes	No
LF Probe Ground Conductor	0.4 mA	Yes	3.2 mA	Yes	1.6 mA	Yes	No

Thermal Condition 3 Testing

Figure 6-13 shows the oscillography captured by the waveform data logger with the system operating in Chamber Temperature Condition 3. The test was conducted for at least 30 minutes per the test protocol. The test was conducted by applying power via a knife switch and power was supplied for a duration of 30-minutes. The waveforms in Figure 6-13 are segregated into three timeframes—application of power, compressor start, and nominal running—where RMS leakage currents are shown in the following figures and tables. The 240-volt supply voltage, both phase currents, and current flow through the grounding conductor were measured with high-frequency and low-frequency response CTs. The difference in the line current was measured though a AEMC 2620 leakage current probe (Z-CT), while the compressor leakage current, condenser leakage current, and the start capacitor leakage current was monitored with AMEC K110 low-frequency current probes. GFCI's react on differential current; therefore, the Z-CT was used as the standard to compare against the other current measurement devices. Note: in all the charts, a value appears at left under the name of the leakage current being measured. This is an artifact showing the value registered at the location of the red cursor which may or may not be visible in the chart. This value has no relevance to the measurements of concern.

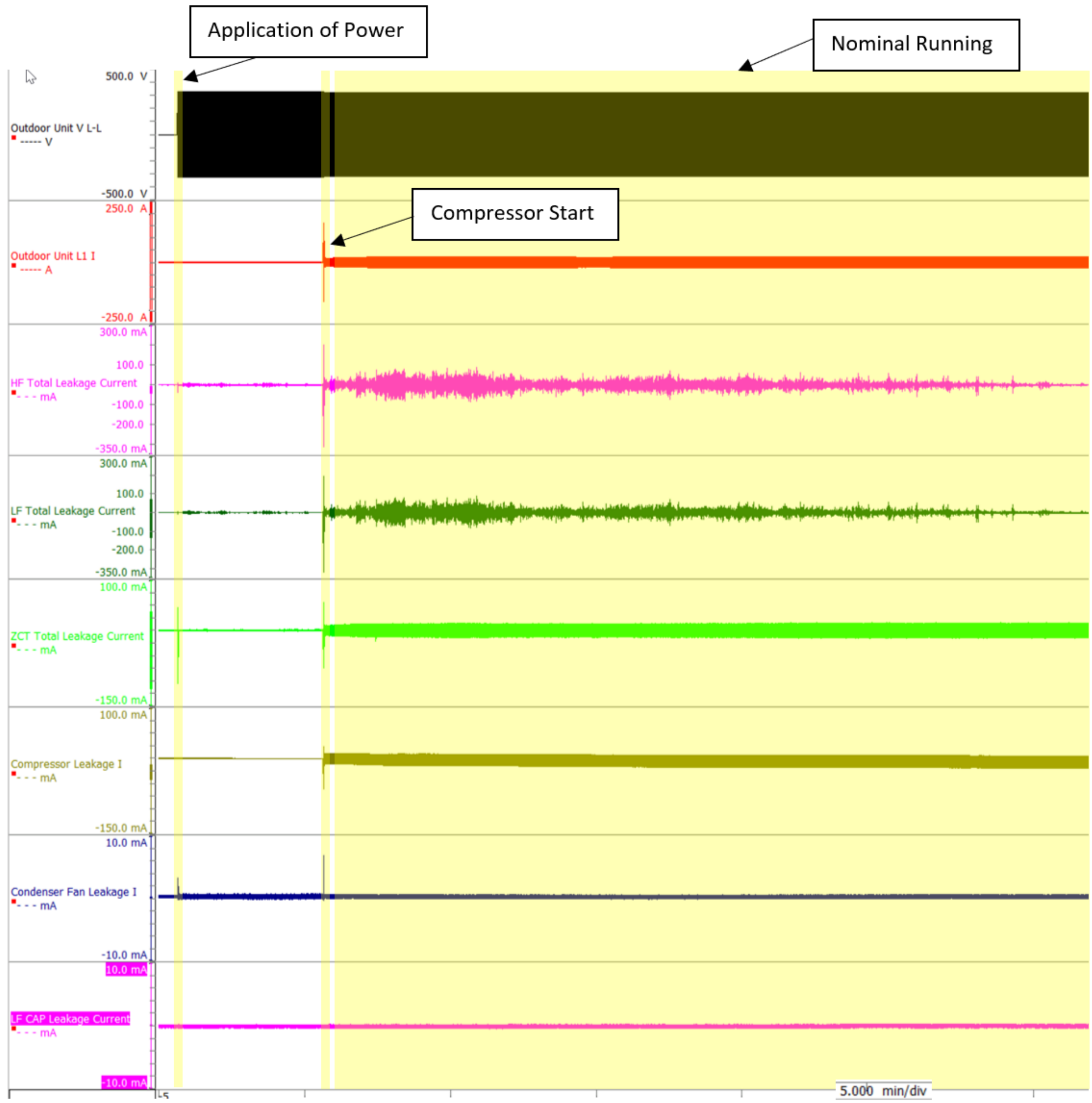


Figure 6-13
Extended Time Off, Startup Chamber Conditions 3, File 107

Figure 6-14 shows a ‘zoomed-in’ view of the time when the knife switch was closed, and power was applied as well as the RMS leakage currents that resulted. The current probes measured a very short burst of current when the switch was closed. The RMS values during this short time period were below the time current requirements of UL 943 and a detailed chart may be seen in **Error! Reference source not found.** below.

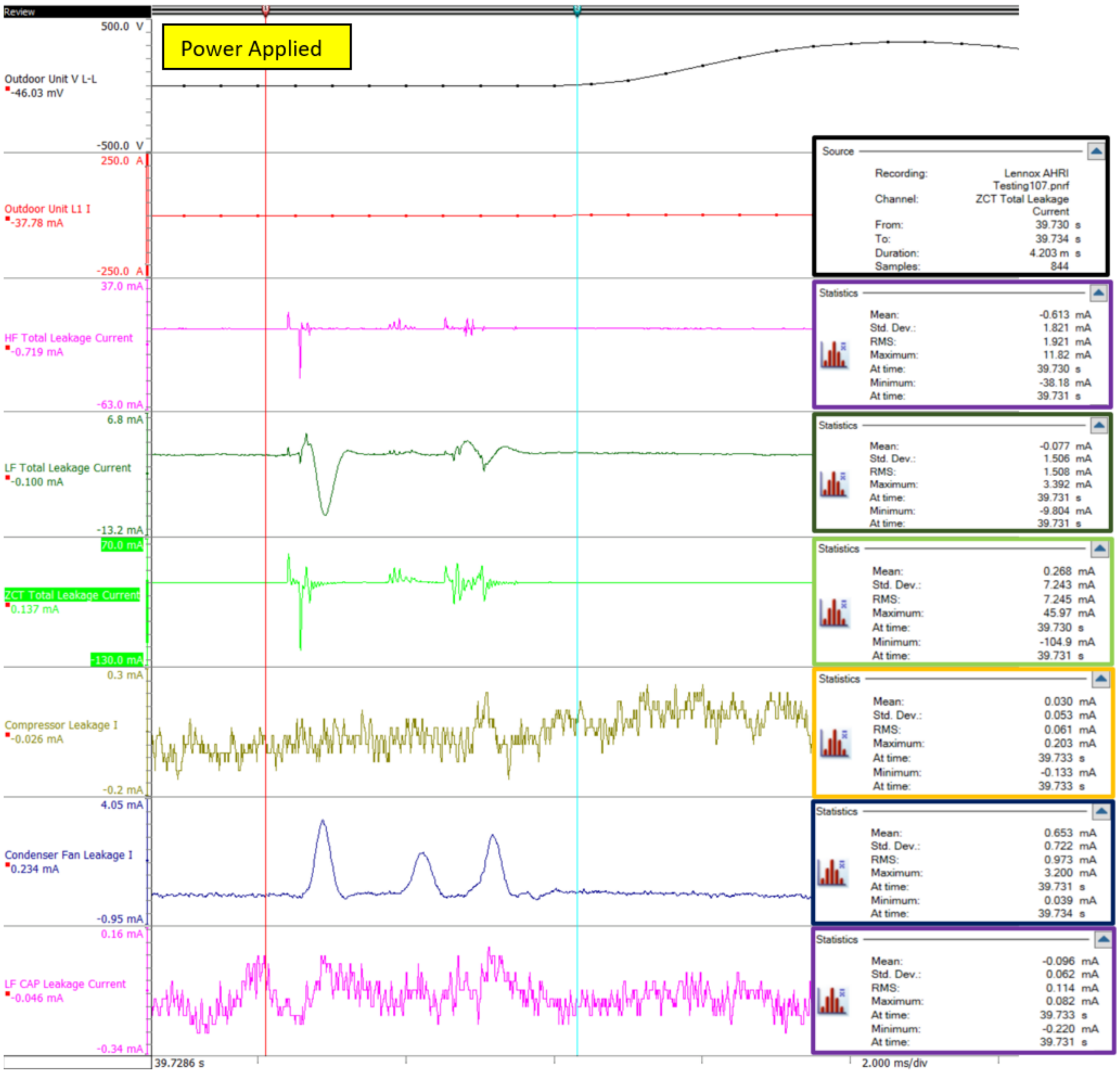


Figure 6-14
Power Applied Leakage Current Measurements

Figure 6-15 is a ‘zoomed-in’ view of when the compressor started as well as the RMS leakage currents that resulted. This was the time during the test when the leakage current was the highest; however, the current measured by the Z-CT was within the operational limits of the time current curve shown in UL 943. These values may be seen in **Error! Reference source not found.** below.

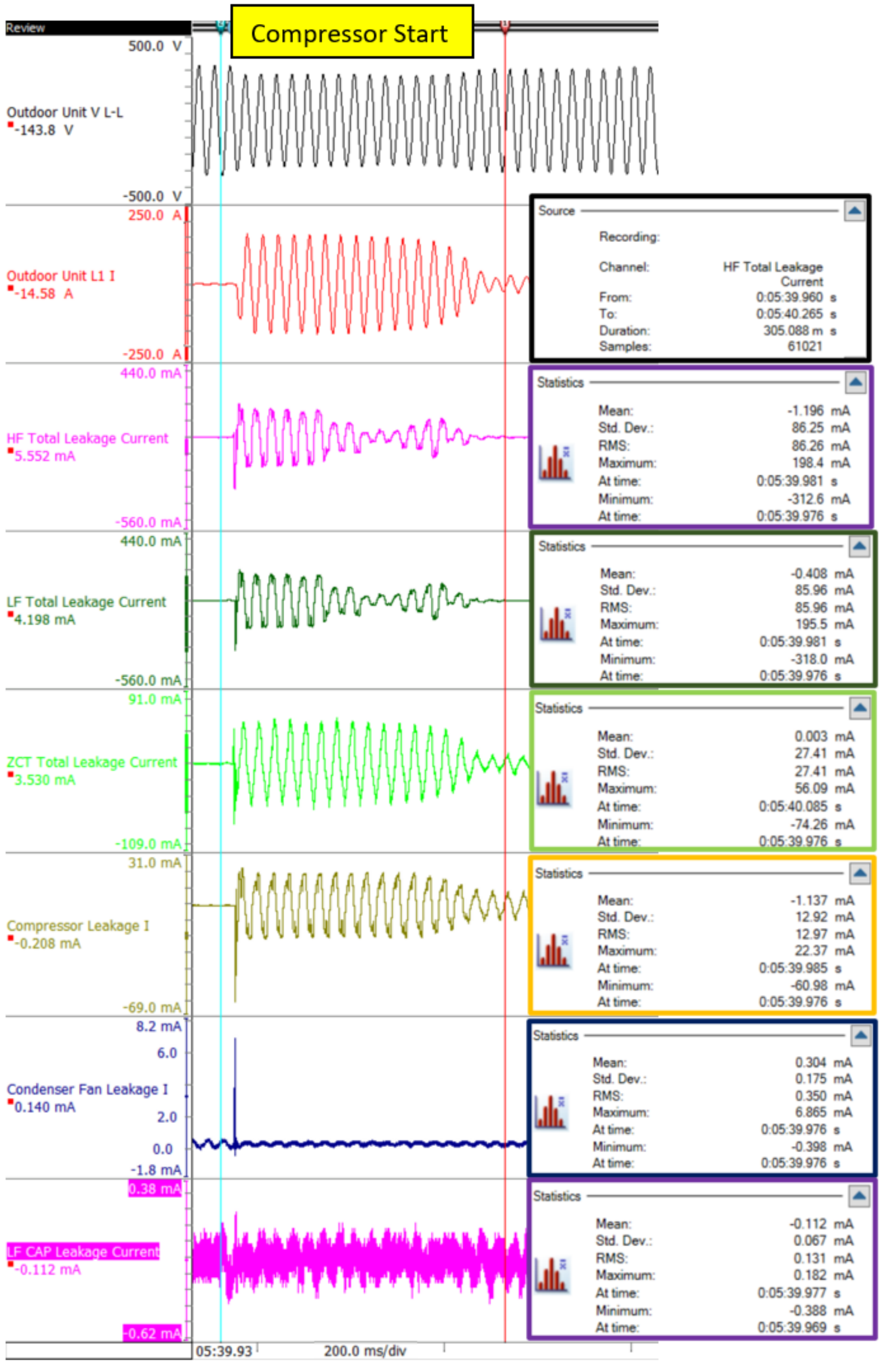


Figure 6-15
Compressor Start Leakage Current Measurements

Figure 6-16 shows the remaining time power was applied to the system (approximately 26-minute, 16 seconds) and the RMS leakage currents that resulted. The oscillography shows the currents during normal operation as the outdoor unit operates. The Z-CT measured values within the operational RMS current limits as per UL 943. The compressor leakage current probe measured RMS current greater than the Z-CT. The reason for the higher measurement is not known; however, another load may be in the system whose leakage current may be phase shifted. Thus, a summation of the currents may have created the lower value reported by the Z-CT.

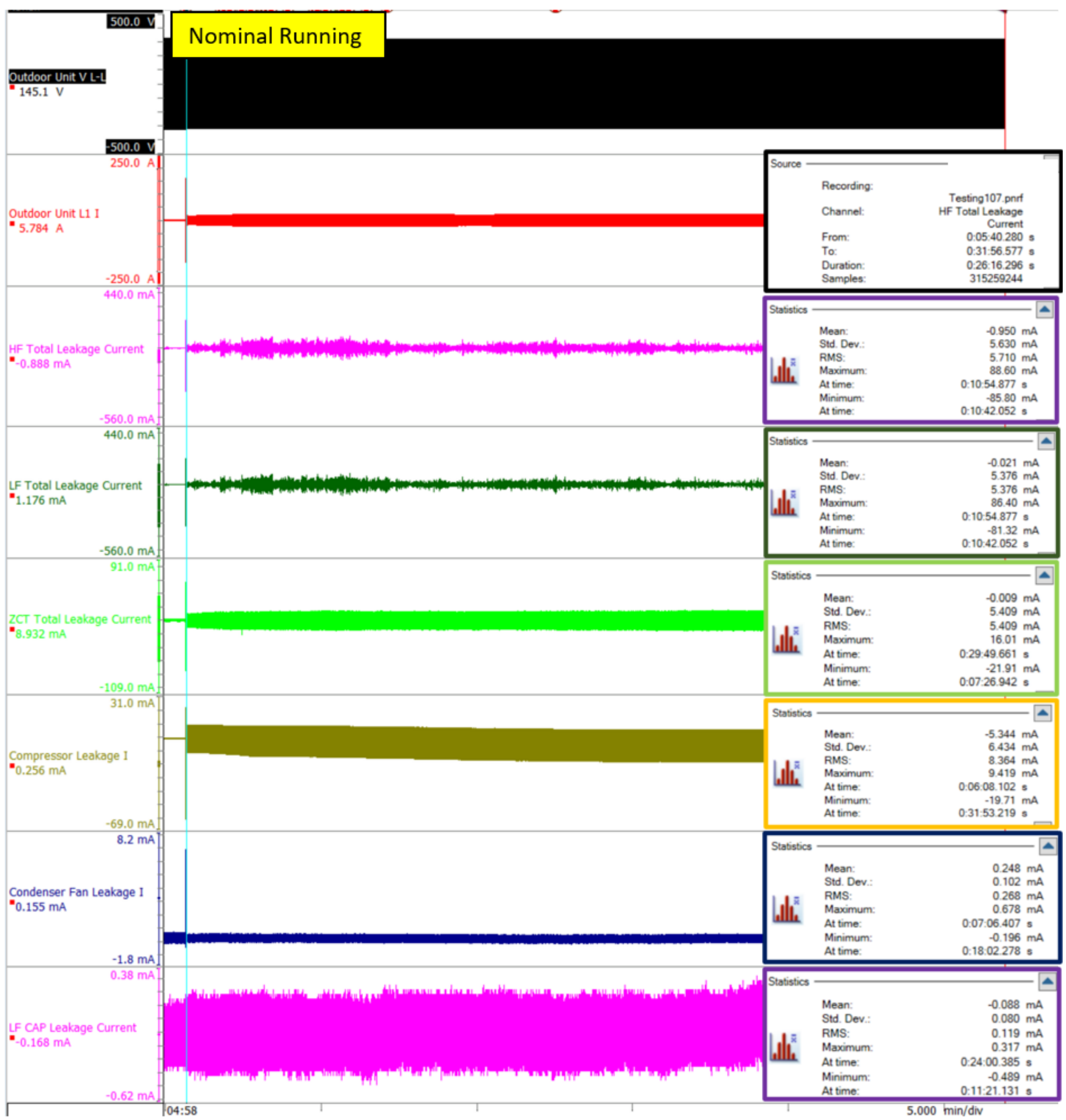


Figure 6-16
Nominal Running Leakage Current Measurements

Error! Reference source not found. shows the RMS current values during the time that power w as applied to the circuit, the compressor started, and the remaining time the compressor was running. The data shows the circuit breaker did not trip at any time during the test and the Z-CT, the standard of measure, did not exceed the maximum current limits during the Application of Power or the Compressor Start measurement intervals as per UL 943. Compressor leakage current level was below the levels measured by the Z-CT during the application of power and when the compressor started; however, compressor leakage current measured above the Z-CT during the compressor running time period of the test. The HF and LF CTs that were connected to the ground conductor measured current considerably lower than the current measured by the Z-CT during the application of power phase of the test yet much higher than the Z-CT during the time period when the compressor started. These current probes measured approximately the same RMS current during the compressor running phase of this test. The difference in the measurements may result from leakage current that may be flowing between the indoor and outdoor units. Future testing may consider the addition of a current probe around the refrigerant lines to investigate another potential leakage current path between the two units.

Table 6-7
Condition 3 Extended Time Off Critical Time Measurements

Note: All measurements are represented as RMS	**Application of Power**		**Compressor Start**		**Compressor Running**		
Measurement Time Base	2 ms/div		200 ms/div		5000 ms/div		
RMS Measurement Time	4.2 ms		305 ms		24 min 16 sec		
UL 943 Limit	**918 mA**	**Within UL 943 Current/Time Limits?**	**46 mA**	**Within UL 943 Current/Time Limits?**	**6 mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	7.2 mA	Yes	27.4 mA	Yes	5.4 mA	Yes	No
Compressor Leakage	0.1 mA	Yes	13.0 mA	Yes	8.4 mA	No	No
Condenser Fan Leakage	1.0 mA	Yes	0.4 mA	Yes	0.3 mA	Yes	No
Capacitor Leakage	0.1 mA	Yes	0.1 mA	Yes	0.1 mA	Yes	No
HF Probe Ground Conductor	1.9 mA	Yes	86.3 mA	No	5.7 mA	Yes	No
LF Probe Ground Conductor	1.5 mA	Yes	86.0 mA	No	5.4 mA	Yes	No

Test 0 Conclusion

Power was applied to the HVAC unit after allowing the unit to dwell without power for at least 12 hours. The first test conducted each day was to energize the HVAC system to measure the leakage current. The testing was conducted according to the test protocol while the thermal chambers were set to each of the temperature modes shown in **Error! Reference source not f ound.**. The GFCI circuit breaker did not trip for any of the tests even though the measured currents exceeded the expected currents for a GFCI trip. Maximum leakage current was observed when the test chambers were set for Test Condition 2, Full Nominal Cooling Mode as seen in **Error! Reference source not found.**.

Test 1 Power Applied

Unit 1 has a single-stage compressor; therefore, the control signal to energize the compressor is “on” or “off” unlike a VFD-controlled compressor that is controlled via an adjustable speed drive. Inrush current occurs when the thermostat commands the outdoor unit to turn on the compressor when heating or cooling is required. Waveforms in this section show where maximum leakage current may occur. The purpose of the power applied test is to observe how the inrush current of the outdoor unit may vary depending the point at which the voltage is applied on the 60-hertz sine wave. The instantaneous voltage is determined by the point-on-wave (POW) of the sinusoidal AC voltage. This test was conducted once at each thermal condition shown in **Error! Reference source not found.** Voltage was applied at 0-degrees POW, 45-degrees POW, and 90-degrees POW at the primary of the 240/240-120-volt transformer with a 7-minute power-off time between events to allow any capacitance to discharge. The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** shows the maximum leakage current recorded during each test, the relative humidity of the temperature chamber during the test, and some general observation notes. **Error! Reference source not found.** also shows that the leakage current measurement at application of voltage was less than 1 milliamp for all tests. The GFCI did not trip for any of the tests.

Table 6-8
Power Applied Test Tabular Data

<table>
<tr><th>Chamber Temperature Condition</th><th>Highest Measured Leakage Current at Application of Voltage (mA) / time</th><th>Notes</th><th>Outdoor Chamber Humidity</th></tr>
<tr><td>1</td><td>0-degrees POW 0.8 mA RMS
45-degrees POW 0.6 mA RMS
90-degrees POW 0.5 mA RMS</td><td rowspan="3">Maximum leakage current was observed when the outdoor unit turned on 5- minutes after voltage was applied. Leakage current less than 1 mA RMS was observed for each test. The GFCI did not trip for any of the tests. Highest Leakage current observed during temperature tests 2 and 3 when compressor started</td><td>22%</td></tr>
<tr><td>2</td><td>0-degrees POW 0.5 mA RMS
45-degrees POW 0.5 mA RMS
90-degrees POW 0.4 mA RMS</td><td>19%</td></tr>
<tr><td>3</td><td>0-degrees POW 0.3 mA RMS
45-degrees POW 0.5 mA RMS
90-degrees POW 0.3 mA RMS</td><td>28%</td></tr>
</table>

Thermal Condition 1 Testing

0-Degree POW

Figure 6-17 through Figure 6-19 show the oscillography of each test while showing the leakage current during the 0-degree tests. Each test waveform shows maximum leakage current occurring at the time when the compressor starts. The waveforms during the POW testing while operating in thermal chamber conditions 2 and 3 as shown in **Error! Reference source not found.** exhibited the same response as test 1; therefore, the waveform data for these two thermal test conditions are not shown. The RMS current measurements from testing in thermal conditions 2 and 3 may be seen in **Error! Reference source not found.** and **Error! Reference source not found.** respectively.

Figure 6-17 shows the entire waveform recording of the 0-degree POW test. The purpose of this figure is to show a "1,000-foot view" of the waveforms during the entire test. The power was off for 7-minutes to allow any capacitors to discharge prior to power being applied at 0-degrees POW. The HVAC system was permitted to operate until the compressor turned on. Once the compressor started the system was allowed to operate for approximately 2 minutes before power is removed.

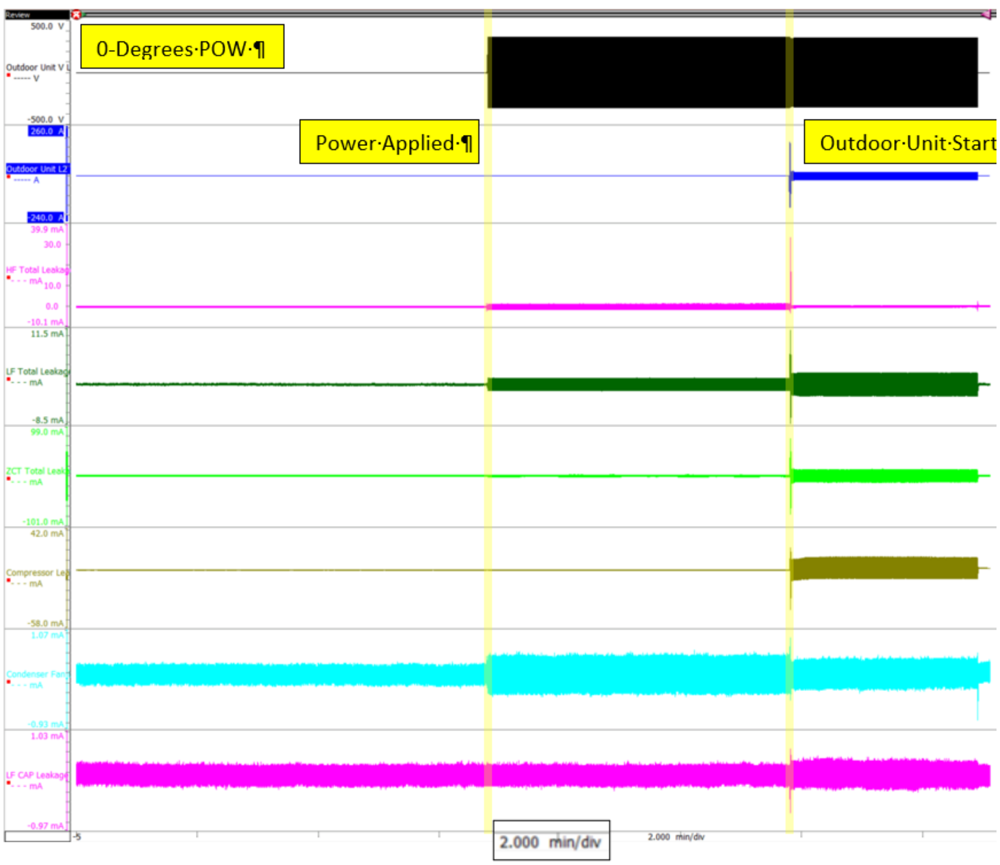


Figure 6-17
Temperature Condition #1, 0 Degree POW Test, File 144

Figure 6-18 shows the waveforms when power was applied to the outdoor unit. The statistical data shows the Z-CT measured 0.8 mA RMS, and the statistical data for the remaining channels are shown in the figure as well. Tabular results for all the POW testing while the thermal chambers were operating in thermal configuration 1 may be seen in **Error! Reference source not found.**.

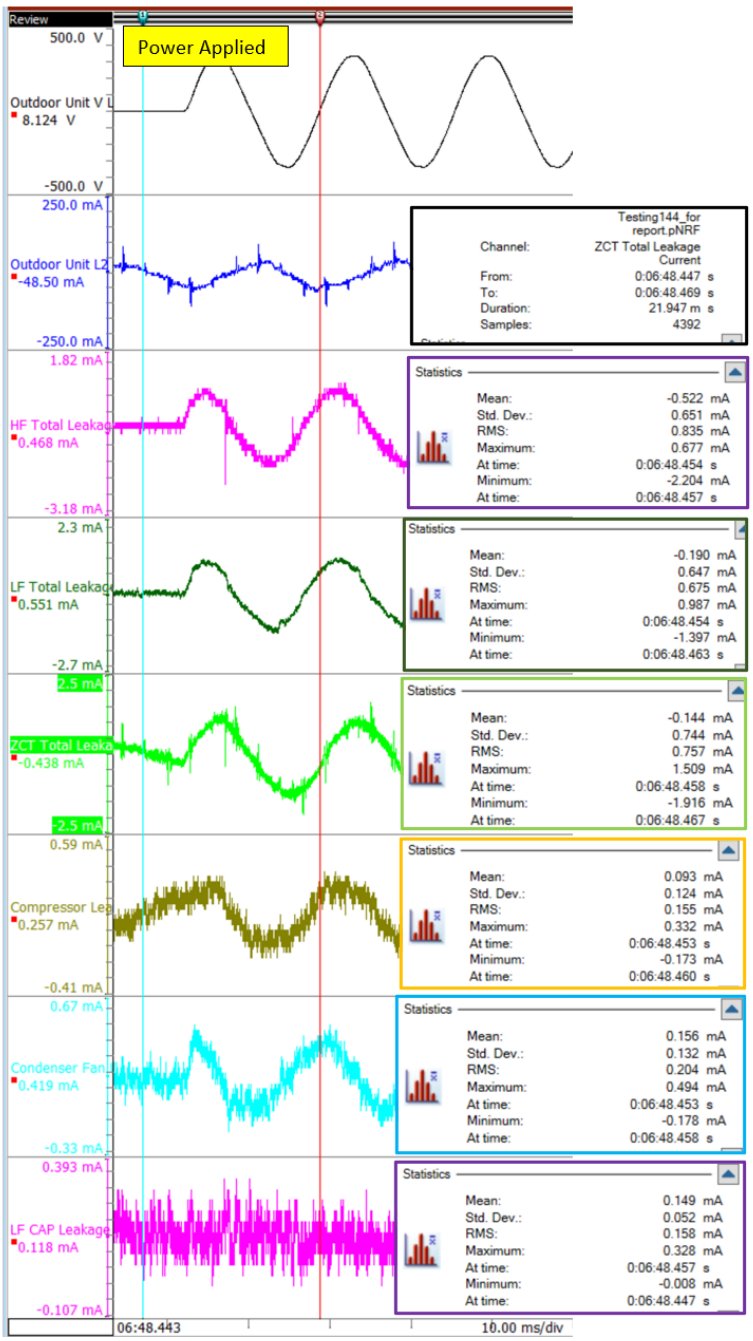


Figure 6-18
Power Applied Leakage Current at 0 deg POW.

Figure 6-19 shows the RMS leakage current measured by at the Z-CT when the compressor started was 32 mA RMS for 327 milliseconds. Therefore, leakage current was higher during the compressor starting cycle than when power was applied. Measurement data throughout this report shows the leakage current during compressor start was very similar in magnitude and duration.

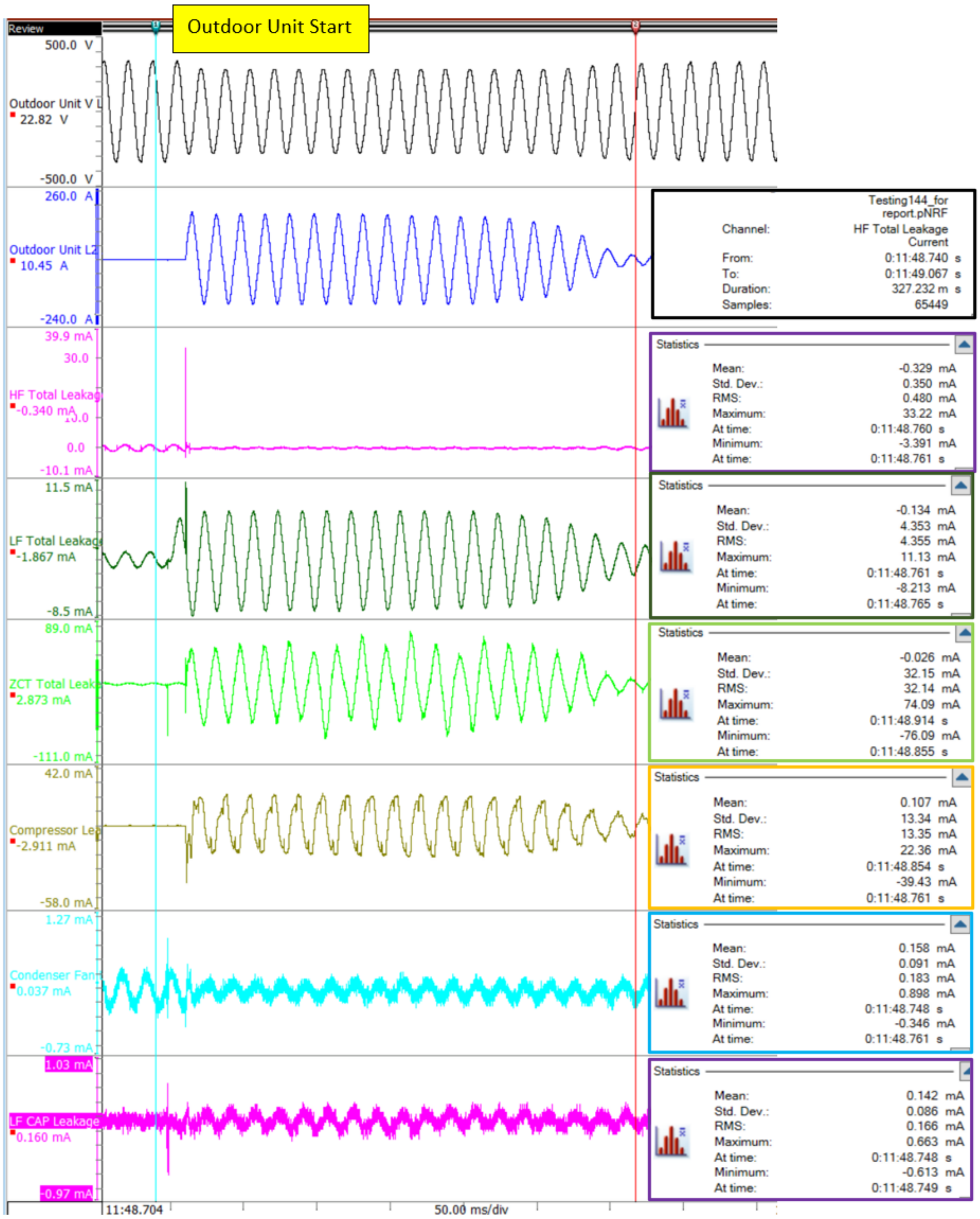


Figure 6-19
Outdoor Unit Start Leakage Current Measurement

45-Degree POW

Figure 6-20 shows the results of the 45-degree POW test. The purpose of this figure is to show a "1,000-foot view" of the waveforms obtained during the entire test. The test was conducted in the same manner as the 0-degree POW test. The current measured by the Z-CT was used to determine the leakage current. The Z-CT waveform is represented by the light green trace shown in Figure 6-20. The waveform shows the leakage current was highest when the compressor started (outdoor unit start).

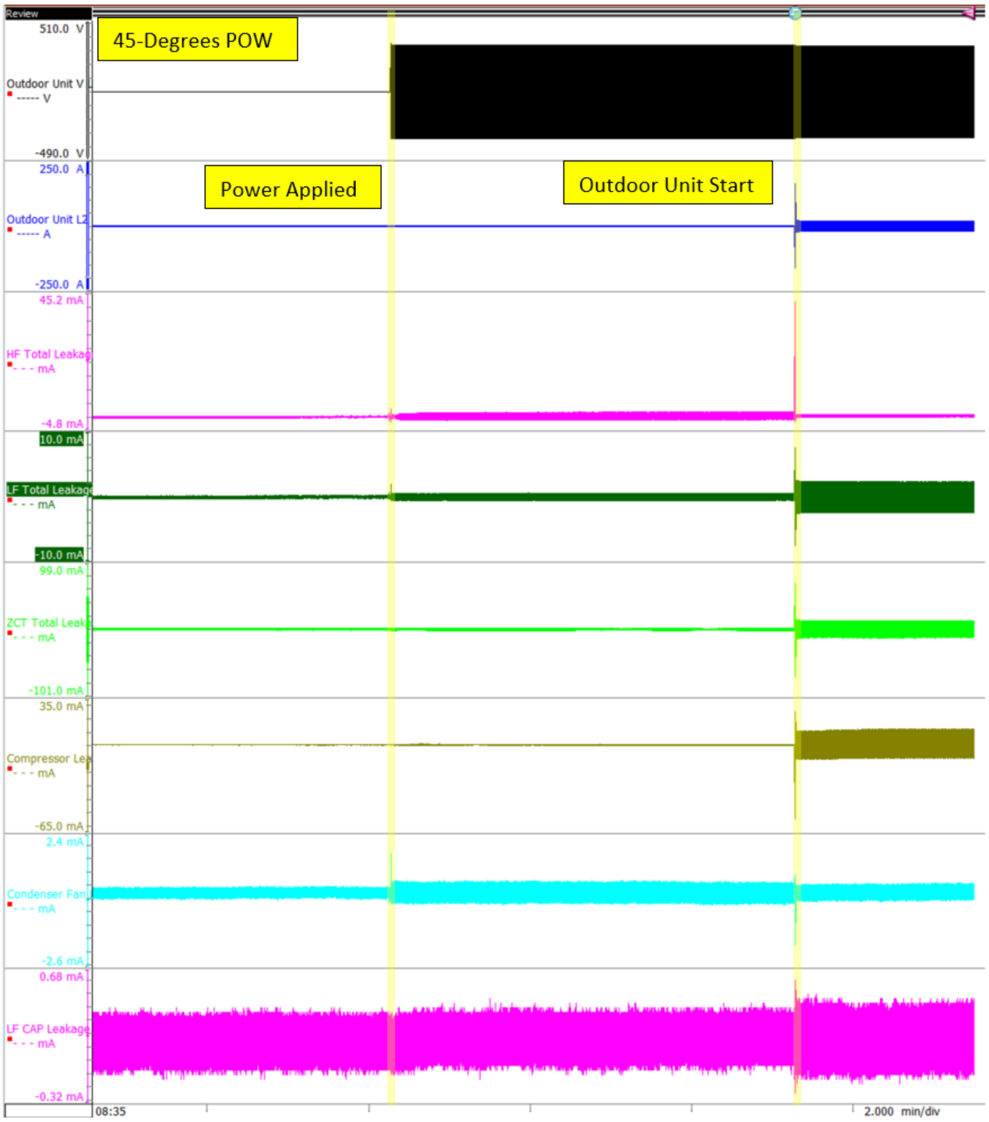


Figure 6-20
Temperature Condition #1, 45 Degrees POW Test, File 145

Figure 6-21 shows the leakage current measured by the Z-CT when power was initially applied at 45-degrees POW. The data shows that, when power was applied, the Z-CT measured 0.6 mA RMS. The statistics are also shown for the other leakage current measurements. Tabular results for all the POW testing while the thermal chambers were operating in thermal configuration 1 may be seen in **Error! Reference source not found.**.

Figure 6-21
Power Applied Leakage Current at 45-deg POW

Figure 6-22 shows that the leakage current, measured at the time the compressor started, was 30 mA RMS for 325 milliseconds. Therefore, leakage current was higher during the compressor starting cycle than when power was applied.

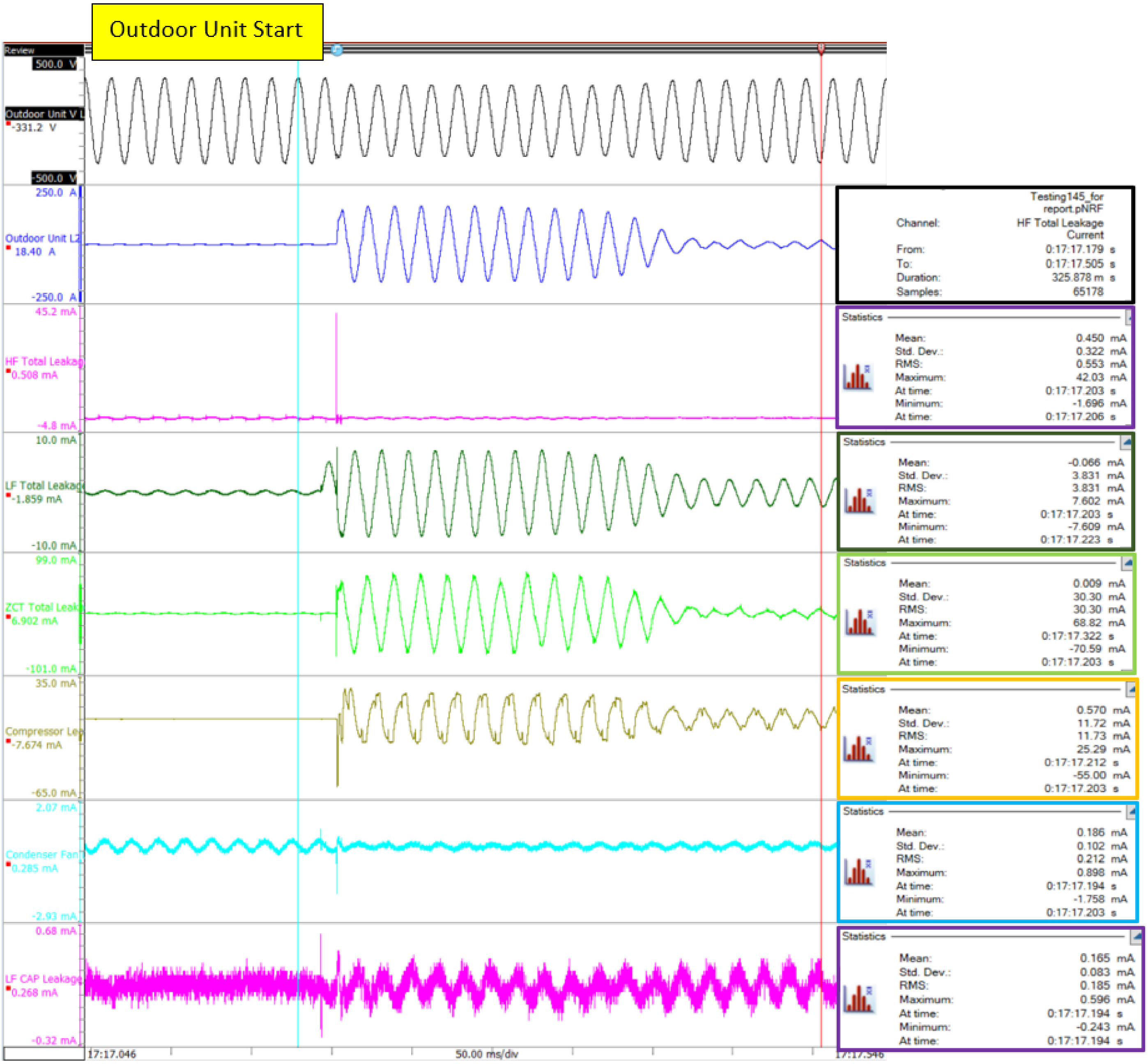


Figure 6-22
Outdoor Unit Start Leakage Current at 45-deg POW

90-Degree POW

Figure 6-23 shows the results of the 90-degree POW test. The purpose of this figure is to show a "1,000-foot view" of the waveforms obtained during the entire test. The test was conducted in the same manner as the 0-degree POW test. The current measured by the Z-CT was used to determine the leakage current. The Z-CT waveform is represented by the light green trace shown in Figure 6-23. The waveform shows the leakage current was higher when the compressor started than when power was initially applied.

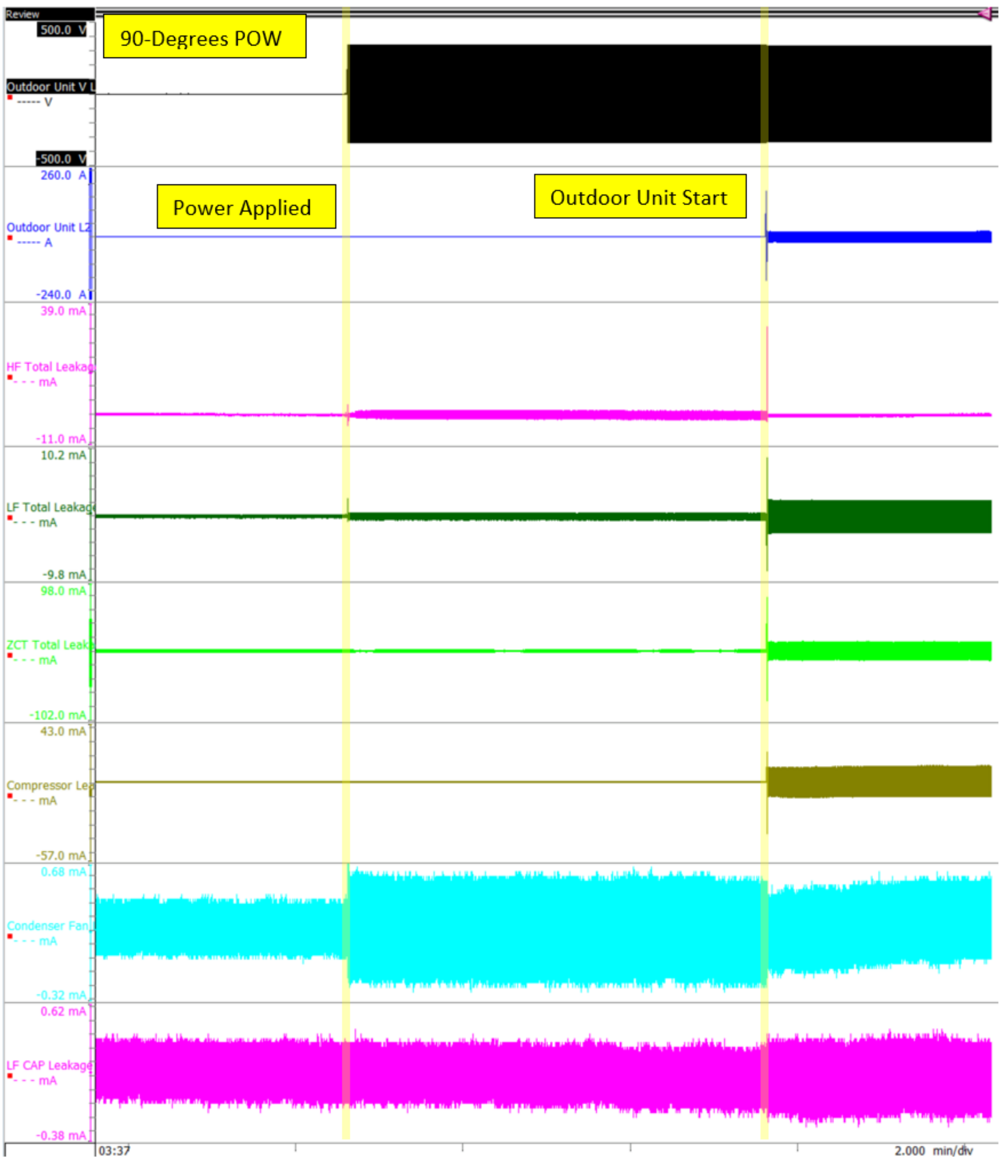


Figure 6-23
Temperature Condition #1, 90 Degrees POW, File 146

Figure 6-24 shows the waveforms when power was applied at 90-degress POW. The statistical data shows that when power was applied, the Z-CT measured 0.5 mA RMS. Tabular results for all the POW testing while the thermal chambers were operating in thermal configuration 1 may be seen in **Error! Reference source not found.**.

Figure 6-24
Power Applied Leakage Current at 90 deg POW.

Figure 6-25 shows the leakage current, measured at the time the compressor started, was 36 mA RMS for 330 milliseconds. Therefore, leakage current was higher during the compressor starting cycle than when power was applied. Measurement data throughout this report shows the leakage current during compressor start was very similar in magnitude and duration.

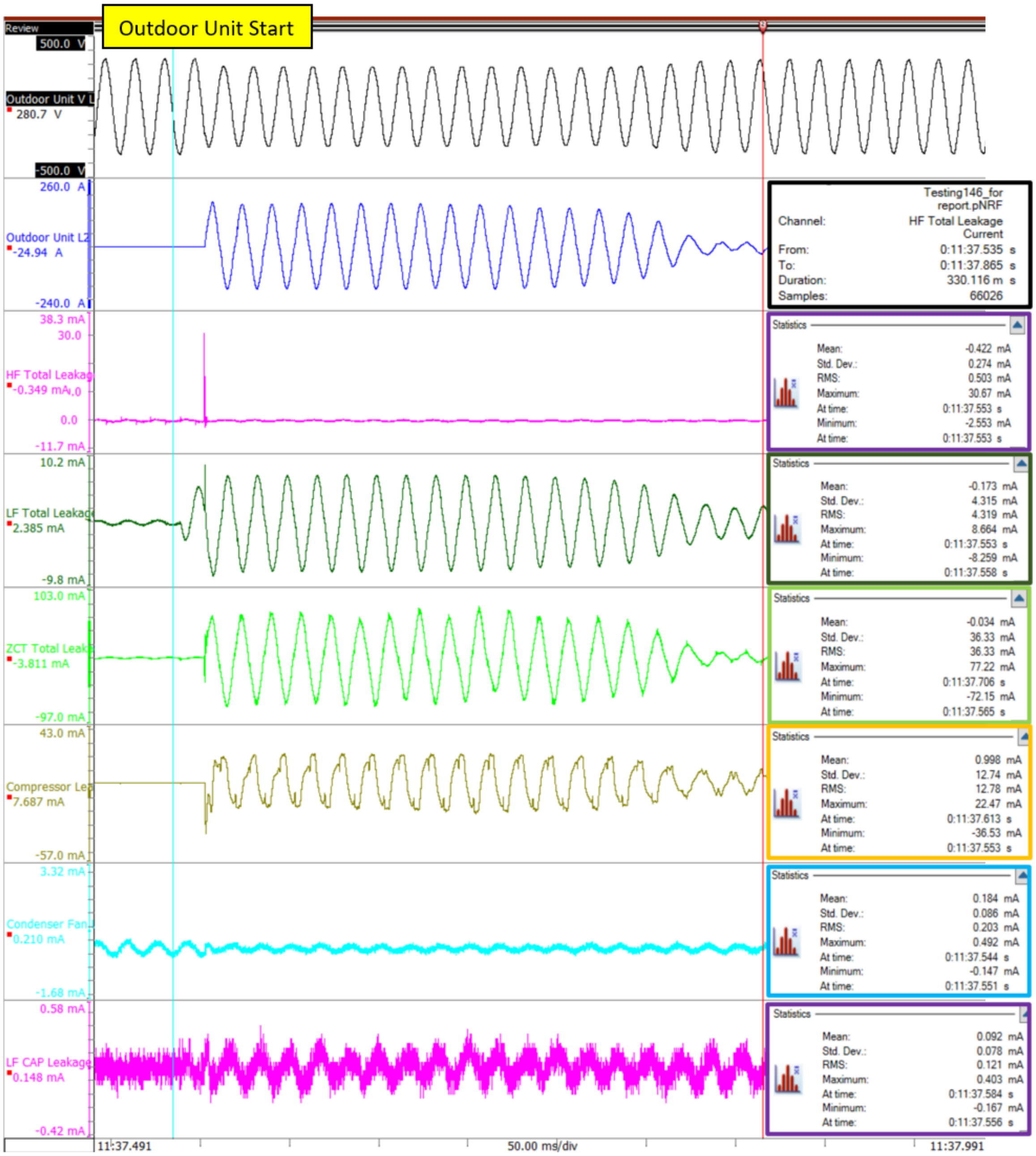


Figure 6-25
Outdoor Unit Start Leakage Current at 90 deg POW.

Error! Reference source not found. shows the RMS current values during the time that power w as applied to the circuit, and when the compressor started when testing was conducted at 0-degrees, 45-degrees, and 90-degrees POW. The data shows the circuit breaker did not trip at any time during the test and the Z-CT, and the measurements did not exceed the maximum current limits as per UL 943.

Table 6-9
Thermal Condition 1 Power Applied Critical Time Measurements

Note: All measurements are represented as RMS	**Application of Power**				**Compressor Start**				
Measurement Time Base	**10 ms/div**				**50 ms/div**				
Point-on Wave	**0-Deg**	**45-Deg**	**90-Deg**		**0-Deg**	**45-Deg**	**90-Deg**		
RMS Measurement Time	22 ms	21 ms	23 ms		327 ms	326 ms	330 ms		
UL 943 Limit	**288 ms**	**298 ms**	**279 ms**	**Within UL 943 Current/Time Limits?**	**44 ms**	**44 ms**	**43 ms**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	0.8 mA	0.6 mA	0.5 mA	Yes	32 mA	30 mA	36 mA	Yes	No
Compressor Leakage	0.2 mA	0.7 mA	0.8 mA	Yes	13 mA	12 mA	13 mA	Yes	No
Condenser Fan Leakage	0.2 mA	0.3 mA	0.3 mA	Yes	0.2 mA	0.2 mA	0.2 mA	Yes	No
Capacitor Leakage	0.2 mA	0.1 mA	0.1 mA	Yes	0.2 mA	0.2 mA	0.1 mA	Yes	No
HF Probe Ground Conductor	0.8 mA	0.4 mA	0.4 mA	Yes	0.5 mA	0.6 mA	0.5 mA	Yes	No
LF Probe Ground Conductor	0.7 mA	0.3 mA	0.4 mA	Yes	4.4 mA	3.8 mA	4.3 mA	Yes	No

Thermal Condition 2 and 3 Tabular Results

Test 1 was conducted again with the thermal conditions set as per **Error! Reference source not found.**. Voltage was applied to the HVAC system at 0-degrees, 45-degrees, and 90-degrees point-on-wave. The response was the same as when the test was conducted with HVAC system in thermal condition 1 shown in **Error! Reference source not found.** Temperature Condition. The waveforms from these tests were provided to the AHRI team and may be seen in the files documented in **Error! Reference source not found.**.

Table 6-10
Test 1 Condition 2&3 Test Files

Chamber Condition	Point-on-Wave (Degrees)	File Number
2	0	147
	45	148
	90	149
3	0	150
	45	151
	90	152

The tabular results for all three tests may be seen in **Error! Reference source not found.**,**Error! Reference source not found.** and **Error! Reference source not found.**. These tables show the RMS leakage current at all locations that were monitored during the test. GFCI's react on differential current; therefore, the Z-CT was used as the standard to compare against the other current measurement devices. The Z-CT was also used as the measurement to compare against all three thermal conditions. These tables show the leakage current did not rise above the limits of UL 943 when power was applied. Each table shows the leakage current was always higher when the outdoor unit started (when the compressor energized) than when power was applied. Although leakage current was higher, the Z-CT current measurements in **Error! Reference source not found.** and **Error! Reference source not found.** show the current levels remained within the limits of UL 943 when the testing was conducted during thermal conditions 1 and 2. However, **Error! Reference source not found.** shows the Z-CT current was above the limits of UL 943 when the outdoor unit was subjected to thermal condition 3. The HF and LF probe measured currents greater than the limits of UL 423 during the thermal condition 2 testing. The CTs also measured currents much higher than the Z-CT. The reason for this phenomenon may be the result of faster frequency response, noise, or unexplained ground current flowing through the ground conductor that is not from the outdoor unit (possibly the indoor unit).

Table 6-11
Thermal Condition 2 Power Applied Critical Time Measurements

Note: All measurements are represented as RMS	**Application of Power**				**Compressor Start**				
Measurement Time Base	**10 ms/div**				**50 ms/div**				
Point-on Wave	**0-Deg**	**45-Deg**	**90-Deg**		**0-Deg**	**45-Deg**	**90-Deg**		
RMS Measurement Time	23 ms	23 ms	23 ms		332 ms	333 ms	333 ms		
UL 943 Limit	**280 mA**	**280 mA**	**280 mA**	**Within UL 943 Current/Time Limits?**	**43 mA**	**43 mA**	**43 mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	0.5 mA	0.5 mA	0.4 mA	Yes	34 mA	36 mA	36 mA	Yes	No
Compressor Leakage	0.2 mA	1.4 mA	1.2 mA	Yes	12 mA	12 mA	11 mA	Yes	No
Condenser Fan Leakage	0.2 mA	0.2 mA	0.2 mA	Yes	0.1 mA	0.1 mA	0.1 mA	Yes	No
Capacitor Leakage	0.4 mA	0.3 mA	0.3 mA	Yes	0.3 mA	0.3 mA	0.4 mA	Yes	No
HF Probe Ground Conductor	1.2 mA	1.3 mA	1.3 mA	Yes	1.3 mA	54 mA	40 mA	No	No
LF Probe Ground Conductor	0.3 mA	1.4 mA	0.3 mA	Yes	4.2 mA	47 mA	36 mA	No	No

Table 6-12
Thermal Condition 3 Power Applied Critical Time Measurements

Note: All measurements are represented as RMS	**Application of Power**				**Compressor Start**				
Measurement Time Base	**10 ms/div**				**50 ms/div**				
Point-on Wave	**0-Deg**	**45-Deg**	**90-Deg**		**0-Deg**	**45-Deg**	**90-Deg**		
RMS Measurement Time	23 ms	23 ms	23 ms		332 ms	332 ms	333 ms		
UL 943 Limit	**280 mA**	**280 mA**	**280 mA**	**Within UL 943 Current/Time Limits?**	**43 mA**	**43 ma**	**43 ma**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	0.3 mA	0.5 mA	0.3 mA	Yes	48 mA	46 mA	42 mA	No	No
Compressor Leakage	0.1 mA	0.5 mA	0.9 mA	Yes	12 mA	13 mA	12 mA	Yes	No
Condenser Fan Leakage	0.4 mA	0.4 mA	0.3 mA	Yes	0.3 mA	0.3 mA	0.2 mA	Yes	No
Capacitor Leakage	0.1 mA	0.1 mA	0.1 mA	Yes	0.3 mA	0.1 mA	0.1 mA	Yes	No
HF Probe Ground Conductor	1.4 mA	1.7 mA	0.9 mA	Yes	8.5 mA	1.5 mA	0.6 mA	Yes	No
LF Probe Ground Conductor	0.2 mA	0.4 mA	0.3 mA	Yes	9.4 mA	4.3 mA	4.1 mA	Yes	No

Test 1 Conclusion

The purpose of the Power Applied test was to determine if the amount of leakage current changed based on when power was applied. Power was applied at 0-degrees POW, 45-degrees POW, and 90-degrees POW using the voltage sag generator plus allowing 7 minutes between tests. The voltage sag generator was connected between the power amplifier and the primary of the split-phase transformer. The testing was conducted as per the test protocol with the thermal chambers set to each of the temperature modes shown in Table 6-3. The GFCI circuit breaker did not trip for any of the tests. Maximum leakage current was observed when the compressor in the outdoor unit turned on 5-minutes after the application of voltage. The RMS leakage current upon application of power was typically 1 mA or less; therefore, this test may not provide significant information when testing HVAC systems with single-stage compressors. However, the data seems to indicate the compressor draws more current in the full nominal heating condition.

Test 2 HVAC Running

It is important to understand the power profile of the EUT throughout a cycle from nominal temperature to arrival at a set temperature. The purpose of this test was to determine the maximum leakage current from the time power is applied to the EUT and while the unit operates for one-hour. This test was conducted with the thermal chambers configured to condition 1 shown in **Error! Reference source not found.**. Other conditions were not tested due t o budge and time constraints. The monitoring was conducted while the HBM Gen 3i was configured to collect data at 250 kilo samples per second; therefore, the measurement was collected across three separate files to reduce the size per file. The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** the RMS leakage current r ecorded by the Z-CT during each test, the relative humidity of the temperature chamber during the test, and some general observation notes.

Table 6-13
Tabular Data from HVAC Running Test

Acquisition File (one per 20-minutes for 1-hour)	Z-CT Leakage Current RMS (mA) / time	Notes	Outdoor Chamber Humidity
1	Compressor Start: 46 mA/327 ms Outdoor Unit Running: 6.2 mA/12 min. 33 sec. Outdoor Unit Off: 0.2 mA/3 min. 21 sec.	The GFCI circuit breaker did not trip for any of the tests. Leakage current measured by the Z-CT was slightly higher than the UL 943 limits when the compressor started and the outdoor running time period.	21%
2	Compressor Start: 44 mA/327 ms Outdoor Unit Running: 7.7 mA/14 min. 27 sec.		
3	Compressor Start: 44 mA/324 ms Outdoor Unit Running: 6.2 mA/5 min. 56 sec.		

First 20-Minute Measurement Period

Figure 6-26 shows the voltage, current, and leakage current at strategic locations about the EUT during the first 20 minutes of the 1-hour test run. The leakage current was analyzed at the point where the outdoor unit started (assuming this is where the compressor turned on), the outdoor unit was running, and when the outdoor unit turned off. The figures following Figure 6-26 show a more detailed analysis each measurement period. *Note: in all the charts, a value appears at left under the name of the leakage current being measured. This is an artifact showing the value registered at the location of the red cursor which may or may not be visible in the chart. This value has no relevance to the measurements of concern.*

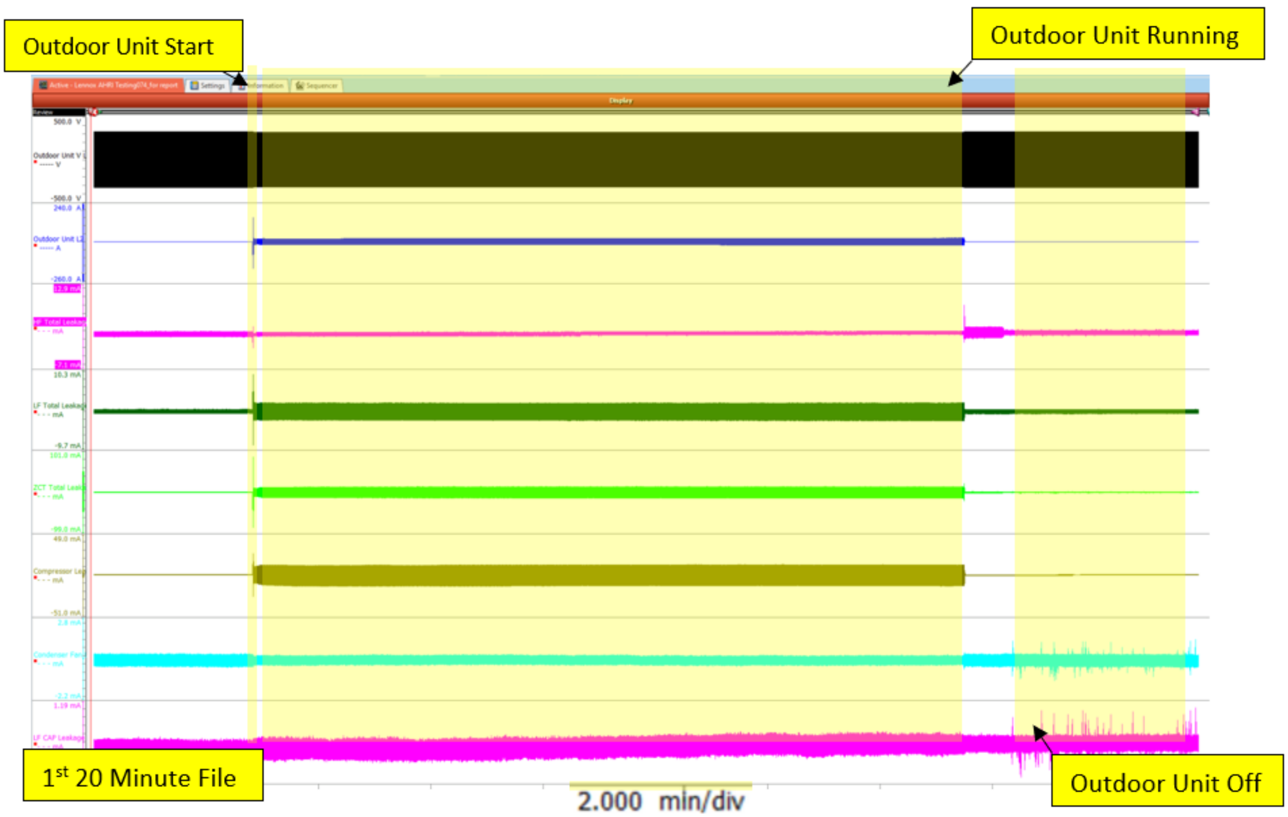


Figure 6-26
First 20-minutes of the HVAC Running Test

Figure 6-27 shows the leakage current measured at the time the outdoor unit started (compressor starts). The RMS current was measured for 327 milliseconds, at which time the Z-CT measured 46 mA. The current measured by the Z-CT was slightly higher than the allowable limits dictated by UL 943. The measurement recorder at the other locations within the circuit are compared in **Error! Reference source not found.** at the end of this section.

Figure 6-27
Leakage Current at Compressor Start

Figure 6-28 shows the leakage current measured after the compressor started during the time the outdoor unit was running. The RMS current was measured for 12-minutes and 33-seconds. The Z-CT measured 6.2 mA RMS which is slightly higher than the allowable limits dictated by UL 943. The measurements recorded at the other locations shown in Figure 6-28 are compared in **Error! Reference source not found.** at the end of this section.

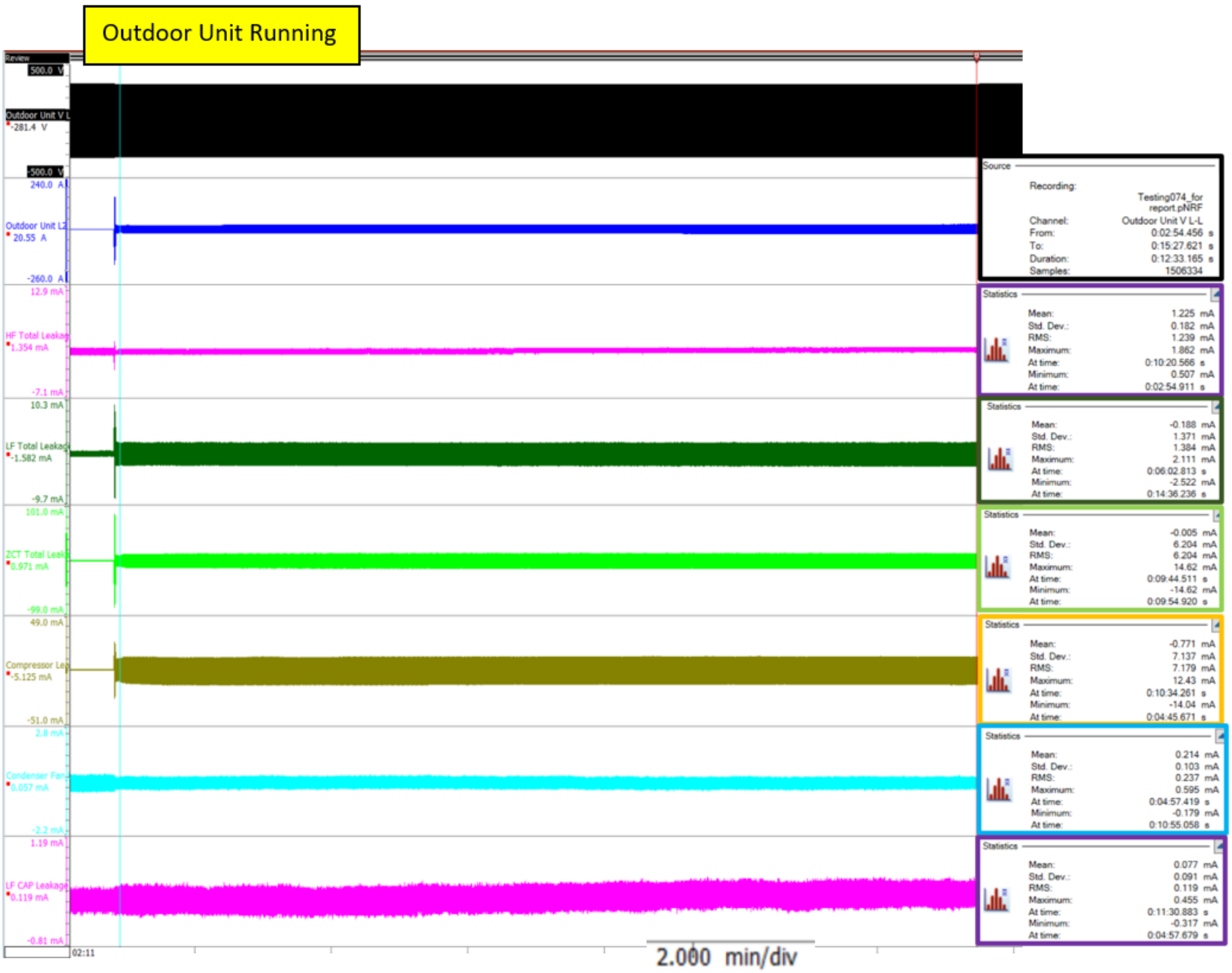


Figure 6-28
Outdoor Unit Running Leakage Current

Figure 6-29 shows the leakage current measured after the compressor started during the time the outdoor unit was running. The RMS current was measured for 3-minutes and 21-seconds. The Z-CT measured 0.2 mA RMS which is well within the allowable limits determined by UL 943. The measurements recorded at the other locations shown in Figure 6-29 are compared in **Error! Reference source not found.** at the end of this section.

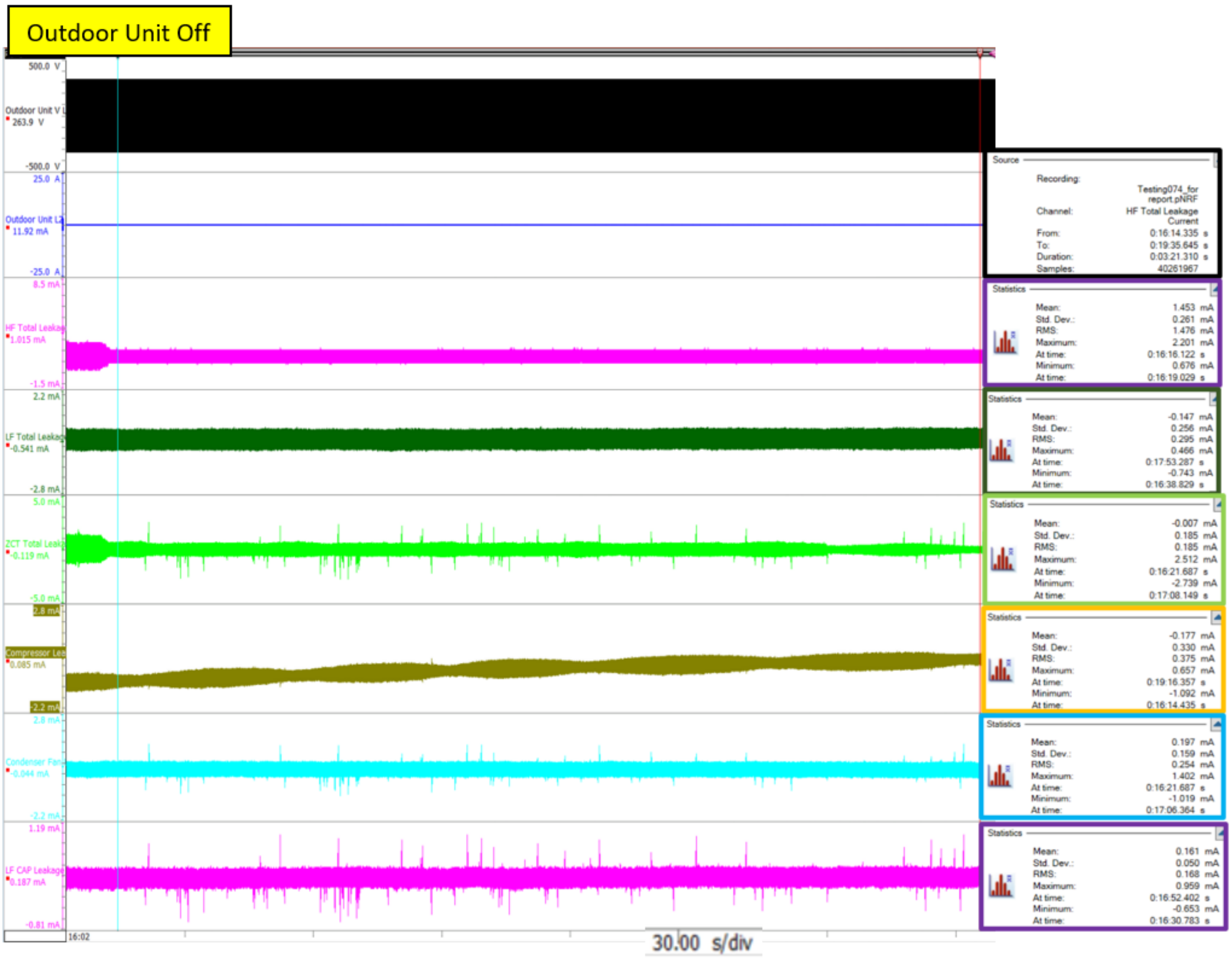


Figure 6-29
Outdoor Unit Off Leakage Current

Second 20-Minute Measurement Period

The second and third measurement yielded approximately the same results as the first 20-minute measurement period; therefore, only the “1,000-foot level waveform” is shown in Figure 6-30. The purpose is to show where the key areas where waveform analysis was conducted. Figure 6-30 shows the voltage, current, and leakage current measured at strategic locations of the EUT for the second 20-minute logging of the 1-hour test run. The waveform shows the compressor turned on about 7 minutes into the scan at which time maximum leakage current of 44 mA for 327 milliseconds was observed. The outdoor unit continued to operate for 14-minutes and 27-seconds after the compressor started where 7.7milliamps RMS was measured. The leakage current measured by the Z-CT revealed the current was above the limits shown in UL 943 for both time periods. All RMS currents measured by the CTs located at the other locations shown in Figure 6-30 are compared in **Error! Reference source not found.** at t he end of this section.

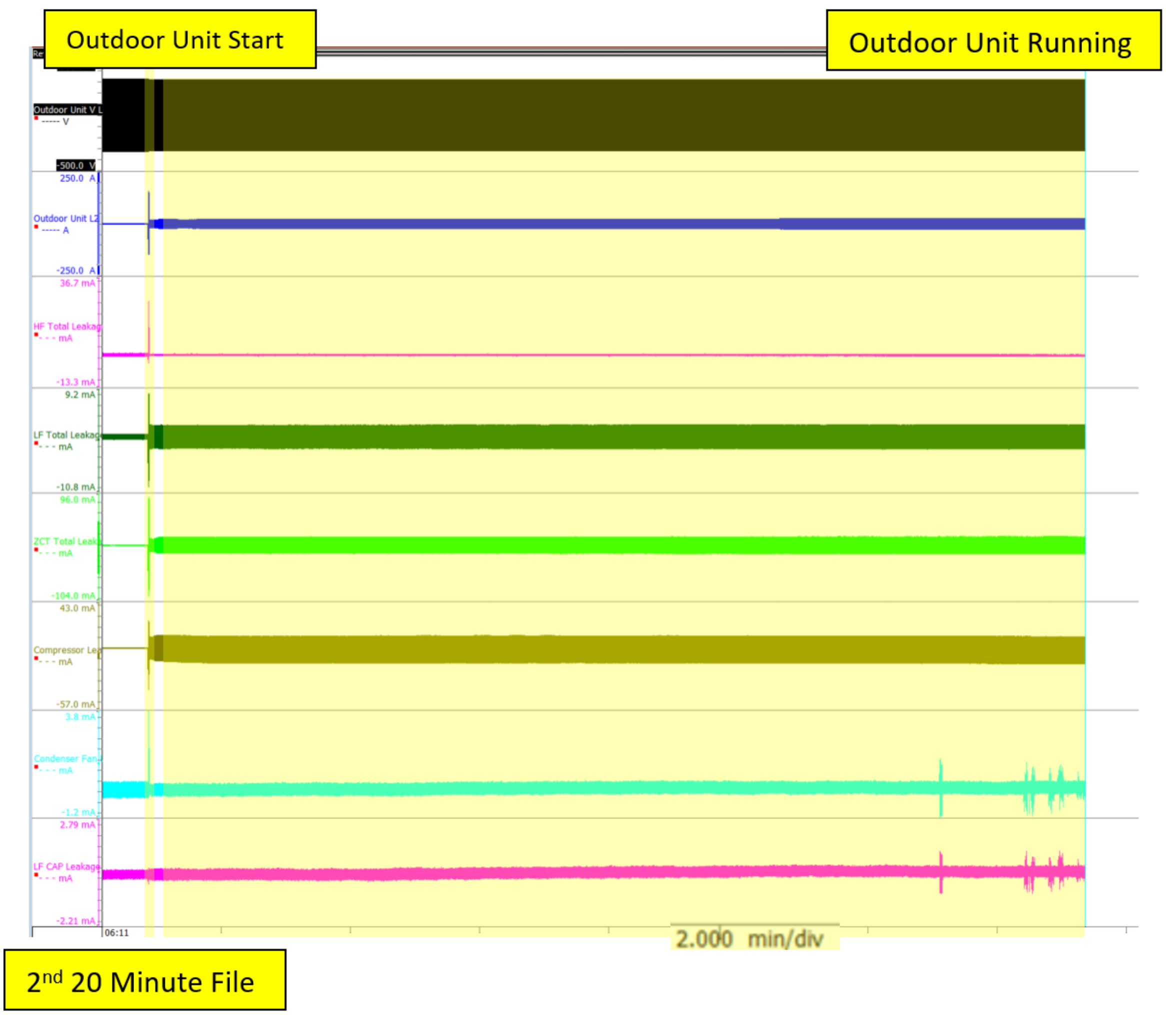


Figure 6-30
Second 20-minute Segment of HVAC Running Test

Final 20-Minute Measurement Period

Figure 6-31 shows the final 20-minutes of the 1-hour test. The waveform shows the compressor turned off in the middle of the scan time for 6 minutes and thirty seconds **Error! Reference source not found.** below shows that the leakage current measured at 44 milliamps for approximately 324 milliseconds when the compressor energized and 6.6 milliamps for 5 minutes and 56 seconds while the outdoor unit was running.

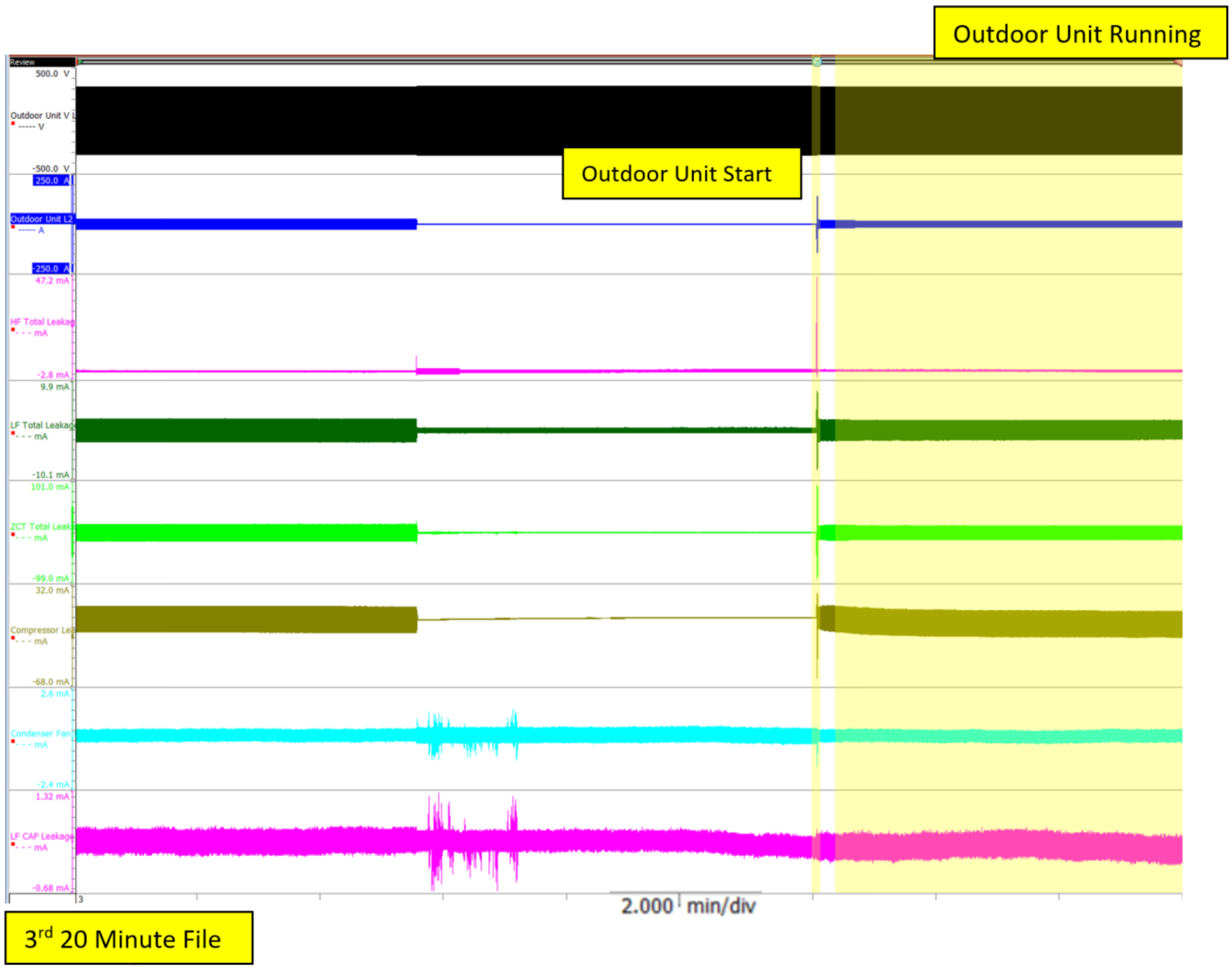


Figure 6-31
Final 20-minutes of HVAC Running Test

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the normal running test. The time when the outdoor unit initially started, ran nominally for a span, and time when the outdoor unit was off for the 1st 20-minute time period was monitored and recorded. The start and running measurements were recorded again for during the second and final measurement period was as well. The leakage RMS leakage current during the off-time period was very low and well under the 6-milliamp requirement of UL 943. The RMS current levels during the time when the outdoor unit was not running was equally low during measurement period 2 and 3; therefore, they were not recorded in the table. The Compressor leakage current probe measured currents higher than the Z-CT. The reason for this phenomenon may be the result of faster frequency response or potentially noise.

Table 6-14
Normal Running Test Critical Time Measurements

Note: All measurements are represented as RMS	**First 20-Minute Scan**				**Second 20-Minute Scan**				**Final 20-Minute Scan**				
Measurement Time Base													
Measurement Period	**Start**	**Run**	**Off**		**Start**	**Run**	**Off**		**Start**	**Run**	**Off**		
RMS Measurement Time	327 ms	12 min 33 sec	3 min 21 sec		327 ms	14 min 27 sec			324 ms	5 min 56 sec			
UL 943 Limit	**44 mA**	**6 mA**	**6 ma**	**Within UL 943 Current/Time Limits?**	**44 mA**	**6 mA**		**Within UL 943 Current/Time Limits?**	**44 mA**	**6 mA**		**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	46 mA	6.2 mA	0.2mA	*No*	44 mA	7.7 mA		No	44 mA	6.6 mA		*No*	No
Compressor Leakage	15 mA	7.2 mA	0.4 mA	No	13 mA	7.1 mA		No	12 mA	9.4 mA		No	No
Condenser Fan Leakage	0.2 mA	0.2 mA	0.3 mA	Yes	0.2 mA	0.2 mA		Yes	0.2 mA	0.2 mA		Yes	No
Capacitor Leakage	0.1mA	0.1mA	0.2mA	Yes	0.2mA	0.3mA		Yes	0.3 mA	0.2 mA		Yes	No
HF Probe Ground Conductor	1.0mA	1.2mA	1.5mA	Yes	1.5mA	1.4mA		Yes	1.7 mA	1.6 mA		Yes	No
LF Probe Ground Conductor	5.0mA	1.3mA	0.3mA	Yes	4.6mA	1.5mA		Yes	4.1 mA	6.6 mA		*No*	No

Note: *No* = Indicate the current was above the UL 943 limits; however, only slightly.

Test 2 Conclusion

The purpose of the HVAC Running test was to measure the power profile and leakage current during a normal operating cycle. Power was applied to the system for one hour with the system operating in the thermal chambers stabilized in the nominal baseline mode. The data was captured in three 20-minute chunks as the file size was very large. Maximum leakage current was observed each time the compressor started, and minimum leakage current was observed when the outdoor unit was off. The Z-CT measured above the allowable limits of UL 943 when the compressor started and while the outdoor was operating nominally. The GFIC circuit breaker did not trip for any of the tests. Figure 6-32 is an FFT of the Z-CT current while the Unit was running during the second 20-minute scan. The data in **Error! Reference source not found.** s hows the GFCI did not trip during the time the outdoor unit was running although the Z-CT measured 7.7 mA which is above the allowable limits in UL 943. The FFT Figure 6-32 shows the current was not linear, in other words, the current spectrum is spread about several multiples of the 60Hz fundamental frequency or "harmonics". It is not known if the GFCI reacts on the sum of the frequencies or only the fundamental frequency which may explain why the Z-CT may report RMS current higher than the limits of UL 943 but not trip the GFCI.

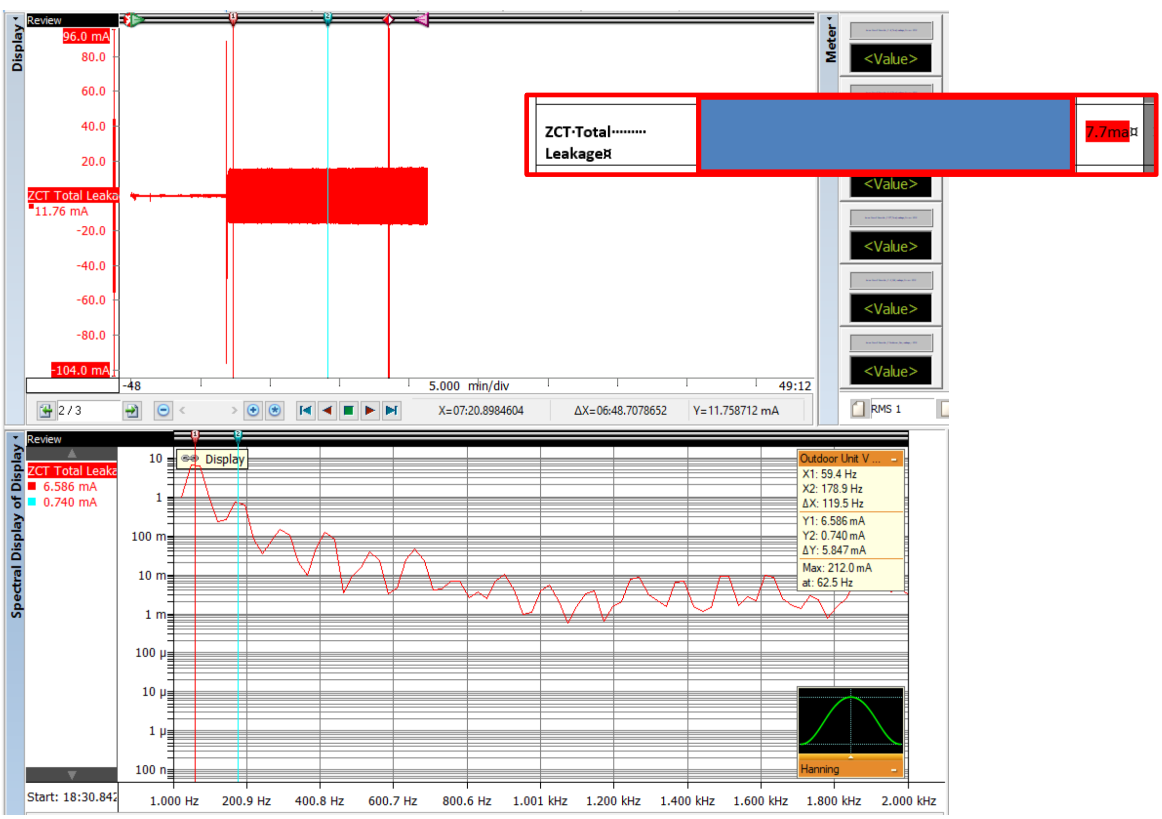


Figure 6-32
FFT of Z-CT Measurement During Second 20-minute Scan

Test 3 Thermostat Cycling Test

HVAC systems do not typically operate continuously as they cycle on and off as required to maintain the temperature setpoint. The purpose of the thermostat cycling test is to determine the maximum leakage current when the HVAC unit cycles on and off. The single-stage HVAC system was tested by controlling the on-off state via a timer and switches shown in Figure 6-33.

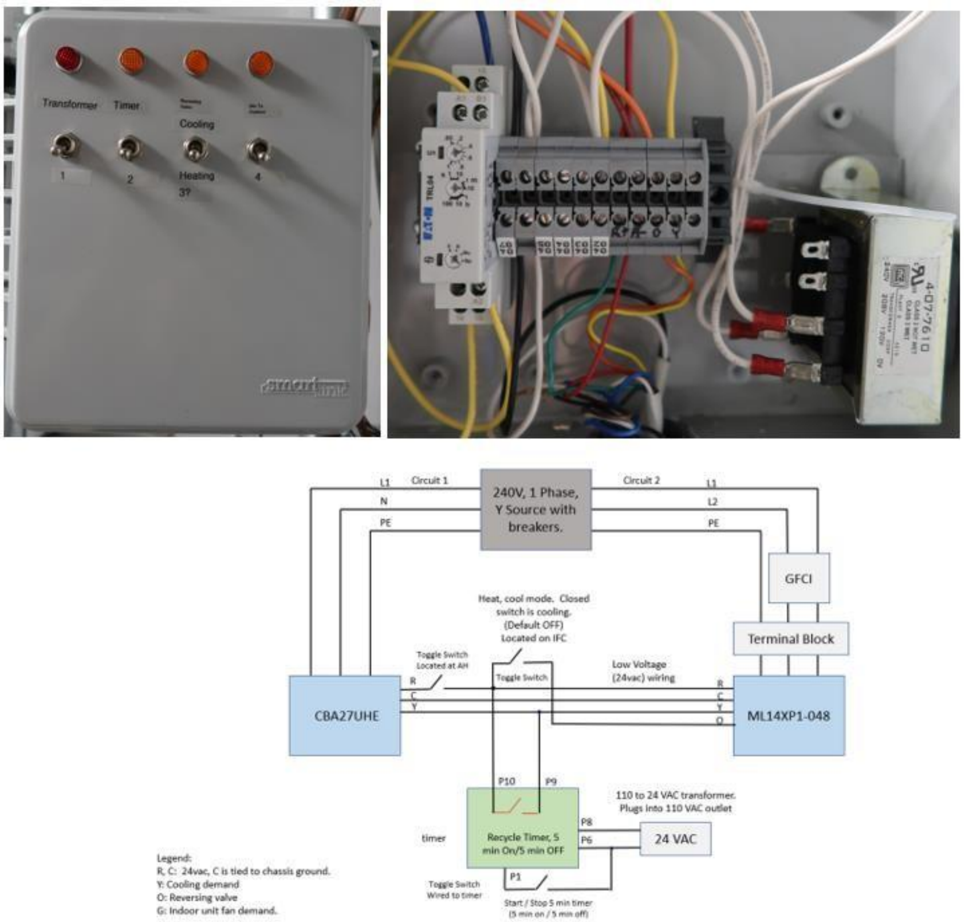


Figure 6-33
Cycle Time (Schematic provided by Unit #1 manufacturer)

The unit was toggled on and off once every 5 minutes for a one-hour period. This test was conducted once at each thermal condition shown in Table 6-3. The monitoring was conducted while the HBM Gen 3i was configured to collect data at 250 kilo samples per second; therefore, the measurement was collected across three separate files to reduce the size per file. The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** shows t he RMS leakage current recorded by the Z-CT during each test, the relative humidity of the temperature chamber during the test, and some general observation notes. Several of the tests in this section returned leakage current values greater than the allowable limits in UL 943. An FFT analysis was conducted of the outdoor unit start while the test was conducted in temperature chamber condition number 2. The results of this analysis may be seen in **Error! R eference source not found.** in the conclusion section of this test.

Table 6-15
Tabular Data from Thermostat Cycling Test

Temperature Chamber Condition	**RMS Leakage Current / time Z-CT**	**Notes**	**Outdoor Chamber Humidity**
1	Outdoor Unit Start 46 mA, 325 ms Outdoor Unit Running 6 mA, 5 minutes 4 seconds	The maximum leakage current was observed each time the compressor started.	21%
2	Outdoor Unit Start 50 mA, 326 ms Outdoor Unit Running 7.4 mA, 5 minutes 5 seconds	Leakage current was 1.4 mA above the current limits in UL 943 during the outdoor unit running timeframe for Temperature conditions 2 and 3.	19%
3	Outdoor Unit Start 41 mA, 325 ms Outdoor Unit Running 7.4 mA, 5 minutes 4 seconds	The circuit breaker did not trip for any of the tests.	77%

Nominal Baseline Condition Testing

The first test was conducted with the thermal chambers configured for temperature chamber condition one, or the Nominal Baseline Condition. Figure 6-34 shows the voltage, current, and leakage current while the thermal chambers were operating in the nominal baseline configuration. Figure 6-34 also highlights the location in the waveform where the leakage current was measured during the first 20 minutes of the one-hour measurement period. The tabular data for all the leakage current measurements for the Nominal Baseline test may be seen in **Error! Reference source not found.** at the end of this section. *Note: in all the charts, a v alue appears at left under the name of the leakage current being measured. This is an artifact showing the value registered at the location of the red cursor which may or may not be visible in the chart. This value has no relevance to the measurements of concern.*

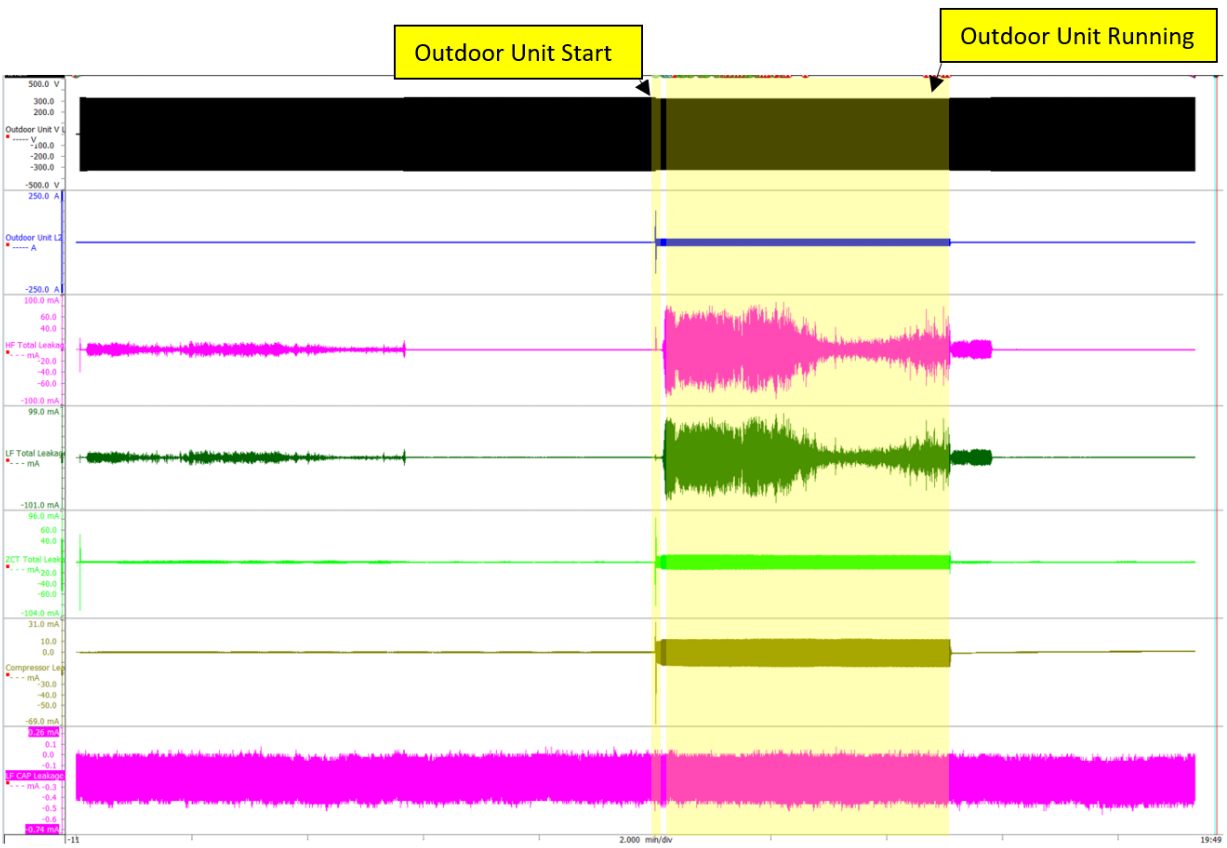


Figure 6-34
Nominal Baseline (First), File 61

Figure 6-35 shows the data where the outdoor unit turned on 10 minutes into the scan. The statistics for each of the leakage current measurements may be seen in the statistic boxes to the right of each waveform.

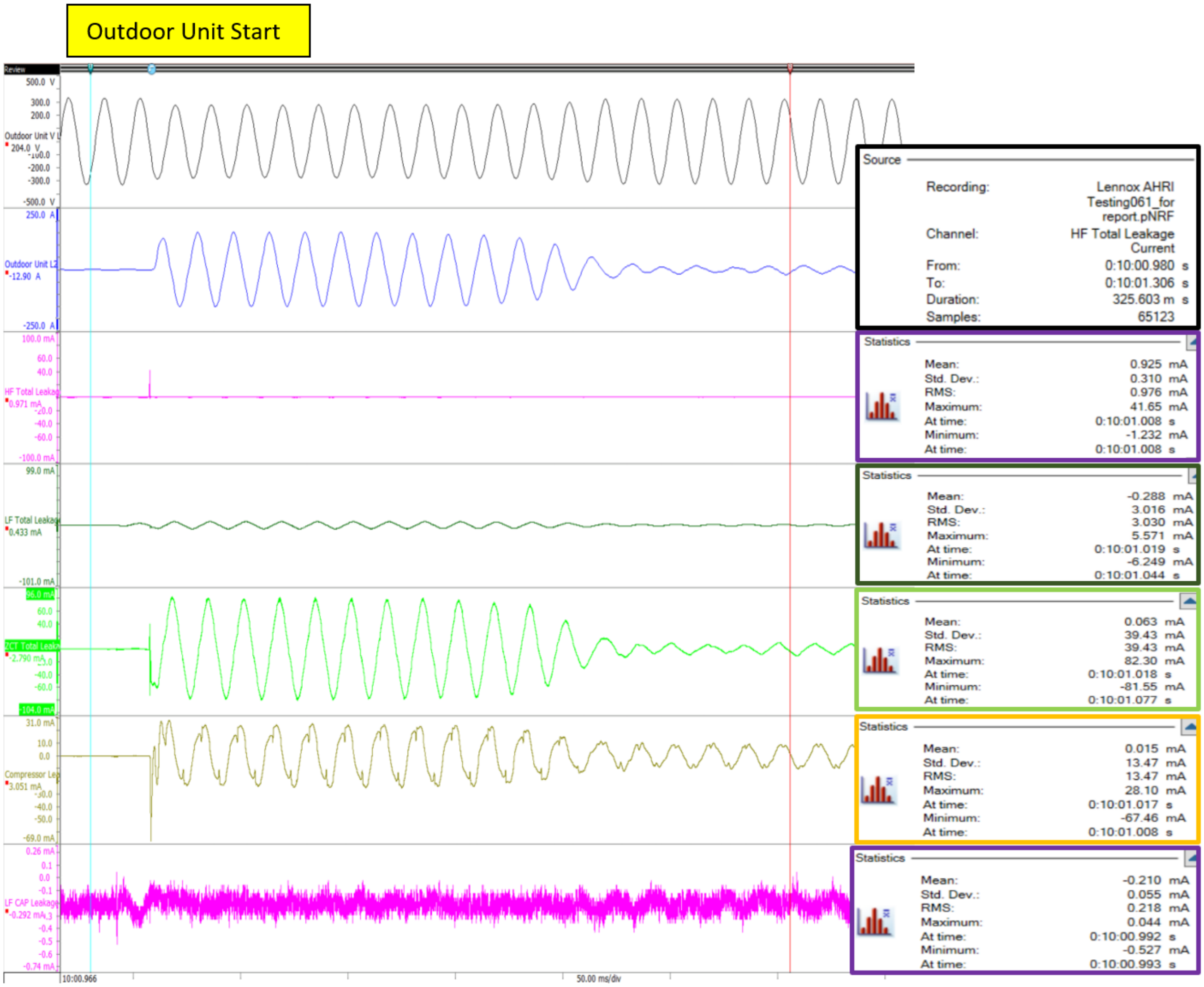


Figure 6-35
Outdoor Unit Start Leakage Current, First 20-Minutes

Figure 6-36 shows the waveforms during the 5-minute period after the compressor started and the outdoor unit was running. The statistics for each of the leakage current measurements may be seen in the statistic boxes to the right of each waveform.

Figure 6-36
Outdoor Unit Running Leakage Current First 20 Minutes

The second 20-minute span of the test (Test Condition 2) is shown in Figure 6-37. The waveform shows two instances the unit cycled on and off. The greatest leakage current was measured when the compressor turned on during the second 20-minute measurement period.

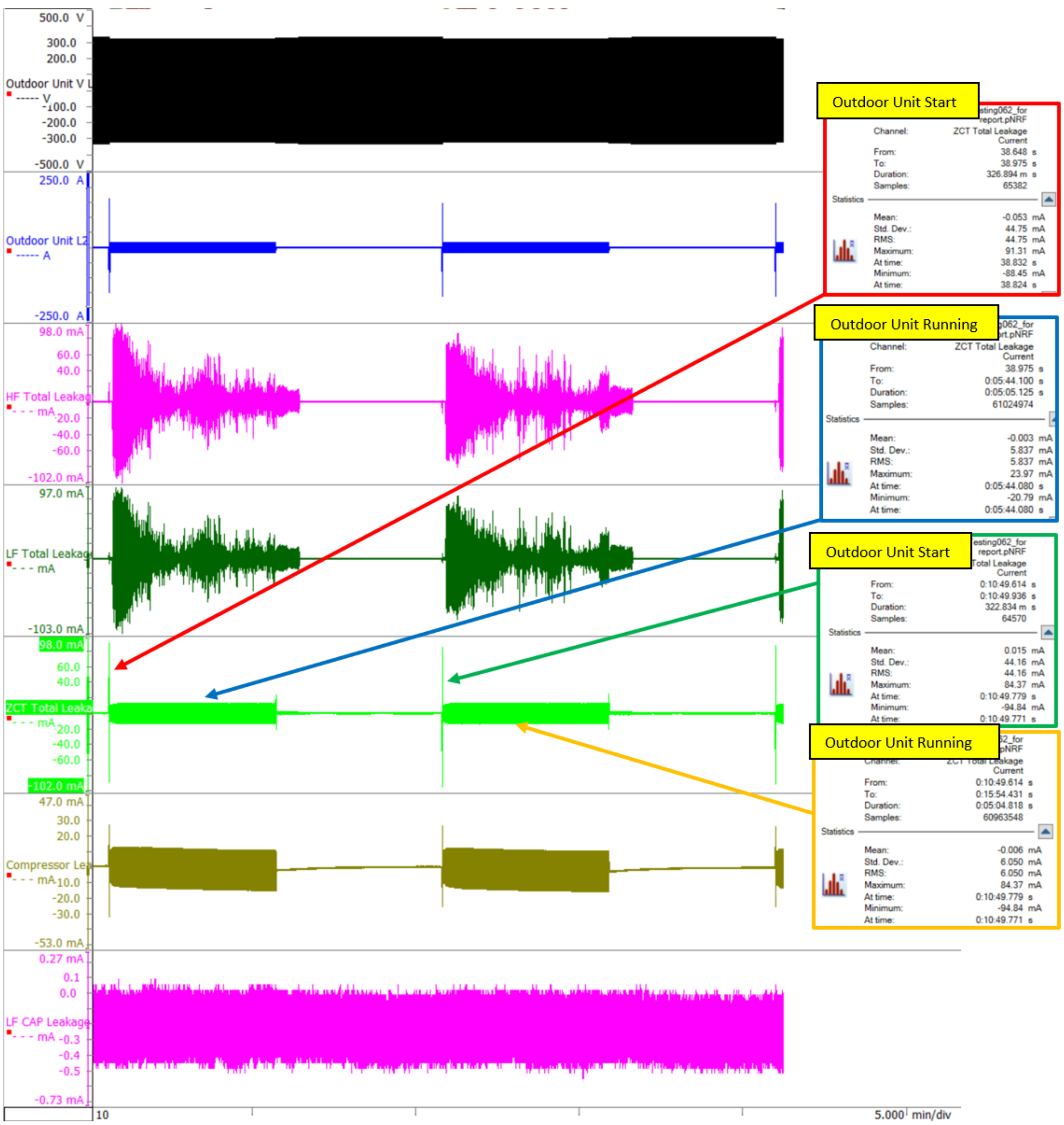


Figure 6-37
Nominal Baseline (Second), File 62

The final 20-mintute span of the test is shown in Figure 6-38. The waveform shows the greatest leakage current the only time the compressor turned on during the third 20-minute measurement period. The unit had already started an “on-off” cycle between ending the second scan and the beginning of the third; therefore, only one full cycle of the outdoor unit is shown in the figure below. The leakage current statistics measured by the Z-CT are shown when the outdoor unit was running and when the outdoor unit started (compressor started) is shown below.

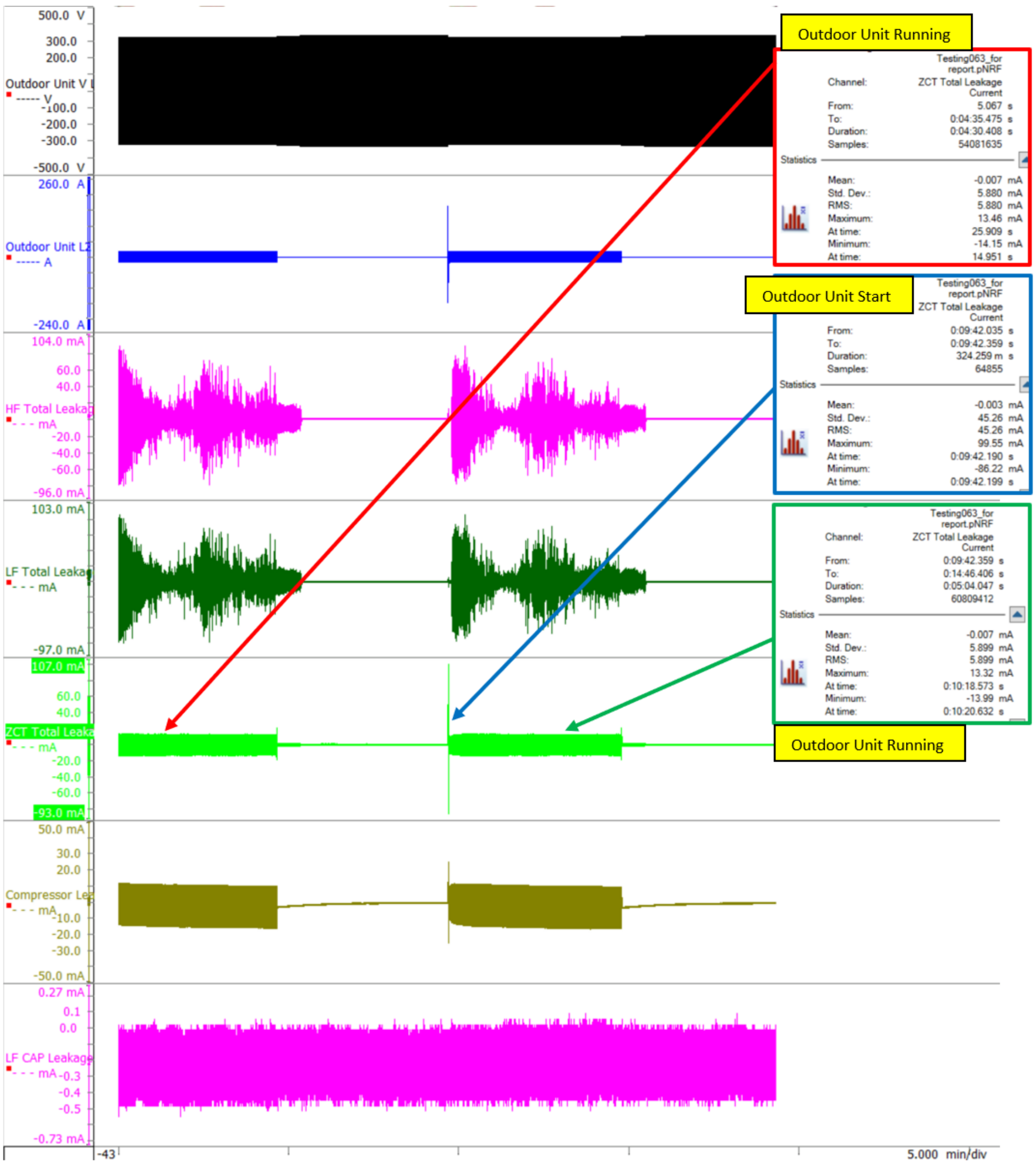


Figure 6-38
Nominal Baseline (Final), File 63

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the Thermostat Cycling Test under normal baseline temperature conditions. The time when the outdoor unit initially started and nominal running was recorded for a one-hour time span. The data was collected at a very fast sample rate; therefore, the data was collected in three 20-minute files. The tabular data shows the leakage current remained very close to the maximum allowable current when the outdoor unit turned on (compressor started). The leakage current measured 6 mA during the 5-minute nominal runtime. The current probes that measure the ground conductor of the outdoor unit measured much higher leakage current values than the Z-CT. The reason for this phenomenon is not known. Some possible causes may be the CTs used to measure the ground conductor have a faster frequency response, noise could have been present, or possible ground current flowing from the indoor unit.

Table 6-16
Tabular Leakage Current Data from the Nominal Baseline Tests

Note: All measurements are represented as RMS	**First 20-Minute Scan**			**Second 20-Minute Scan**			**Final 20-Minute Scan**			
Measurement Time Base	**50 ms/div**									
Measurement Period	**Start**	**Run**		**Start**	**Run**		**Start**	**Run**		
RMS Measurement Time	325 ms	5 min 4 sec		326 ms	5 min 5 sec		325 ms	5 min 4 sec		
UL 943 Limit	**44 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	39 mA	5.4 mA	Yes	45 mA	6 mA	*No*	46 mA	6 mA	*No*	No
Compressor Leakage	13 mA	7.3 mA	No							
Capacitor Leakage	0.2 mA	0.2 mA	Yes							
HF Probe Ground Conductor	1.0 mA	19 mA	No							
LF Probe Ground Conductor	3.0 mA	19 mA	No							

Note: Only the Z-CT data was analyzed for second and third scan

Full Nominal Cooling Condition Testing

The second test was conducted with the thermal chambers configured for thermal condition two, or the Full Nominal Cooling condition. Figure 6-39 shows the voltage, current, and leakage current while the thermal chambers were operating in the full nominal cooling configuration. Figure 6-39 also highlights the location in the waveform where the leakage current was measured during the first 20 minutes of the one-hour measurement period. The tabular data for all the leakage current measurements for the Full Nominal Cooling Condition may be seen in **Error! Reference source not found.** at the end of this section.

Figure 6-39
Full Nominal Cooling (First), File 64

Figure 6-40 shows the data where the outdoor unit turned on 10 minutes into the scan. The statistics for each of the leakage current measurements may be seen in the statistic boxes to the right of each waveform.

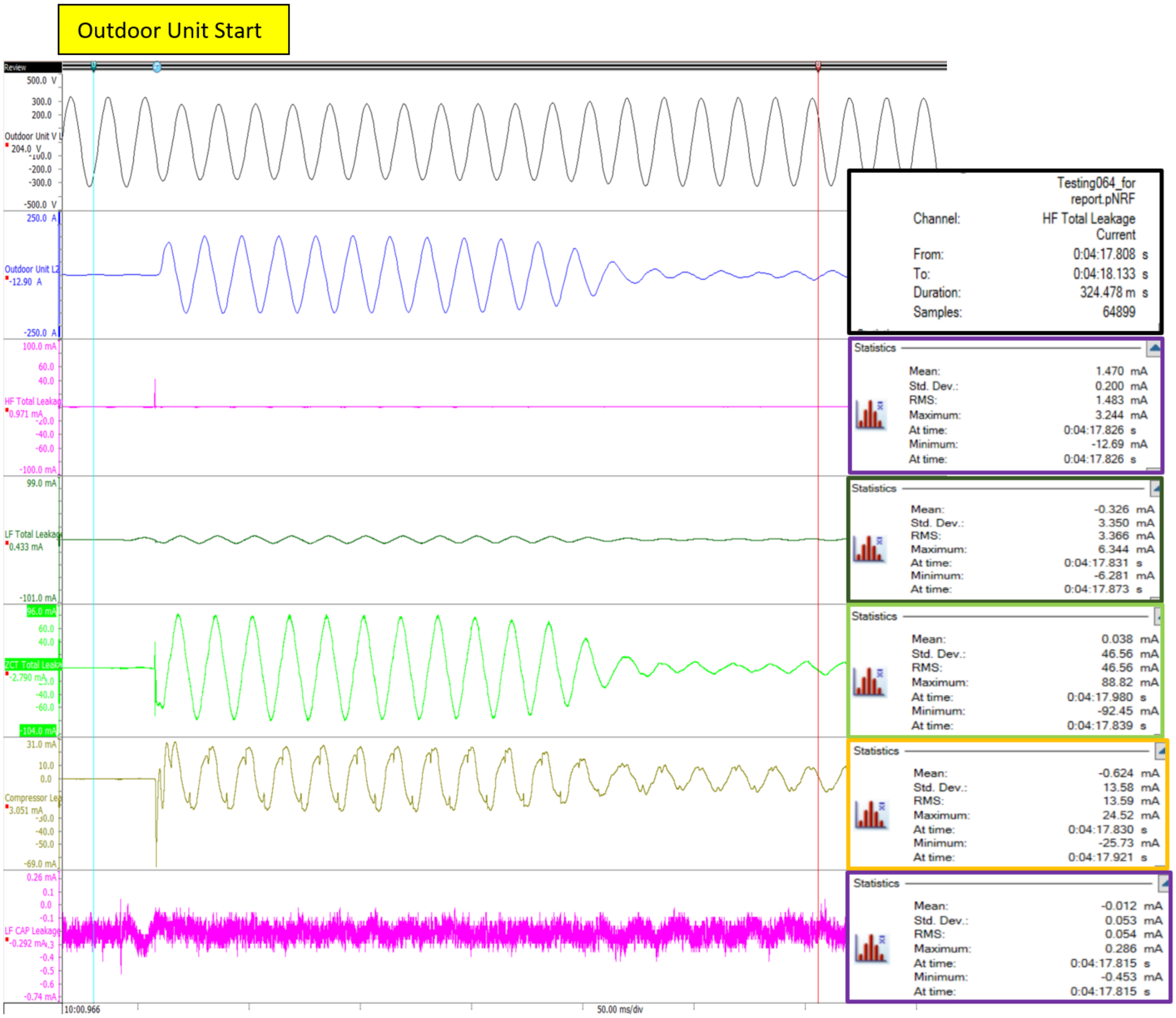


Figure 6-40
Outdoor Unit Start Leakage Current, First 20-Minutes

Figure 6-41 shows the waveforms during the 5-minute period after the compressor started and the outdoor unit was running. The statistics for each of the leakage current measurements may be seen in the statistic boxes to the right of each waveform.

Figure 6-41
Outdoor Unit Running Leakage Current, First 20-Minutes

Note: The final two files only show the Statistics for the Z-CT at startup of the outdoor unit and the 5-minute runtime of the outdoor unit to see if there is a significant change in the leakage current over the duration of the test. This abbreviated analysis was done to save time.

The second 20-minute span of the test is shown in Figure 6-42. Figure 6-42 shows the compressor cycled on twice during the measurement period. Maximum total leakage current was measured by the Z-CT when the compressor started the first time in the scan. The tabular data for all the leakage current measurements may be seen in the analysis boxes to the right of the waveforms. A tabular analysis of the leakage current measured by the Z-CT may be seen in **Error! Reference source not found.** at the end of this section.

Figure 6-42
Full Nominal Cooling (Second), File 65

The final 20-mintute span of the Nominal Cooling Test is shown in Figure 6-43. The figure shows the compressor cycled on twice during the measurement period. Maximum total leakage current was measured by the Z-CT when the compressor started the first time in this scan. A tabular analysis of the leakage current measured by the Z-CT may be seen in **Error! Reference source not found.** at the end of this section.

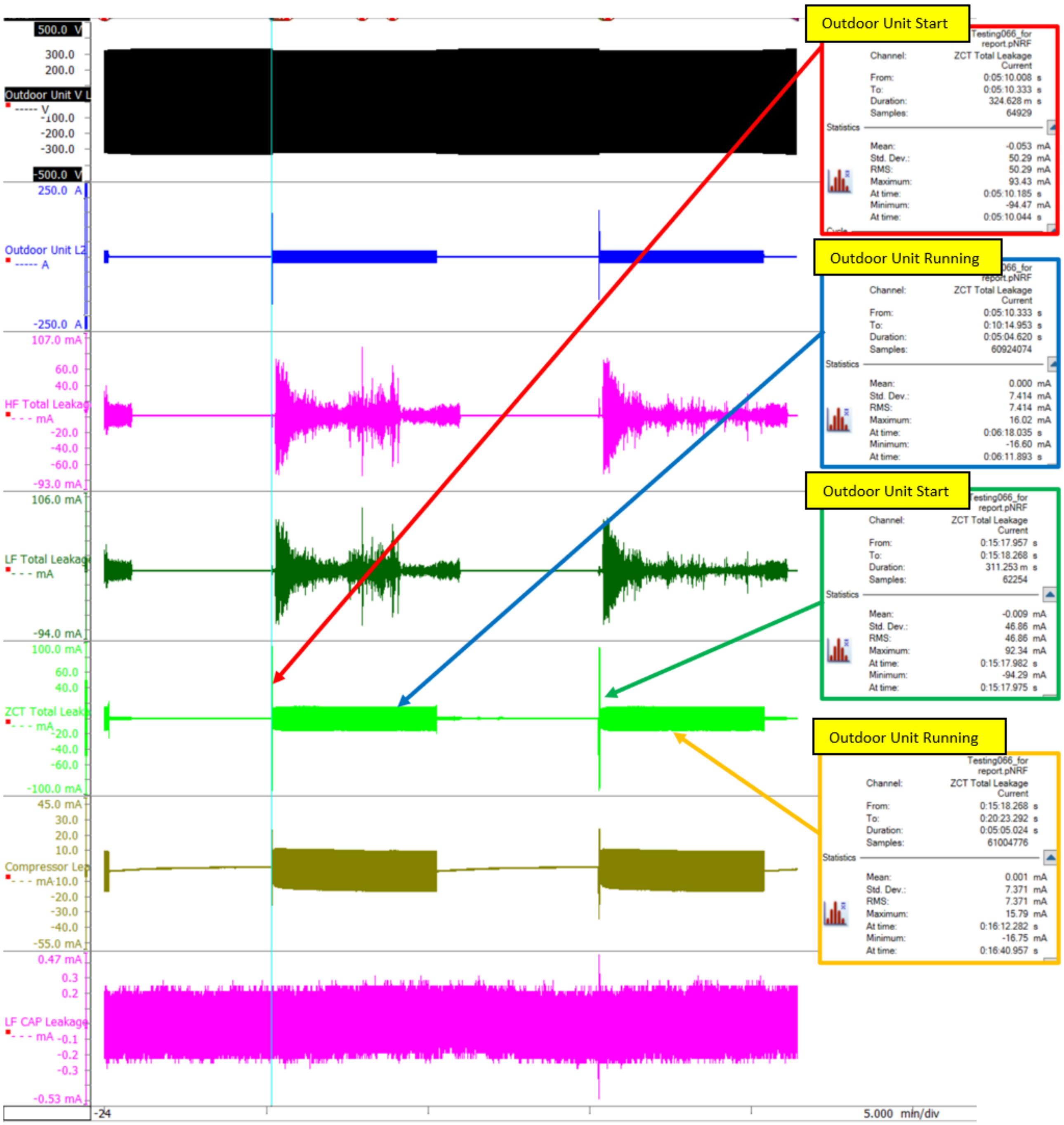


Figure 6-43
Full Nominal Cooling (Final), File 66

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the Thermostat Cycling Test under nominal cooling temperature conditions. The time period when the outdoor unit initially started and nominal running was recorded for a one-hour time span. The data was collected at a very fast sample rate; therefore, the data was collected in three 20-minute files. The leakage current measured between 7.2 and 7.4 mA during the 5-minute nominal runtime which is above the allowable limits of UL 943. The current probes that measure the ground conductor of the outdoor unit measured much higher leakage current values than the Z-CT. The reason for this phenomenon is not known. Some possible causes may be the CTs used to measure the ground conductor have a faster frequency response, noise could have been present, or possible ground current flowing from the indoor unit.

Table 6-17
Tabular Leakage Current Data from the Nominal Cooling Tests

Note: All measurements are represented as RMS	**First 20-Minute Scan**			**Second 20-Minute Scan**			**Final 20-Minute Scan**			
Measurement Time Base	**50 ms/div**	**1 min/div**								
Measurement Period	**Start**	**Run**		**Start**	**Run**		**Start**	**Run**		
RMS Measurement Time	324 ms	5 min 4 sec		287 ms	5 min 1 sec		325 ms	5 min 4 sec		
UL 943 Limit	**44 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**48 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	47 mA	7.2 mA	No	50 mA	7.4 mA	No	50 mA	7.4 mA	No	No
Compressor Leakage	14 mA	7.3 mA	No							
Capacitor Leakage	0.1 mA	0.1 mA	Yes							
HF Probe Ground Conductor	1.5 mA	10 mA	No							
LF Probe Ground Conductor	3.4 mA	9.8 mA	No							

Note: Z-CT data only analyzed for second and third scan

Full Nominal Heating Condition Testing

The third test was conducted with the thermal chambers configured for condition three, or the Full Nominal Heating condition. The waveforms in Figure 6-44 show the voltage, current, and leakage currents while the thermal chambers were operating in the nominal heating configuration. Figure 6-44 also highlights the location in the waveform where the leakage current was measured during the first 20 minutes of the one-hour measurement period. The tabular data for all the leakage current measurements for the Full Nominal Heating test may be seen in **Error! Reference source not found.** at the end of this section.

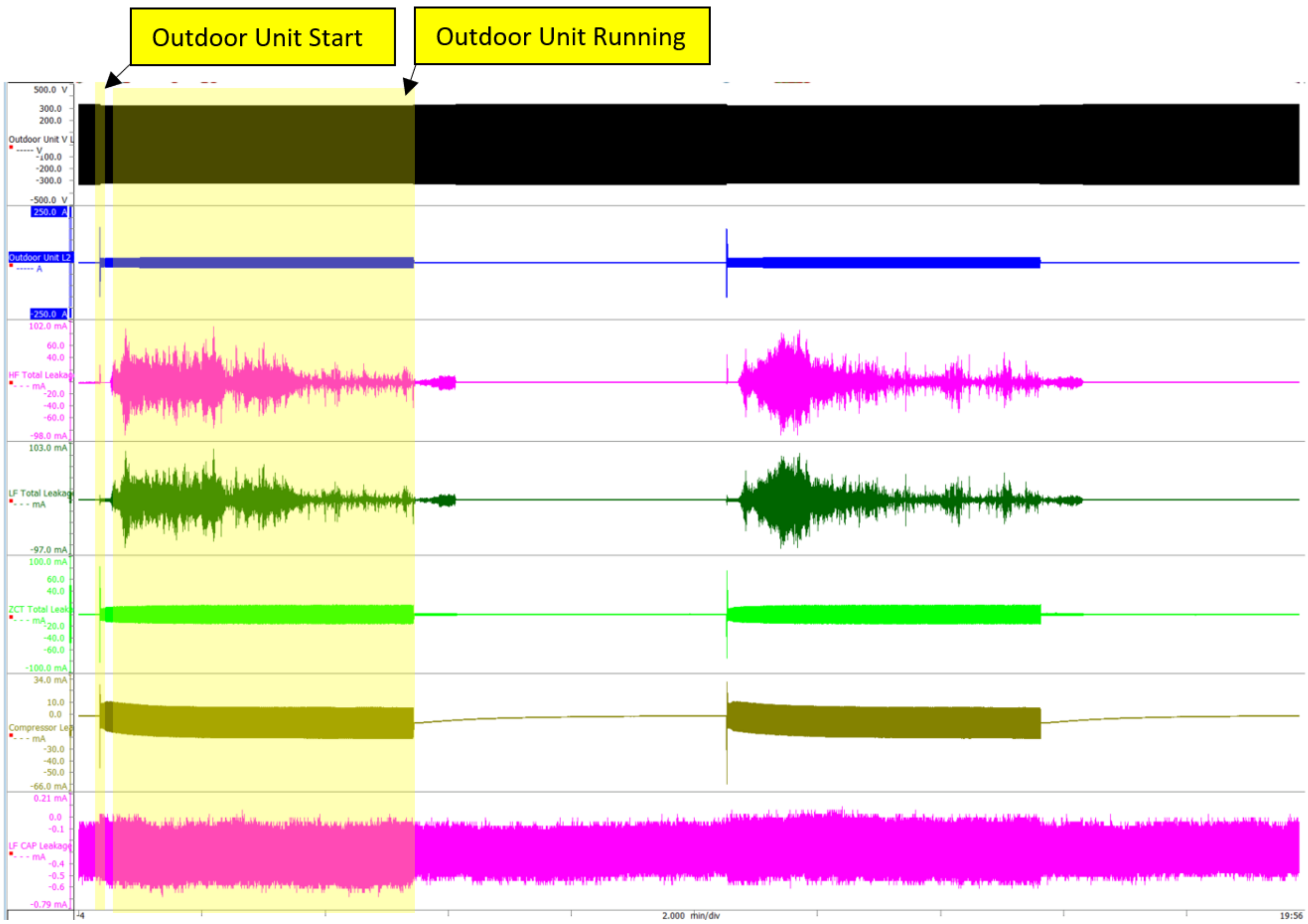


Figure 6-44
Full Nominal Heating (First), File 71

Figure 6-45 shows the data where the outdoor unit turned on 10 minutes into the scan. The statistics for each of the leakage current measurements may be seen in the statistic boxes to the right of each waveform.

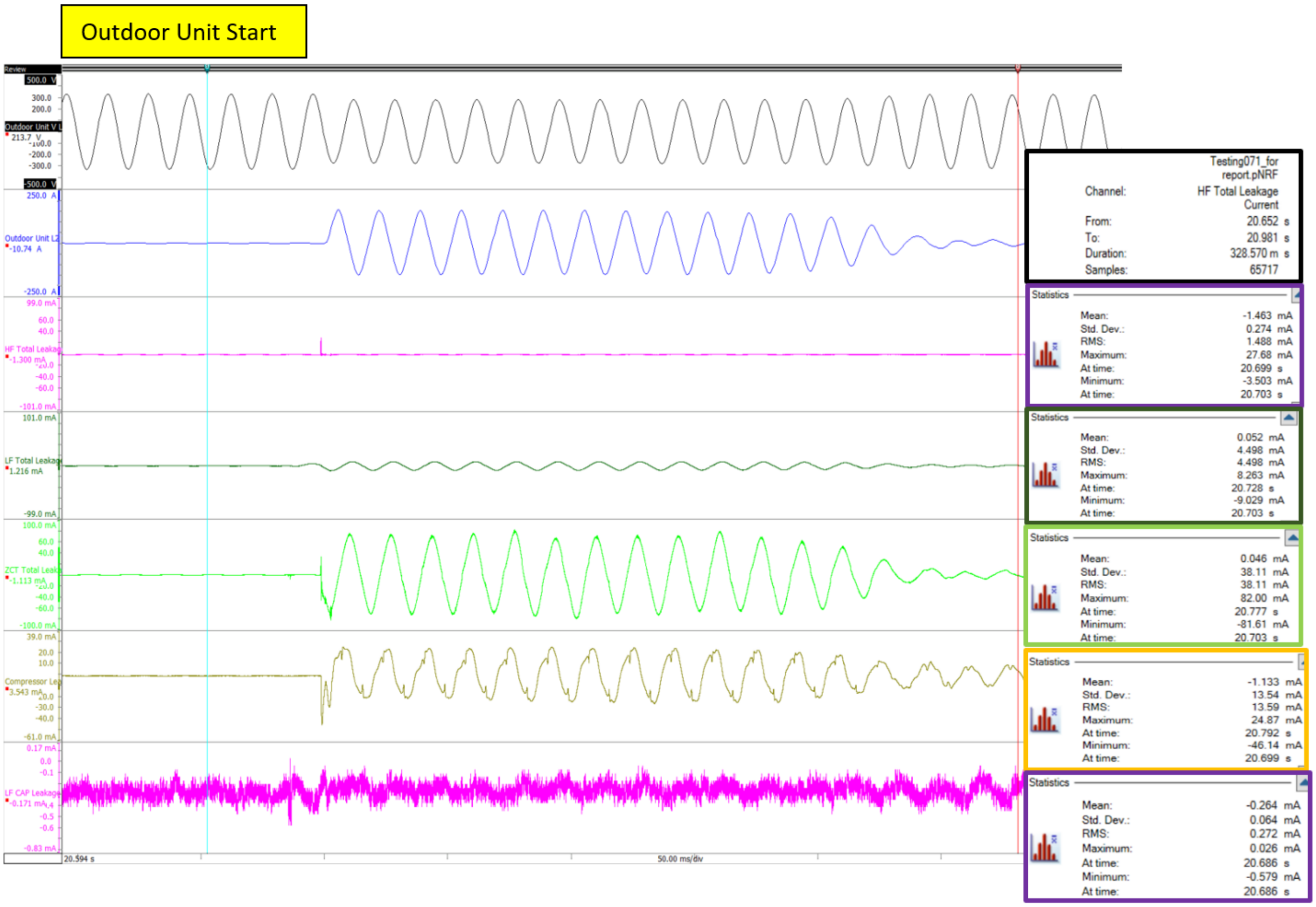


Figure 6-45
Outdoor Unit Start Leakage Current, First 20-Minutes

Figure 6-46 shows the waveforms during the 5-minute period after the compressor started and the outdoor unit was running. The statistics for each of the leakage current measurements may be seen in the statistic boxes to the right of each waveform.

Figure 6-46
Outdoor Unit Running Leakage Current, First 20-Minutes

Note: The final two files only show the Statistics for the Z-CT at startup of the outdoor unit and the 5-minute runtime of the outdoor unit to see if there is a significant change in the leakage current over the duration of the test. This abbreviated analysis was done to save time.

The second 20-minute span of the test is shown in Figure 6-47. The waveforms show the voltage, current, and leakage currents while the thermal chambers were operating in the nominal heating configuration.

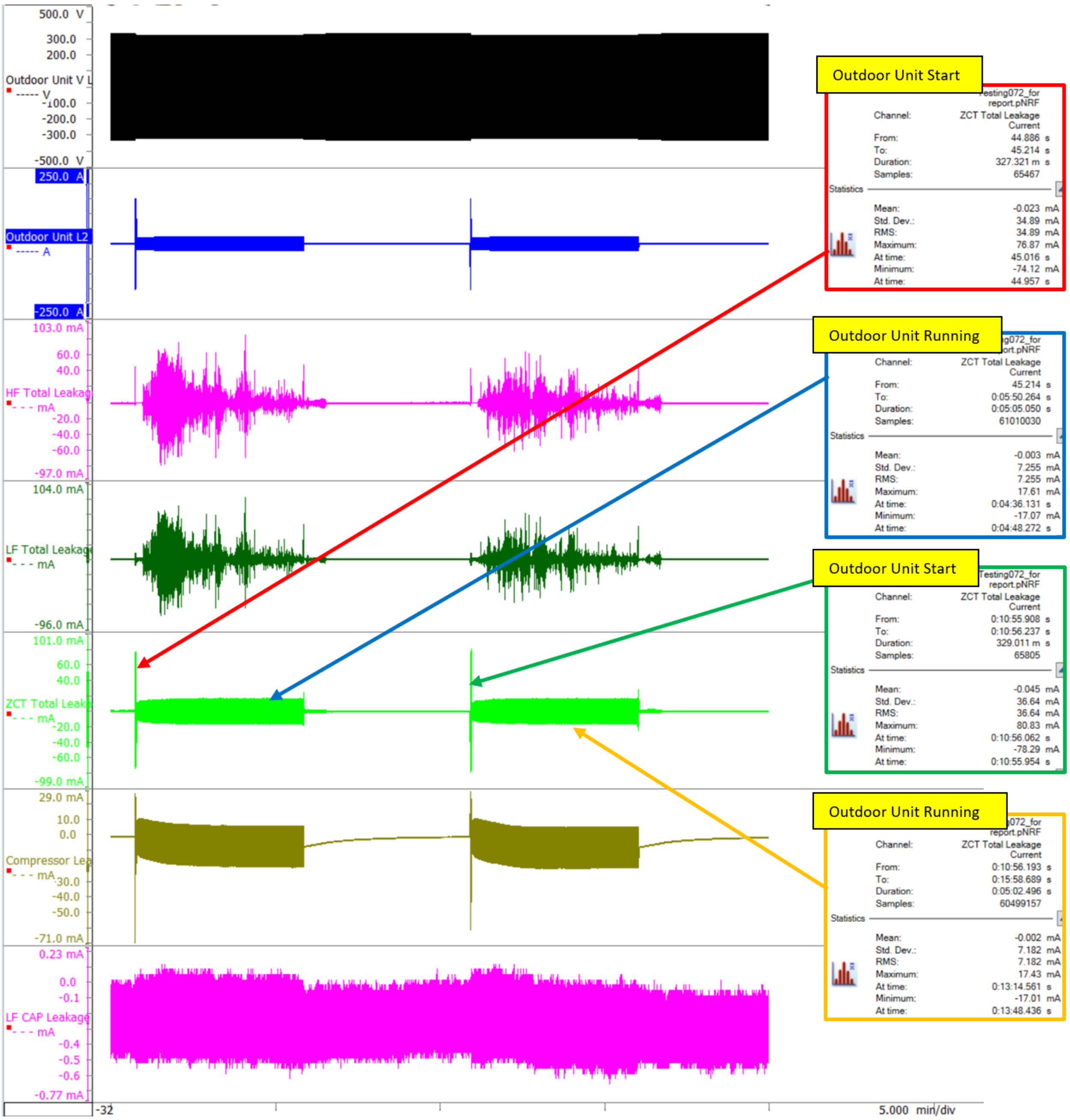


Figure 6-47
Full Nominal Heating (Second), File 72

The third and final 20-minute span of the test is shown in Figure 6-48. The waveforms show the voltage, current, and leakage currents while the thermal chambers were operating in the nominal heating configuration. The waveforms in Figure 6-48 shows the statistical information including the RMS current measurements of the Z-CT when the outdoor unit starts and while it is operating. The tabular data for all the leakage current measurements for the Z-CT may be seen in **Error! Reference source not found.** at the end of this section.

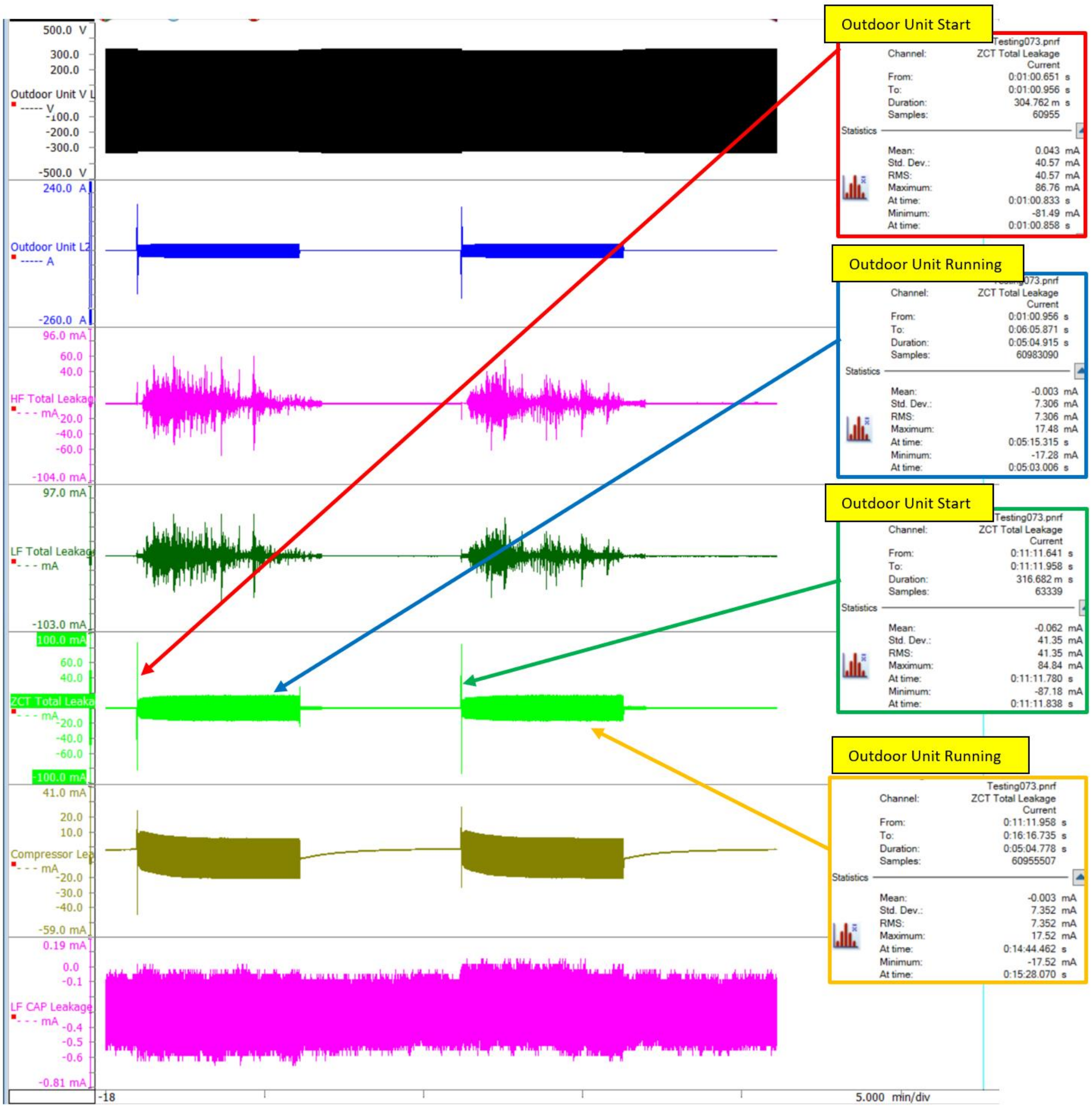


Figure 6-48
Full Nominal Heating (Final), File 73

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the Thermostat Cycling Test under nominal heating temperature conditions. The time when the outdoor unit initially started and nominal running was recorded for a one-hour time span. The data was collected at a very fast sample rate; therefore, the data was collected in three 20-minute files. The tabular data shows the leakage current remained below the maximum allowable current when the outdoor unit turned on (compressor started). The leakage current measured between 7.0 mA and 7.4 mA during the 5-minute nominal runtime which is above the allowable limits of UL 943. The current probes that measure the ground conductor of the outdoor unit measured much higher leakage current values than the Z-CT. The reason for this phenomenon is not known. Some possible causes may be the CTs used to measure the ground conductor have a faster frequency response, noise could have been present, or possible ground current flowing from the indoor unit.

Table 6-18
Tabular Leakage Current Data from the Nominal Heating Tests

Note: All measurements are represented as RMS	**First 20-Minute Scan**			**Second 20-Minute Scan**			**Final 20-Minute Scan**			
Measurement Time Base	**50 ms/div**	**1 min/div**								
Measurement Period	**Start**	**Run**		**Start**	**Run**		**Start**	**Run**		
RMS Measurement Time	328 ms	5 min 4 sec		329 ms	5 min 5 sec		316 ms	5 min 5 sec		
UL 943 Limit	**44 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**45 mA**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	38 mA	7.0 mA	No	37 mA	7.2 mA	No	41 mA	7.4 mA	No	No
Compressor Leakage	14 mA	9.9 mA	No							
Capacitor Leakage	0.3 mA	0.3 mA	Yes							
HF Probe Ground Conductor	1.5 mA	10 mA	No							
LF Probe Ground Conductor	4.5 mA	9.7 mA	No							

Note: Z-CT data only analyzed for second and third scan

Test 3 Conclusion

The purpose of the HVAC Cycling test was to identify critical points in the operating process of the EUT that create the most leakage current. The test was conducted during all three temperature conditions to determine if the temperature or heating and cooling mode affects the magnitude of the leakage current. **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.** contain all the tabular data for the Thermostat cycling test. **Error! Reference source not found.** shows the Z-CT measured current levels within or just outside the limits of UL 943 when the outdoor unit started and when the outdoor unit operated nominally. However, **Error! Reference source not found.** and **Error! Reference source not found.** show the leakage current levels were above the limits of UL 943 for the time spans measured during the forementioned conditions. The greatest leakage current was measured during the Nominal Cooling Condition test, although the GFCI never tripped during any of the testing.

Figure 6-49 is an FFT of the current measured by the Z-CT the last time the compressor started when testing was conducted in the full nominal cooling condition. The time base for this FFT was 300 milliseconds, and UL 943 shows the maximum allowable current for 300 milliseconds is 46 milliamps. The FFT shows the fundamental 60-Hz current was 48 amps and the 2nd harmonic was 2.9 amps. The FFT shows the harmonic spectrum out to 2 kHz, and the FFT shows current contribution from other frequencies. If the GFCI is only reacting on the fundamental frequency component this may explain why the GFCI did not trip.

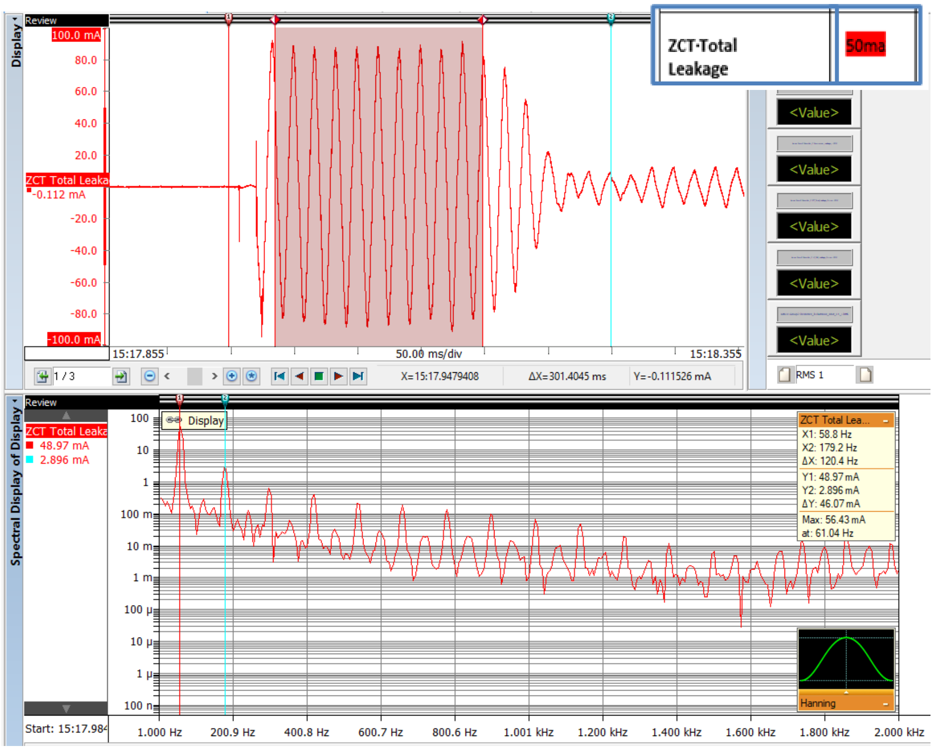


Figure 6-49
FFT of the Compressor Startup during the Nominal Cooling Cycle

Test 4 Defrost Cycle Test

HVAC manufacturers hypothesized that leakage current may differ when HVAC units are in the defrost mode. The manufacturer of Unit 1 provided a procedure to force the unit into defrost mode. The information below is a description of how the compressor was forced into defrost mode.

Figure 6-50 is a diagram of the defrost circuit board. The circuit board was reconfigured to forcibly enable defrost mode. To accomplish this, the unit was manually configured into **Test Mode**. The jumper was removed from the defrost termination pins and placed across the **TEST** pins thus applying 24 VAC to force defrost. Additionally, the Y1 input was turned on and a switch was attached to both the high-pressure switch and defrost thermostat terminals. By using these switches, it enabled test engineers to force defrost to initiate without entering the thermal chamber. It was then confirmed by the O-Out terminals that no power was applied to the reversing valve. This procedure was conducted as per the defrost system instructions provided in the installation manual.

Once the above was completed, the switch connected to the high-pressure switch was flipped to “closed” and the switch for the defrost terminal was flipped and held for 3 seconds to initiate a force defrost. After 3 minutes of active defrost, the high-pressure switch was positioned back to open ending the test.

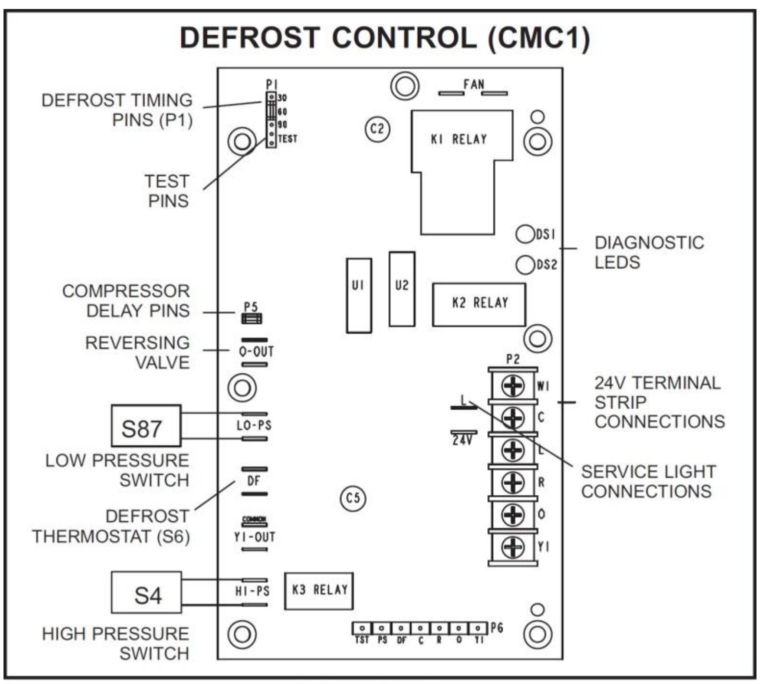


FIGURE 15

Figure 6-50
Defrost Control Circuit Board Connections from Manual

The defrost test was conducted when the thermal chambers were configured in Temperature condition 3 as shown in Table 6-3 of this report. The relative humidity of the outdoor chamber was 38%.

Figure 6-51 shows the waveforms for the entire defrost test. The figure shows the system was placed into defrost mode 5 times within the one and half hour test. This section of the report shows the detailed comparison of all the leakage current measurements for the application of power, the first time the outdoor unit started, and the first defrost cycle. **Error! Reference source not found.** shows all the leakage currents measured during the first defrost cycle, while **Error! Reference source not found.** shows all the current measurements from the Z-CT when the outdoor unit starts and during defrost mode for the remaining 4 defrost cycles.

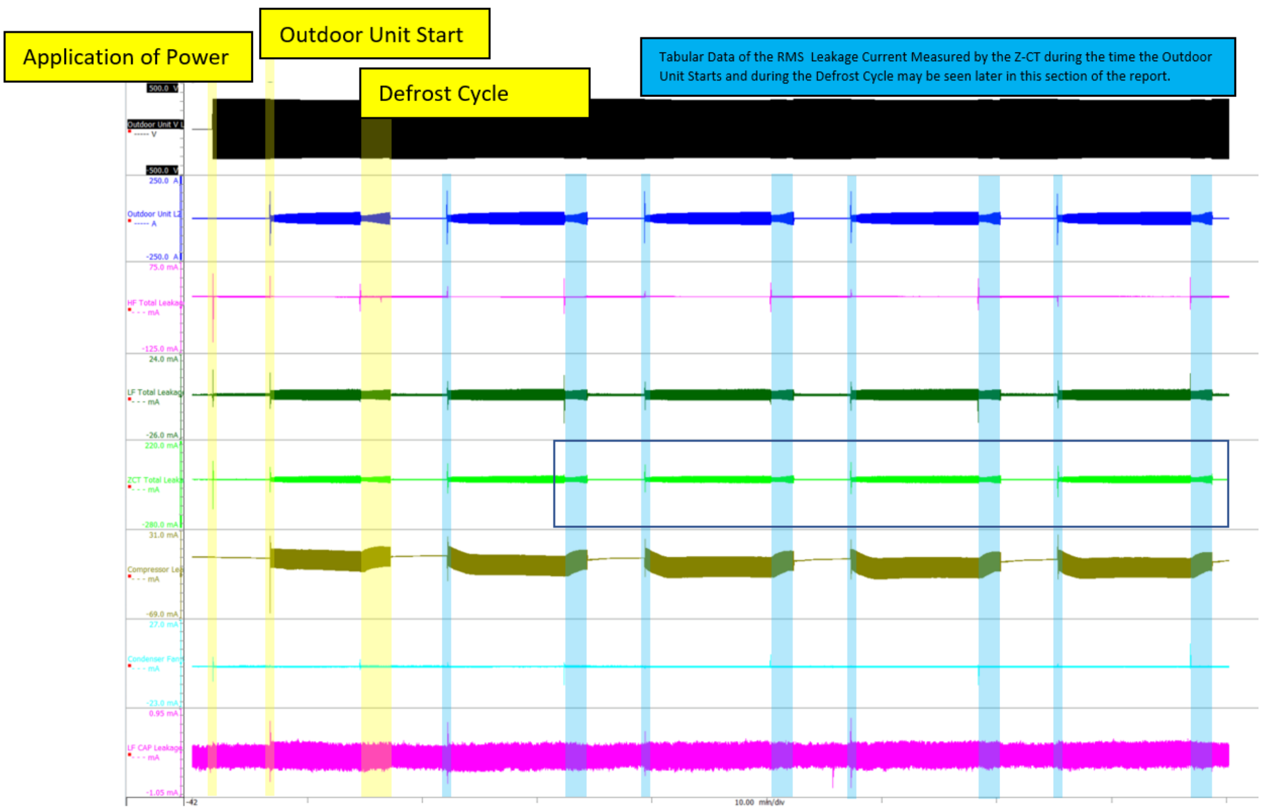


Figure 6-51
Defrost Test, File 104

Figure 6-52 shows the voltage, current, and leakage current at strategic locations throughout the outdoor unit when power was applied. The statistics for all the leakage currents are shown to the right of the waveforms. A table of all the leakage current measurements for the first defrost cycle may be seen in **Error! Reference source not found.**.

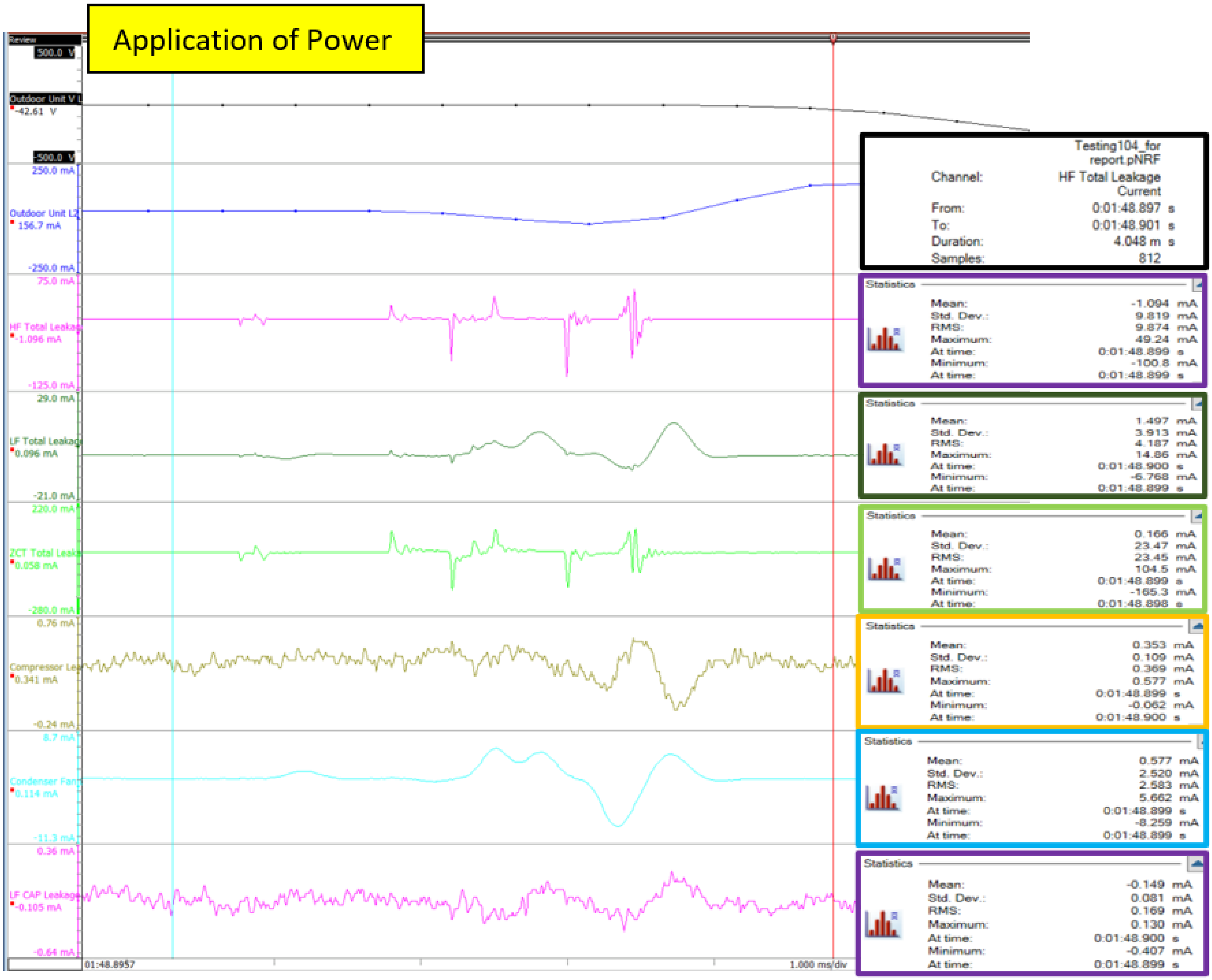


Figure 6-52
Application of Power Leakage Current Waveforms

Figure 6-53 shows the voltage, current, and leakage current at strategic locations throughout the outdoor unit when the outdoor unit start (compressor energizes). The statistics for all the leakage currents are shown to the right of the waveforms. A table of all the leakage current measurements for the first defrost cycle may be seen in **Error! Reference source not found.**.

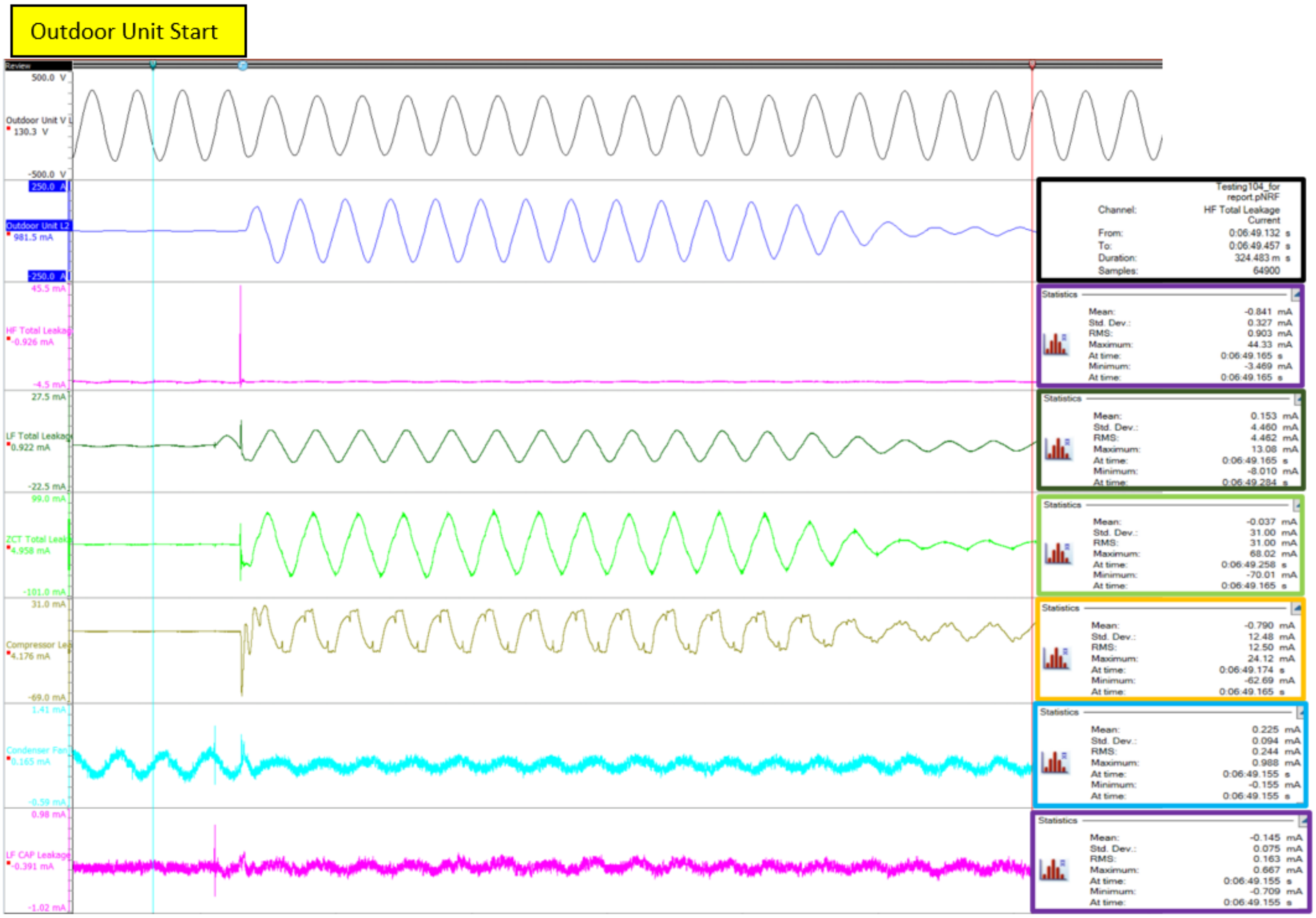


Figure 6-53
Outdoor Unit Starts Leakage Current Waveforms

Figure 6-54 shows the voltage, current, and leakage current at strategic locations throughout the outdoor unit during the defrost cycle. The statistics for all the leakage currents are shown to the right of the waveforms. A table of all the leakage current measurements for the first defrost cycle may be seen in **Error! Reference source not found.**.

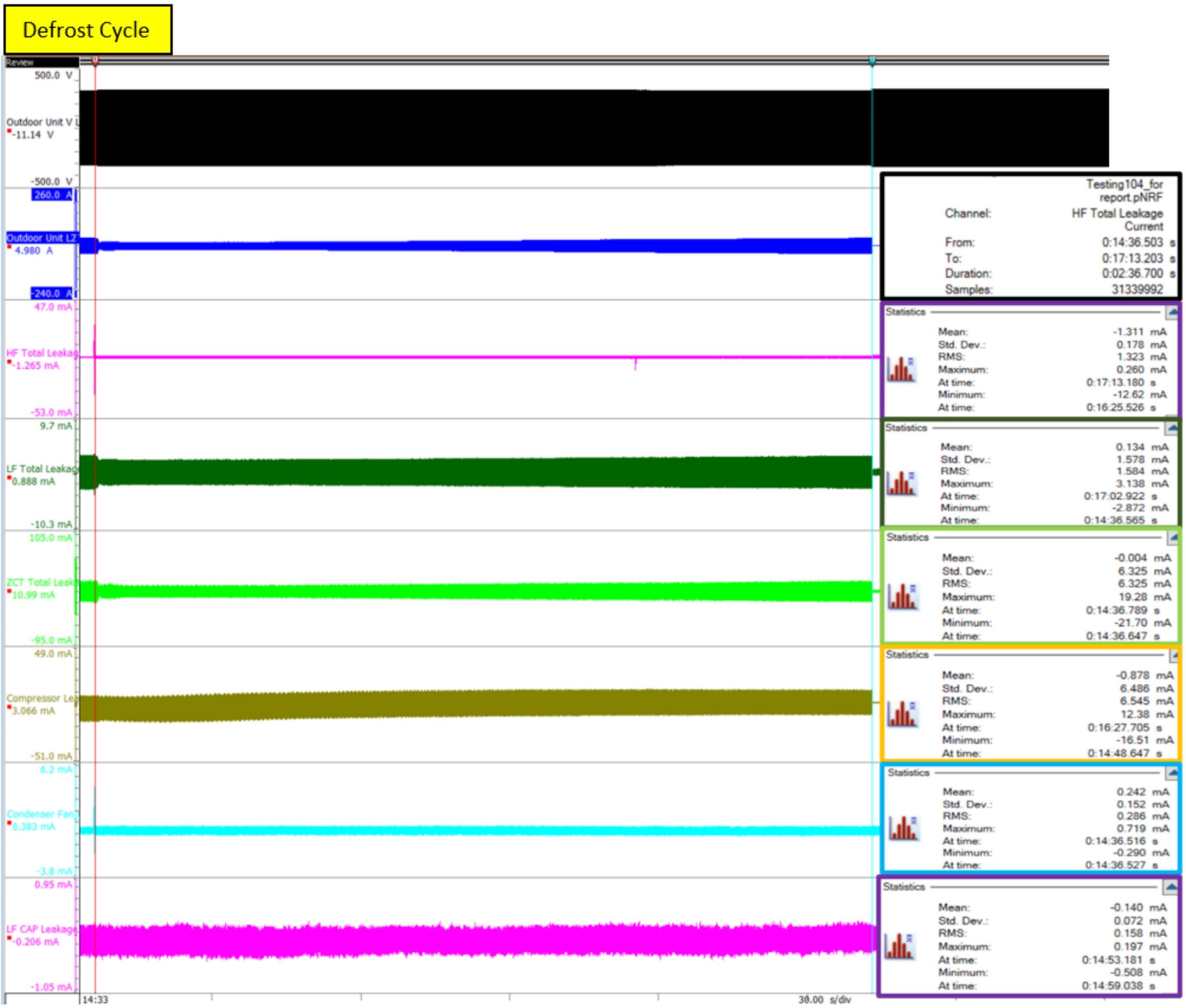


Figure 6-54
Defrost Cycle Leakage Current Measurements

Table 6-19
Leakage Currents for 1st Defrost Mode

Note: All measurements are represented as RMS	Application of Power		Compressor Start		Defrost Cycle		
Measurement Time Base	1 ms/div		50 ms/div		30 s/div		
RMS Measurement Time	4.0 ms		324 ms		2 min 37 sec		
UL 943 Limit	**950 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	23 mA	Yes	31 mA	Yes	6.3 mA	No	No
Compressor Leakage	0.4 mA	Yes	13 mA	Yes	6.5 mA	No	No
Condenser Fan	2.6 mA	Yes	0.2 mA	Yes	0.3 mA	Yes	No
Capacitor	0.2 mA	Yes	0.2 mA	Yes	0.2 mA	Yes	No
HF Probe Ground Conductor	9.9 mA	Yes	0.9 mA	Yes	1.3 mA	Yes	No
LF Probe Ground Conductor	4.2 mA	Yes	4.5 mA	Yes	1.6 mA	Yes	No

Note: The current probes attached to the Z-CT and the Compressor measured above 6ma by only a couple tenths of an amp.

The results of the final four measurements were similar; therefore, a detailed analysis of the waveforms was not supplied in this report. The leakage current measurements when the compressor starts and during the defrost cycle are shown in **Error! Reference source not f ound.**.

Table 6-20
Leakage Current Measurements from Z-CT for every Defrost Cycle

Note: All measurements are represented as RMS	**Compressor Start**		**Defrost Cycle**		
Measurement Time Base	50 ms/div		30 s/div		
RMS Measurement Time	324-328 ms		2 min 0 sec- 2 min 37 sec		
UL 943 Limit	**44 mA**	**Within UL 943 Current/Time Limits?**	**6 mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
Defrost Cycle 1	31 mA	Yes	6.3 mA	No	No
Defrost Cycle 2	37 mA	Yes	6.3 mA	No	No
Defrost Cycle 3	35 mA	Yes	6.5 mA	No	No
Defrost Cycle 4	33 mA	Yes	6.5 mA	No	No
Defrost Cycle 5	33 mA	Yes	6.5 mA	No	No

Note: The current probes attached to the Z-CT and the Compressor measured above 6 mA by only a couple of tenths of a milliamp.

Test 4 Conclusion

The purpose of the HVAC Defrost Cycle test: to identify the power profile and leakage current when the HVAC system transitioned to and during a defrost cycle. The system was permitted to operate through five defrost cycles. A data file was recorded throughout the 1.5-hour measurement period. The defrost cycle was enabled for 2 minutes for each of the 5 times the test was executed. **Error! Reference source not found.** shows the leakage current was just a bove the maximum allowable leakage current for the measurement time period as dictated by UL 943. The maximum leakage current occurred when the compressor started; however, the current was significantly lower than the maximum allowable time period dictated by UL 943. Therefore, the data shows that leakage current during defrost mode may not be the cause of nuisance tripping of GFCI circuit breakers—as with the previous tests, *the GFCI circuit breaker did not trip for any of the tests.*

Test 5 Voltage Interruption Test

HVAC systems are installed in real-world residential and commercial power systems. These systems may experience interruptions in voltage as well as voltage sags that may cause internal components such as relays and contactors to open. Depending on the topology of the system, the compressor may experience a low-impedance interruption—as if the compressor is connected to the secondary of the power transformer feeding the load, or a high-impedance interruption or open circuit condition should a contactor isolate the compressor from the power system. The hypothesis is that the leakage current may differ when voltage interruptions occur between the two conditions. The tests were conducted when the outdoor unit was subjected to thermal conditions 2 and 3 as shown in **Error! Reference source not found.**. **Error! Re ference source not found.** shows the leakage current for each of the tests.

Table 6-21
Tabular Data from Voltage interruption Test

Type Of Interruption	Thermal Temperature Condition	Z-CT Measured Leakage Current (mA RMS) / time	Notes	Outdoor Chamber Humidity
Low Impedance	**2**	Power Applied 6 mA/6 ms Compressor Start 44 mA/328 ms Unit Running 6.8 mA/7 min 8 sec	The highest leakage current was measured when the test was conducted under thermal condition 3. The GFCI did not trip during these tests	24%
High Impedance	**2**	Power Applied 6 mA/5 ms Compressor Start 44 mA/326 ms Unit Running 6.6 mA/2 min 45 sec		
Low Impedance	**3**	Power Applied 7.2 mA/5 ms Compressor Start 29 mA/329 ms Unit Running 7.9 mA/8 min 23 sec		39%
High Impedance	**3**	Power Applied 7.3 mA/4 ms Compressor Start 30 mA/325 ms Unit Running 8.1 mA/10 min 23 sec		

Temperature Condition 2 Tests

Low Impedance Interruption Test

Figure 6-55 shows the waveforms for the low-impedance interruption test while the thermal chambers were configured in Condition 2 as shown in **Error! Reference source not found.**. REF _Ref149288457 \h Figure 6-55 shows where the voltage interruption was executed, the outdoor unit started (compressor energized), and the period of time where the outdoor unit was permitted to run. The leakage current during these time periods were analyzed and are discussed in this section of the report. *Note: in all the charts, a value appears at left under the name of the leakage current being measured. This is an artifact showing the value registered at the location of the red cursor which may or may not be visible in the chart. This value has no relevance to the measurements of concern.*

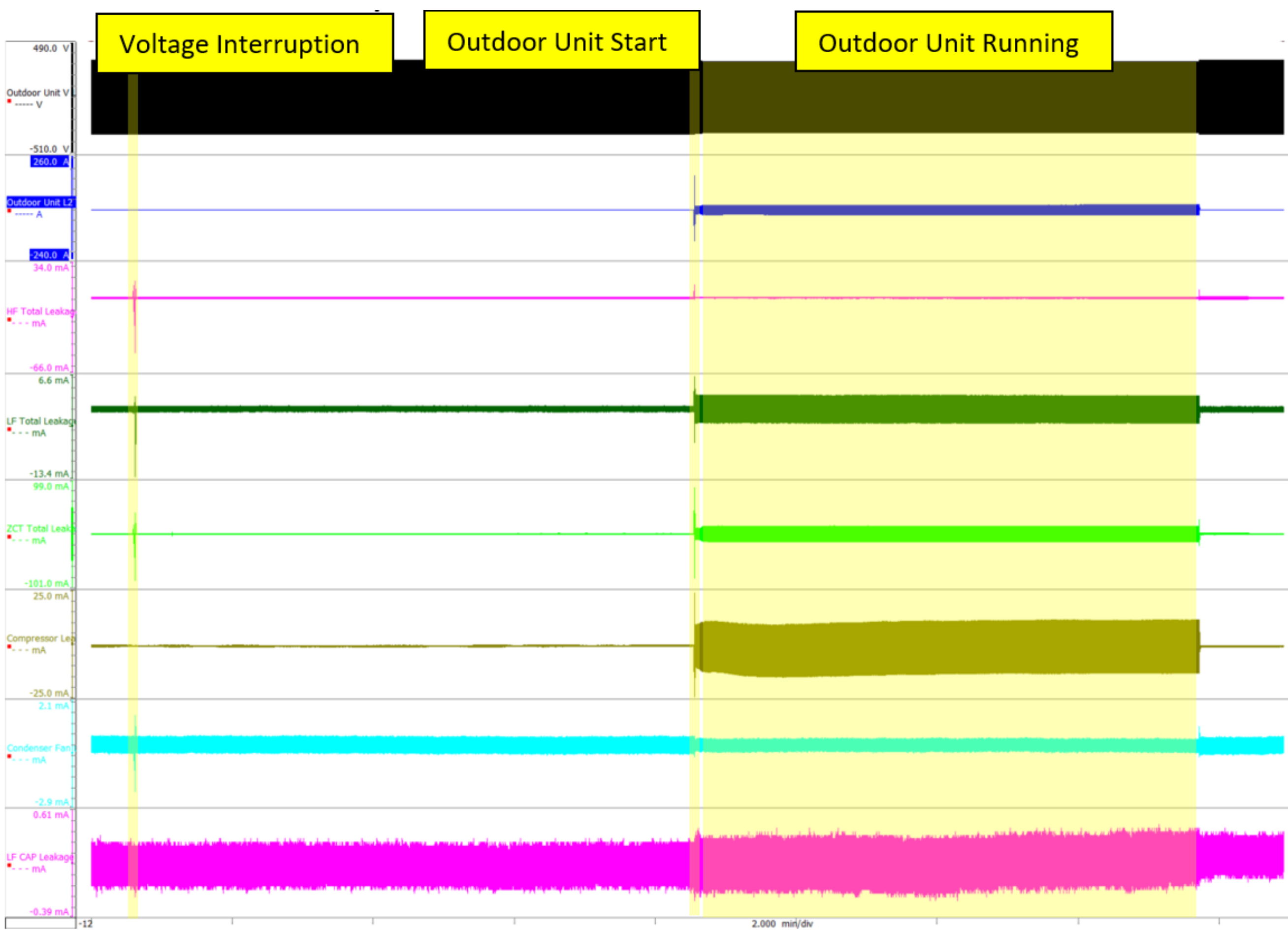


Figure 6-55
Chamber Condition 2, Lowe-Impedance-Interruption, File 96

Figure 6-56 shows the 1-second voltage interruption event and the leakage current that resulted when the voltage returned after the interruption. The waveforms in the red outline show the 1-ms time period when voltage was applied after the 1-second interruption. The statistical data shown to the right of the waveforms is associated with the waveforms and time period within the red box. The 200-ms/division waveform is shown to draw attention to the voltage waveform in order to show that a low impedance voltage interruption creates a crisp transition from full nominal voltage to 0 volts. The high impedance interruption creates a different transition that will be shown in the next section. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

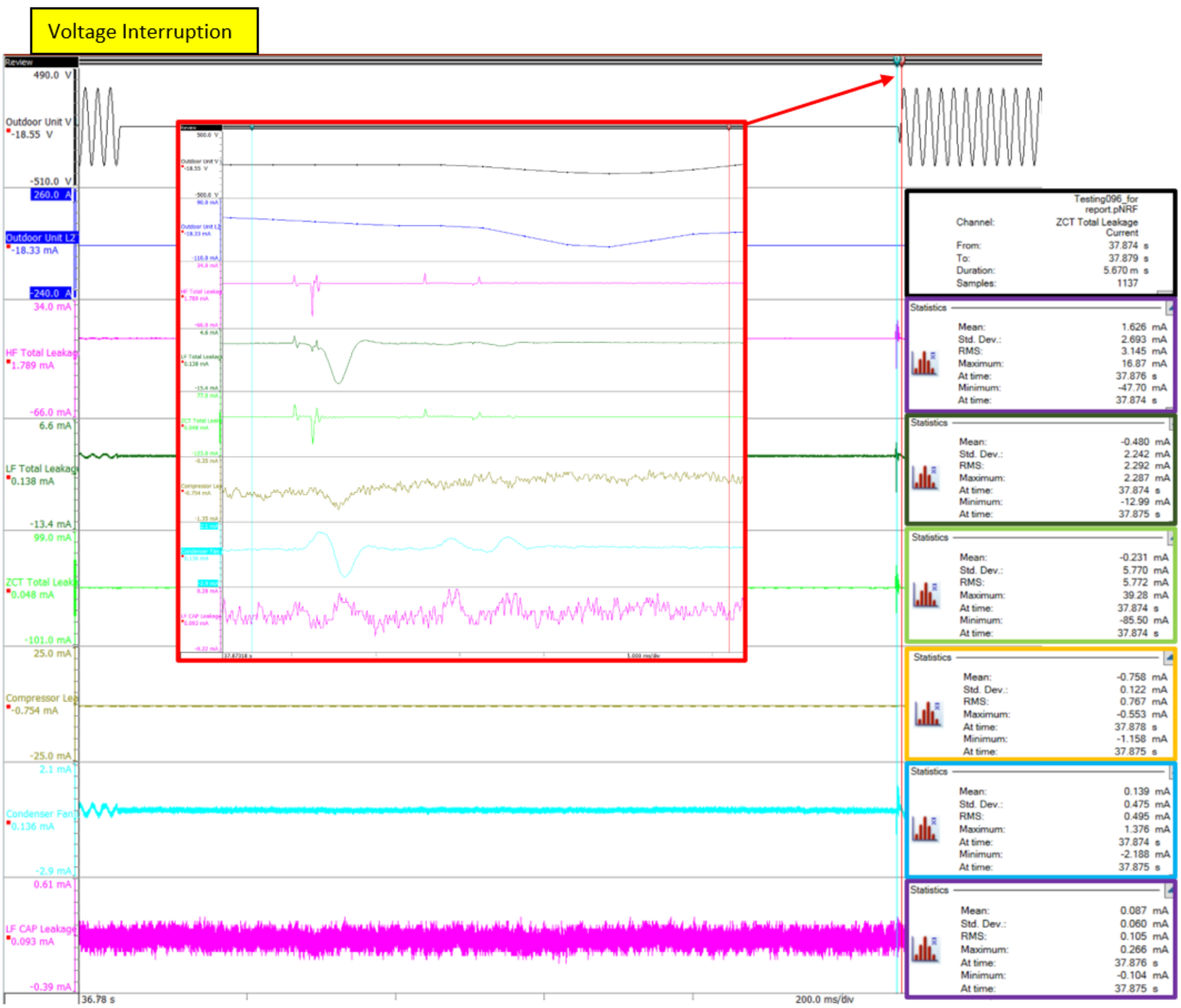


Figure 6-56
1-second Voltage Interruption

Figure 6-57 shows the waveforms during the period where the outdoor unit starts, or when the compressor energizes. During this time period there is a significant inrush when the compressor starts. The leakage current from the Z-CT increases as the line current increases as seen in Figure 6-57. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

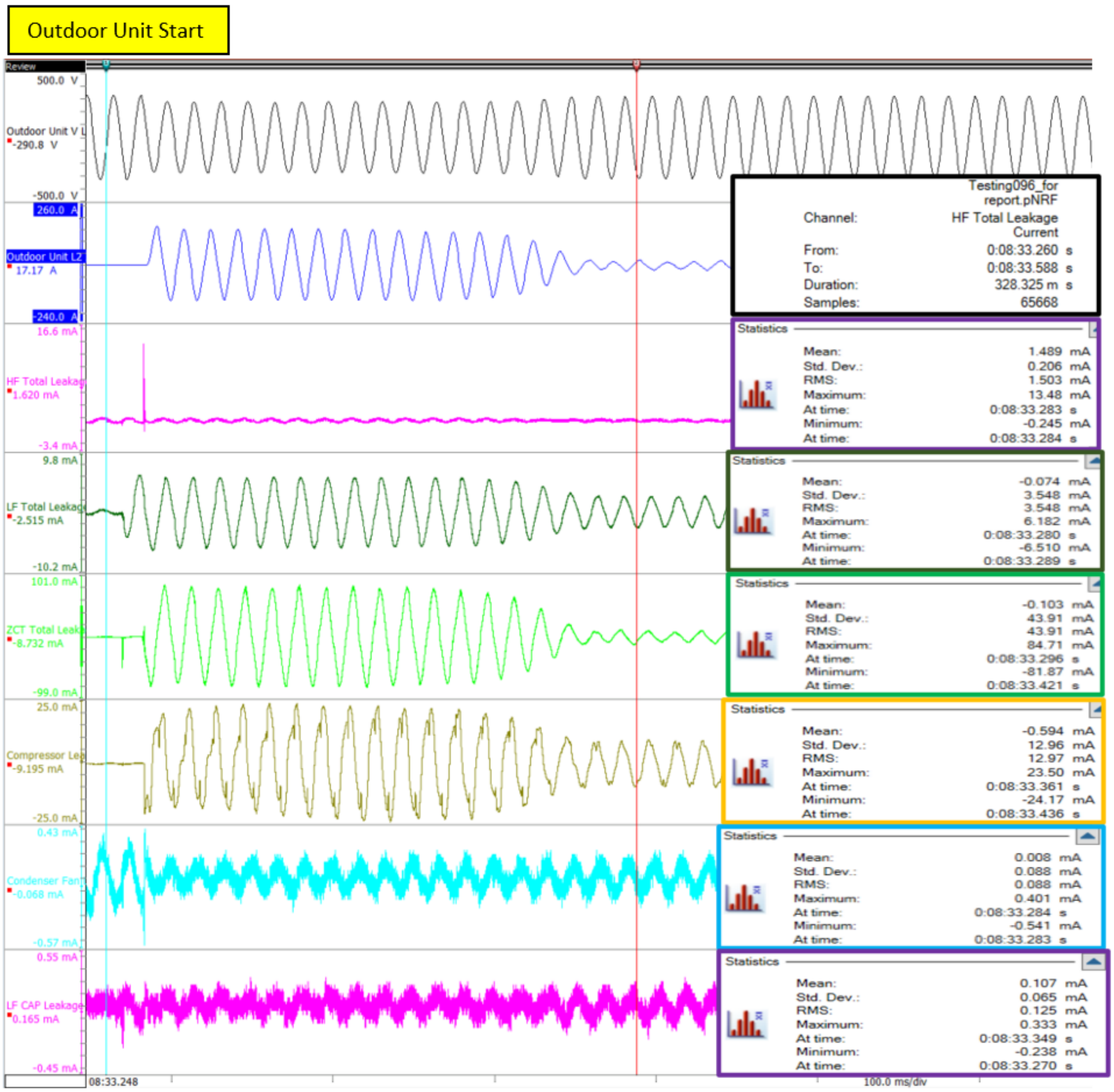


Figure 6-57
Maximum Leaking Current When Compressor Starts

Figure 6-58 shows the waveforms during the period where the outdoor unit was running nominally. During this time period the leakage current was significantly lower than when the compressor started. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

Figure 6-58
Leakage Current When Outdoor Unit is Operating

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the low impedance interruption test. The measurements when the voltage returned after the interruption, the outdoor unit started, and a period after the compressor started and the unit operated nominally was monitored and recorded. The leakage RMS leakage measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the RMS current measured by the Z-CT during the outdoor running time period was 0.8 mA above the RMS current limitations of UL 943 The reason for this phenomenon is the RMS current may be a combination of fundamental and higher order frequency components. The GFCI may only respond to the fundamental current. An FFT of the current measured by the Z-CT is shown in Figure 6-71 at the end of this section of the report.

Table 6-22
Tabular Data from the Low Impedance Interruption Test

Note: All measurements are represented as RMS	**Application of Power**		**Compressor Start**		**Outdoor Unit Running**		
Measurement Time Base	1 ms/div		100 ms/div		2 min/div		
RMS Measurement Time	6 ms		328 ms		7 min 8 sec		
UL 943 Limit	**715 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	5.7 mA	Yes	44 mA	Yes	6.8 mA	No	No
Compressor Leakage	0.8 mA	Yes	13 mA	Yes	6.9 mA	No	No
Condenser Fan	0.5 mA	Yes	0.1 mA	Yes	0.1 mA	Yes	No
Capacitor	0.3 mA	Yes	0.1 mA	Yes	0.1 mA	Yes	No
HF Probe Ground Conductor	3.1 mA	Yes	1.5 mA	Yes	1.4 mA	Yes	No
LF Probe Ground Conductor	2.3 mA	Yes	3.5 mA	Yes	1.7 mA	Yes	No

High Impedance Interruption Test

Figure 6-59 shows the waveforms for the high-impedance interruption test while the thermal chambers were configured in Condition 2 as shown in **Error! Reference source not found.**. REF _Ref149288627 \h Figure 6-59 shows where the voltage interruption was executed, the outdoor unit started (compressor energized), and the period of time where the outdoor unit was permitted to run. The leakage current during these time periods were analyzed and discussed in this section of the report.

Figure 6-59
Chamber Condition 2, High-impedance Interruption, File 97

Figure 6-60 shows the 1-second voltage interruption event and the leakage current that resulted when the voltage returned after the interruption. The waveforms in the red outline show the 1-ms time period when voltage was applied after the 1-second interruption. The statistical data shown to the right of the waveforms is associated with the waveforms and time period within the red box. The 200-ms/division waveform is shown to draw attention to the voltage waveform in order to show that a high impedance voltage interruption creates a ringing effect due to the back electromotive force (EMF) when transitioning from full nominal voltage to 0 volts. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.** shows all the tabular measurement data for the RMS leakage current measured during the high impedance interruption test. The measurements when the voltage returned after the interruption, when the outdoor unit started, a period after the compressor started, and when the unit operated nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the Z-CT RMS current during the outdoor running time period was 0.6 mA above the RMS current limitations of UL 943 The reason for this phenomenon may be the RMS current may be a combination of fundamental and higher order frequency components. The GFCI may only respond to the fundamental current. An FFT of the current measured by the Z-CT is shown in Figure 6-71.

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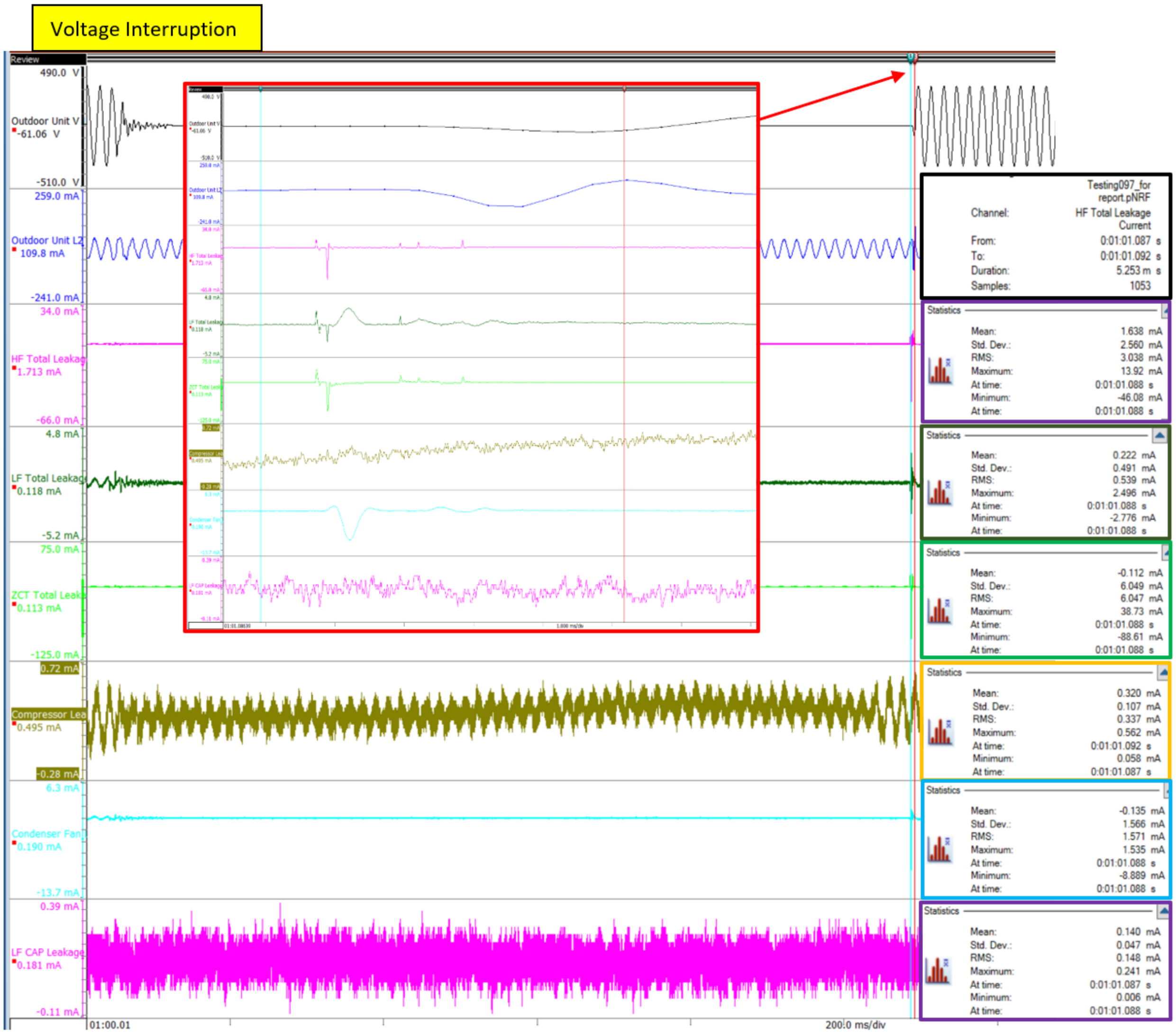

Figure 6-60
One-second Interruption

Figure 6-61 shows the waveforms during the period where the outdoor unit starts, or when the compressor energizes. During this time period there is a significant inrush when the compressor starts. The leakage current from the Z-CT increases as the line current increases as seen in Figure 6-61. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.** shows all the tabular measurement data for the RMS leakage current measured during the high impedance interruption test. The measurements when the voltage returned after the interruption, when the outdoor unit started, a period after the compressor started, and when the unit operated nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the Z-CT RMS current during the outdoor running time period was 0.6 mA above the RMS current limitations of UL 943 The reason for this phenomenon may be the RMS current may be a combination of fundamental and higher order frequency components. The GFCI may only respond to the fundamental current. An FFT of the current measured by the Z-CT is shown in Figure 6-71.

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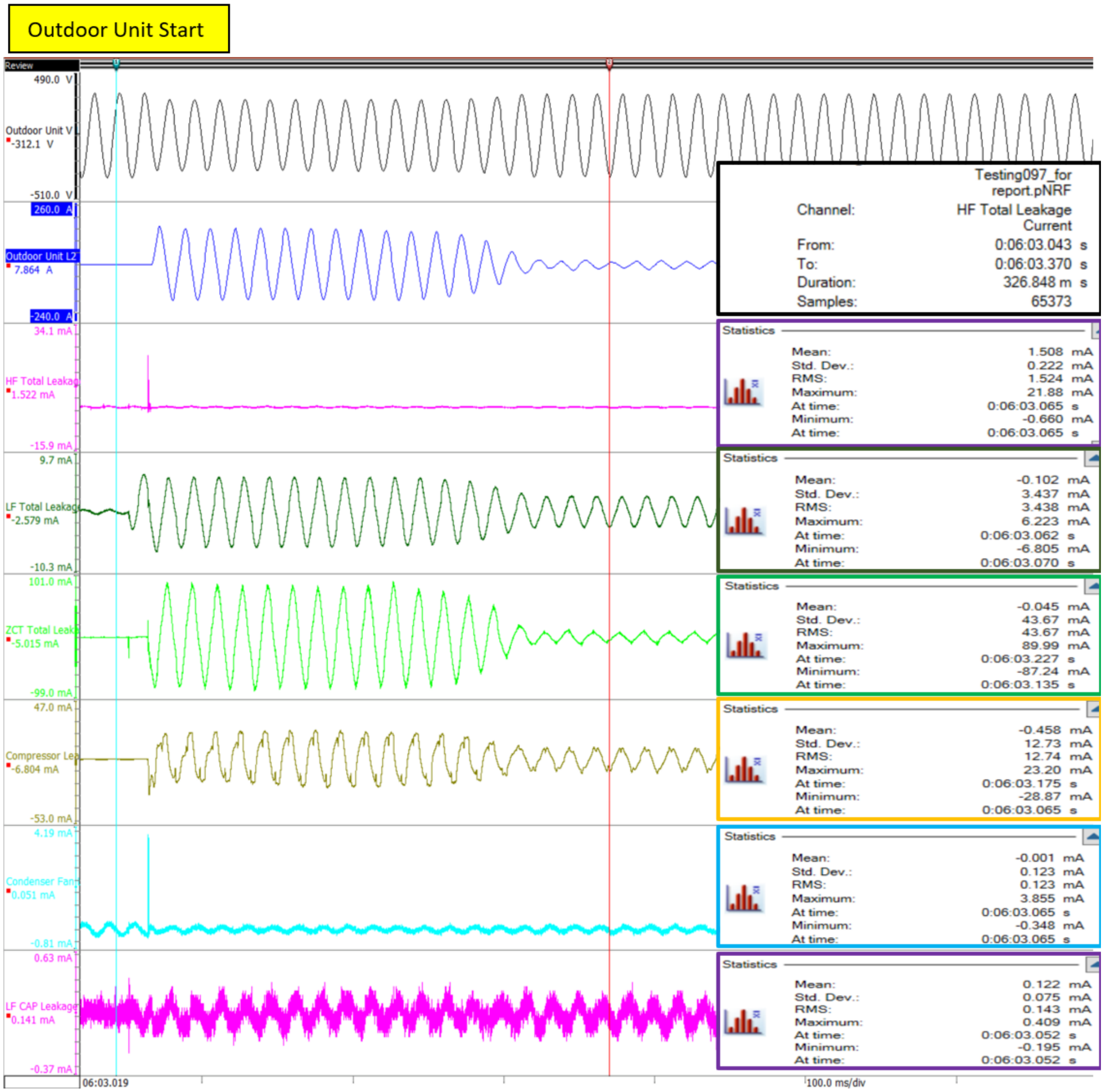

Figure 6-61
Chamber Condition 2, Compressor Start

Figure 6-62 shows the waveforms during the period where the outdoor unit was running nominally. During this time period the leakage current was significantly lower than when the compressor started although the leakage current measured by the Z-CT is slightly above the limits in UL 943. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.** shows all the tabular measurement data for the RMS leakage current measured during the high impedance interruption test. The measurements when the voltage returned after the interruption, when the outdoor unit started, a period after the compressor started, and when the unit operated nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the Z-CT RMS current during the outdoor running time period was 0.6 mA above the RMS current limitations of UL 943 The reason for this phenomenon may be the RMS current may be a combination of fundamental and higher order frequency components. The GFCI may only respond to the fundamental current. An FFT of the current measured by the Z-CT is shown in Figure 6-71.

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Outdoor Unit Running

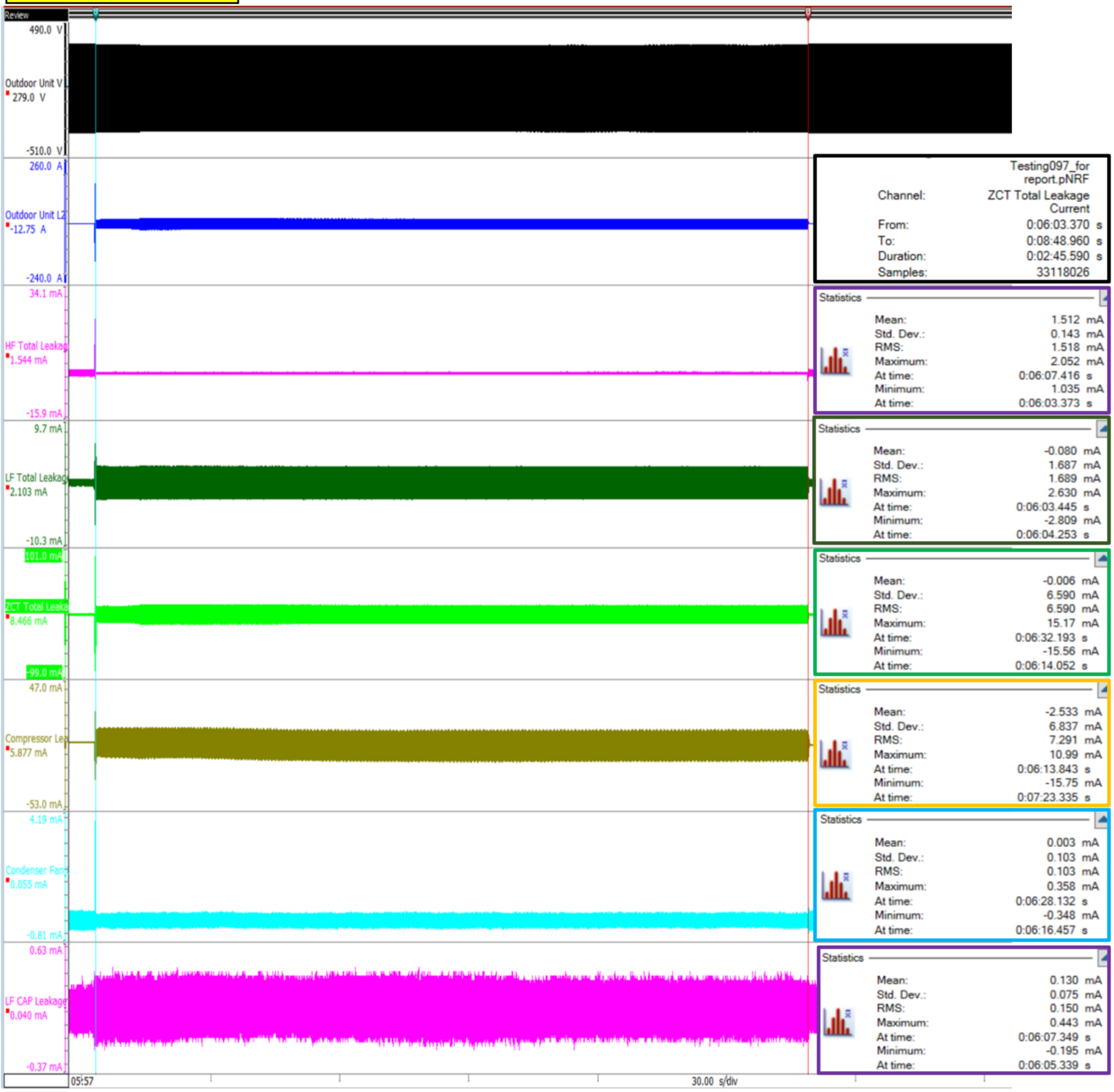


Figure 6-62
Chamber Condition 2 Outdoor Unit Running

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the high impedance interruption test. The measurements when the voltage returned after the interruption, when the outdoor unit started, a period after the compressor started, and when the unit operated nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the Z-CT RMS current during the outdoor running time period was 0.6 mA above the RMS current limitations of UL 943 The reason for this phenomenon may be the RMS current may be a combination of fundamental and higher order frequency components. The GFCI may only respond to the fundamental current. An FFT of the current measured by the Z-CT is shown in Figure 6-71.

Table 6-23
Tabular Data from the High Impedance Interruption Test

Note: All measurements are represented as RMS	**Application of Power**		**Compressor Start**		**Outdoor Unit Running**		
Measurement Time Base	1 ms/div		100 ms/div		2 min/div		
RMS Measurement Time	5 ms		326 ms		2 min 45 sec		
UL 943 Limit	**813 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	6 mA	Yes	44 mA	Yes	6.6 mA	No	No
Compressor Leakage	0.3 mA	Yes	13 mA	Yes	7.3 mA	No	No
Condenser Fan	1.6 mA	Yes	0.1 mA	Yes	0.1 mA	Yes	No
Capacitor	0.1 mA	Yes	0.1 mA	Yes	0.2 mA	Yes	No
HF Probe Ground Conductor	3.0 mA	Yes	1.5 mA	Yes	1.5 mA	Yes	No
LF Probe Ground Conductor	0.5 mA	Yes	3.4 mA	Yes	1.7 mA	Yes	No

Temperature Condition 3 Tests

Low Impedance Interruption Test

Figure 6-63 shows the waveforms for the low-impedance interruption test while the thermal chambers were operating under condition 3 shown in **Error! Reference source not found.**.
 REF _Ref149289019 \h Figure 6-63 shows where the voltage interruption was executed, the outdoor unit started (compressor energized), and the period of time where the outdoor unit was permitted to run. The leakage current during these time periods were analyzed and are discussed in this section of the report.

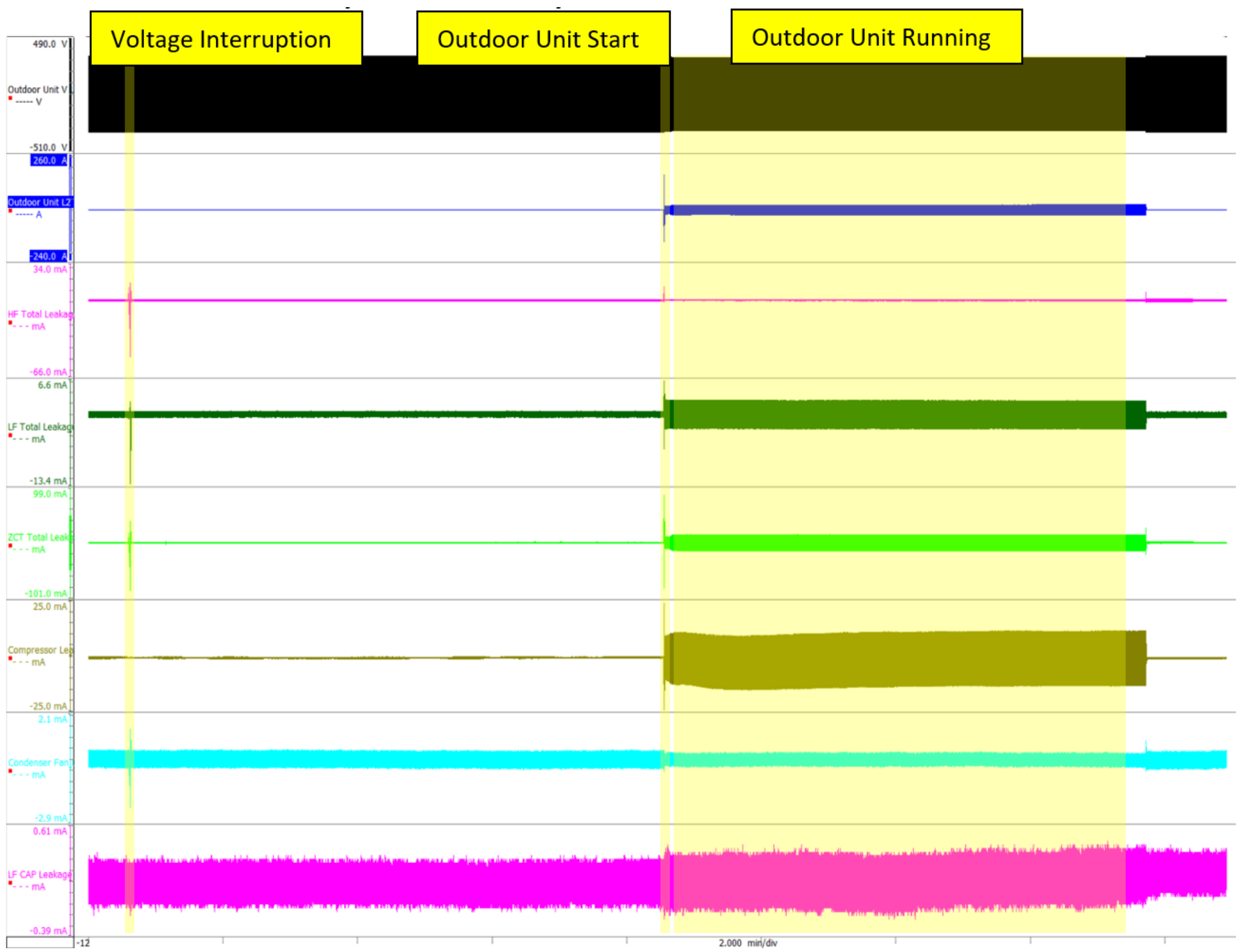


Figure 6-63
Chamber Condition 3, Low-impedance Interruption

Figure 6-64 shows the 1-second voltage interruption event and the leakage current that resulted when the voltage returned after the interruption. The waveforms in the red outline show the 1-ms time period when voltage was applied after the 1-second interruption. The statistical data shown to the right of the waveforms is associated with the waveforms and time period within the red box. The 200-ms/division waveform is shown to draw attention to the voltage waveform in order to show that a low impedance voltage interruption creates a crisp transition from full nominal voltage to 0 volts. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

Figure 6-64
One-second Interruption

Figure 6-65 shows the waveforms during the period where the outdoor unit starts, or when the compressor energizes. During this time period there is a significant inrush when the compressor starts. The leakage current from the Z-CT increases as the line current increases as seen in Figure 6-65. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

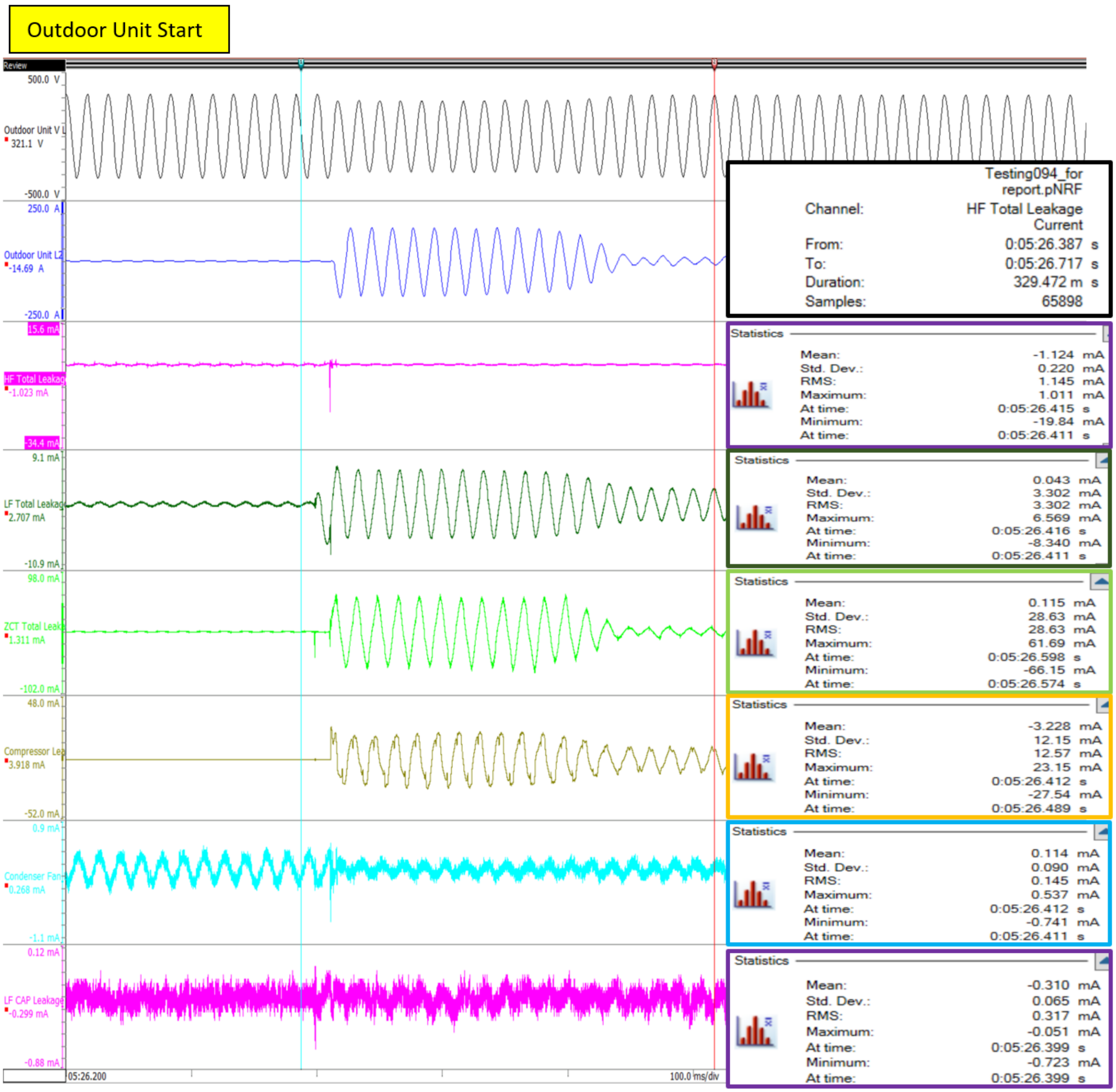


Figure 6-65
Leakage Current at Compressor Start

Figure 6-66 shows the waveforms during the period where the outdoor unit was running nominally. During this time period the leakage current was significantly lower than when the compressor started; however, the Z-CT measured leakage current values greater than the acceptable limits of UL 943. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

Figure 6-66
Leakage Current When Outdoor Unit is Running

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the low impedance interruption test. The measurements when the voltage returned after the interruption, the outdoor unit started, and a period after the compressor started and the unit operated nominally was monitored and recorded. The leakage RMS leakage measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the Z-CT RMS current during the outdoor running time period was 1.9 mA above the RMS current limitations of UL 943 The reason for this phenomenon may be the RMS current may be a combination of fundamental and higher-order frequency components. The GFCI may only respond to the fundamental current.

Table 6-24
Tabular Data from the Low Impedance Interruption Test

Note: All measurements are represented as RMS	**Application of Power**		**Compressor Start**		**Outdoor Unit Running**		
Measurement Time Base	1 ms/div		100 ms/div		2 min/div		
RMS Measurement Time	5 ms		329 ms		8 min 23 sec		
UL 943 Limit	**813 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	7.2 mA	Yes	29 mA	Yes	7.9 mA	No	No
Compressor Leakage	14 mA	Yes	13 mA	Yes	14.1 mA	No	No
Condenser Fan	0.5 mA	Yes	0.1 mA	Yes	0.2 mA	Yes	No
Capacitor	0.3 mA	Yes	0.3 mA	Yes	0.3 mA	Yes	No
HF Probe Ground Conductor	3.0 mA	Yes	1.1 mA	Yes	1.3 mA	Yes	No
LF Probe Ground Conductor	2.1 mA	Yes	3.3 mA	Yes	1.9 mA	Yes	No

High Impedance Interruption Test

Figure 6-67 shows the waveforms for the high-impedance interruption test while the thermal chambers were configured in Condition 3 as shown in **Error! Reference source not found.**. REF _Ref149289183 \h Figure 6-67 shows where the voltage interruption was executed, the outdoor unit started (compressor energized), and the period of time where the outdoor unit was permitted to run. The leakage current during these time periods were analyzed and discussed in this section of the report.

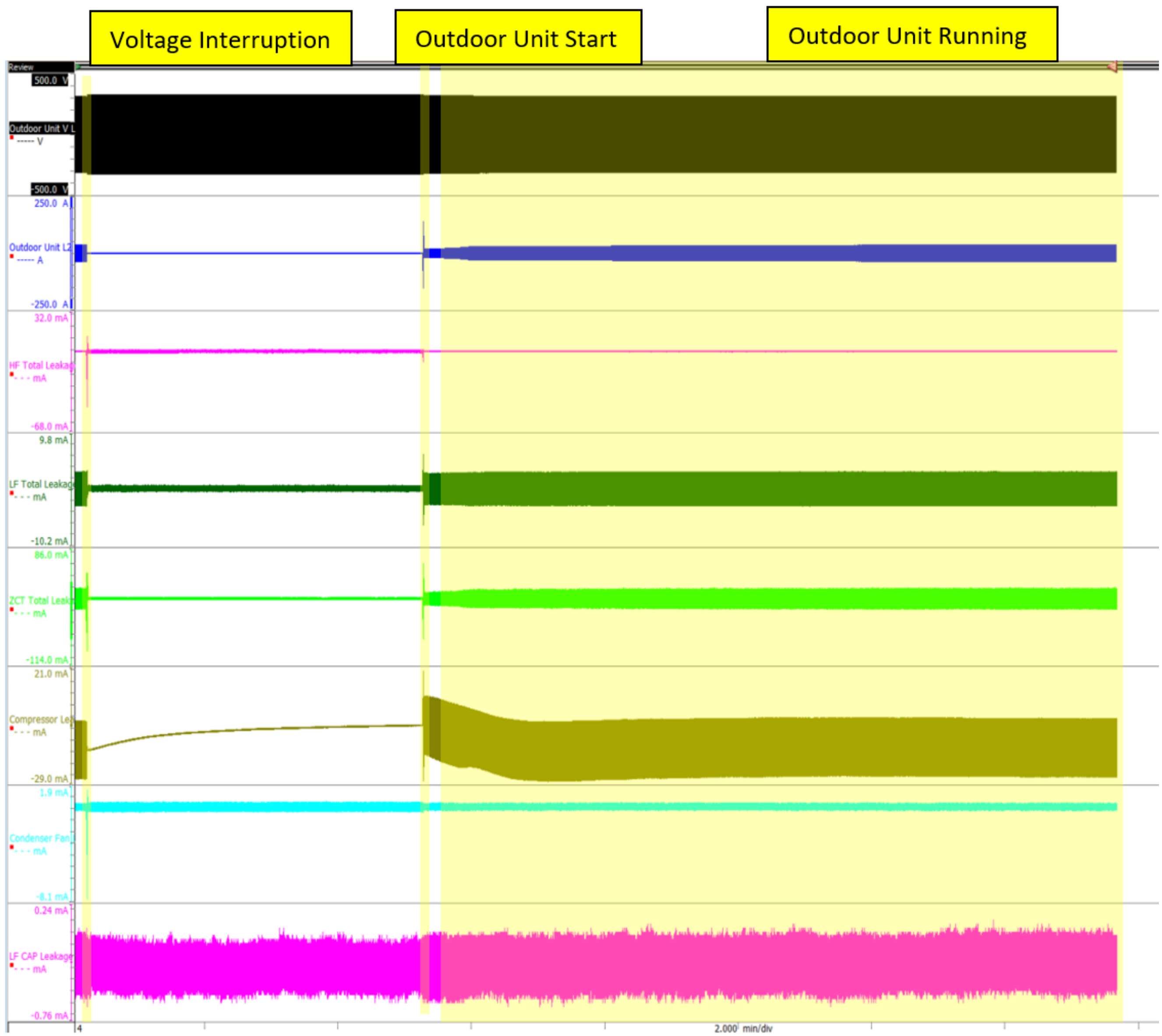


Figure 6-67
Chamber Condition 3, High-impedance Interruption

Figure 6-68 shows the 1-second voltage interruption event and the leakage current that resulted when the voltage returned after the interruption. The waveforms in the red outline show the 1-ms time period when voltage was applied after the 1-second interruption. The statistical data shown to the right of the waveforms is associated with the waveforms and time period within the red box. The 200-ms/division waveform is shown to draw attention to the voltage waveform in order to show that a high impedance voltage interruption creates a ringing effect due to the back electromotive force (EMF) when transitioning from full nominal voltage to 0 volts. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

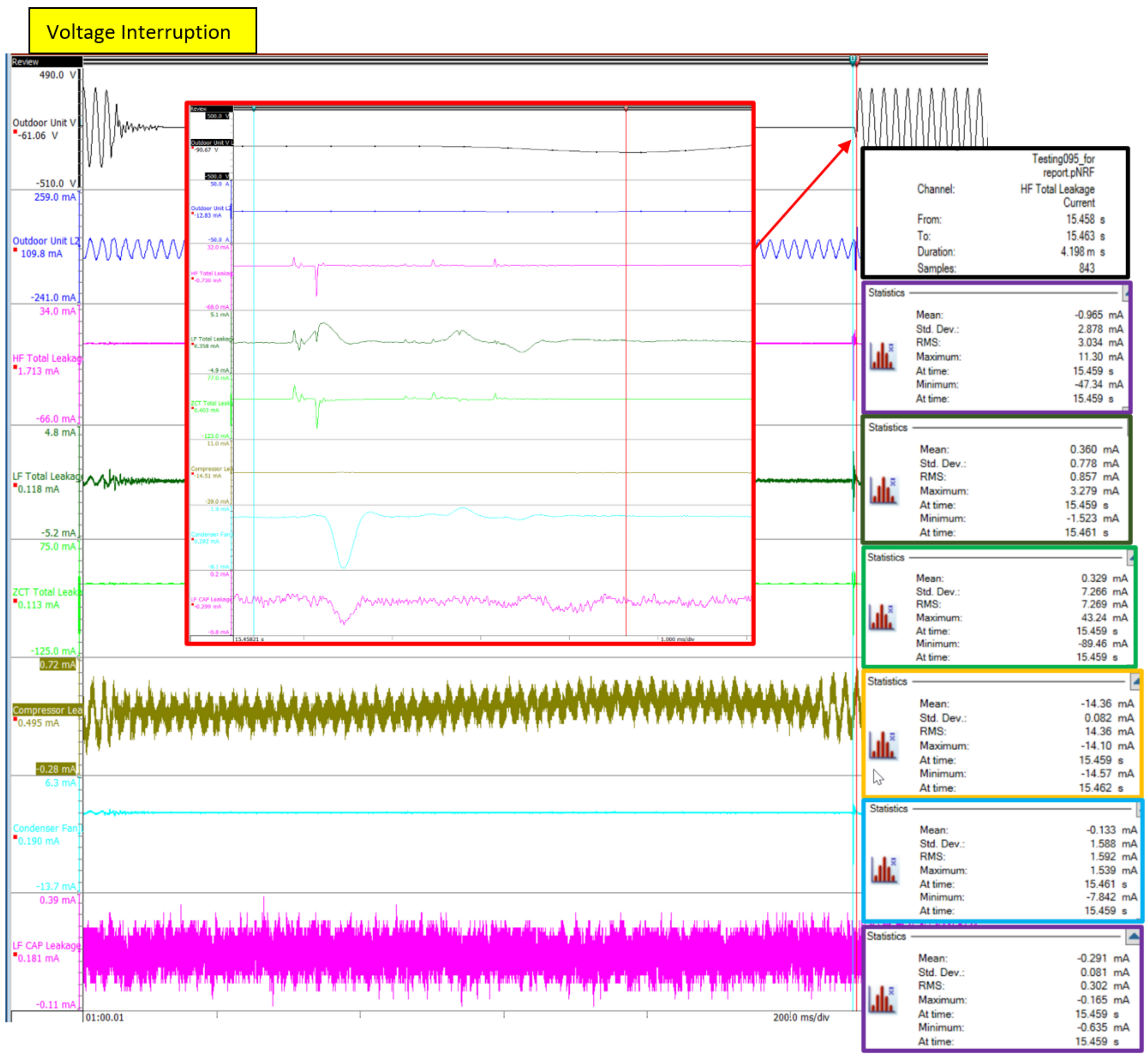


Figure 6-68
One-second Interruption

Figure 6-69 shows the waveforms during the period where the outdoor unit started, or when the compressor energized. During this time period there is a significant inrush when the compressor started. The leakage current from the Z-CT increased as the line current increased as seen in the figure below. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

Figure 6-69
Leakage Current at Compressor Start

Figure 6-70 shows the waveforms during the period where the outdoor unit was running nominally. During this time period the leakage current was significantly lower than when the compressor started. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

Figure 6-70
Leakage Current while the Outdoor Unit Running

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the high-impedance interruption test. The measurements when the voltage returned after the interruption, the outdoor unit started, and a period after the compressor started and the unit operated nominally was monitored and recorded. The RMS leakage measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the Z-CT RMS current during the outdoor running time period was 0.6 mA above the RMS current limitations of UL 943 The reason for this phenomenon may be the RMS current may be a combination of fundamental and higher order frequency components. The GFCI may only respond to the fundamental current, an FFT of the current measured by the Z-CT. An example may be seen in Figure 6-71 where the fundamental current measured 5.7 mA, the second harmonic measured 0.8 mA, and more RMS current was spread across other frequencies.

Table 6-25
Tabular Data from the High Impedance Interruption Test

Note: All measurements are represented as RMS	**Application of Power**		**Compressor Start**		**Outdoor Unit Running**		
Measurement Time Base	1 ms/div		100 ms/div		2 min/div		
RMS Measurement Time	4 ms		325 ms		10 min 23 sec		
UL 943 Limit	**950 mA**	**Within UL 943 Current/ Time Limits?**	**44 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	7.3 mA	Yes	30 mA	Yes	8.1 mA	No	No
Compressor Leakage	14 mA	Yes	13 mA	Yes	15 mA	No	No
Condenser Fan	1.6 mA	Yes	0.1 mA	Yes	0.2 mA	Yes	No
Capacitor	0.3 mA	Yes	0.3 mA	Yes	0.3 mA	Yes	No
HF Probe Ground Conductor	3.0 mA	Yes	1.1 mA	Yes	1.2 mA	Yes	No
LF Probe Ground Conductor	0.9 mA	Yes	3.4 mA	Yes	1.9 mA	Yes	No

Test 5 Conclusion

High- and low-impedance voltage interruptions were applied to the HVAC system while operating in temperature conditions 2 and 3 shown in **Error! Reference source not found.**. The m aximum leakage current for each test was observed when voltage returned after the one-second interruption of voltage was created and when the compressor started. The leakage current was only present for a few hundred micro-seconds at the return of the voltage; however, the leakage current was present for hundreds of milli-seconds when the compressor first started. None of the leakage current events resulted in the tripping of the GFCI.

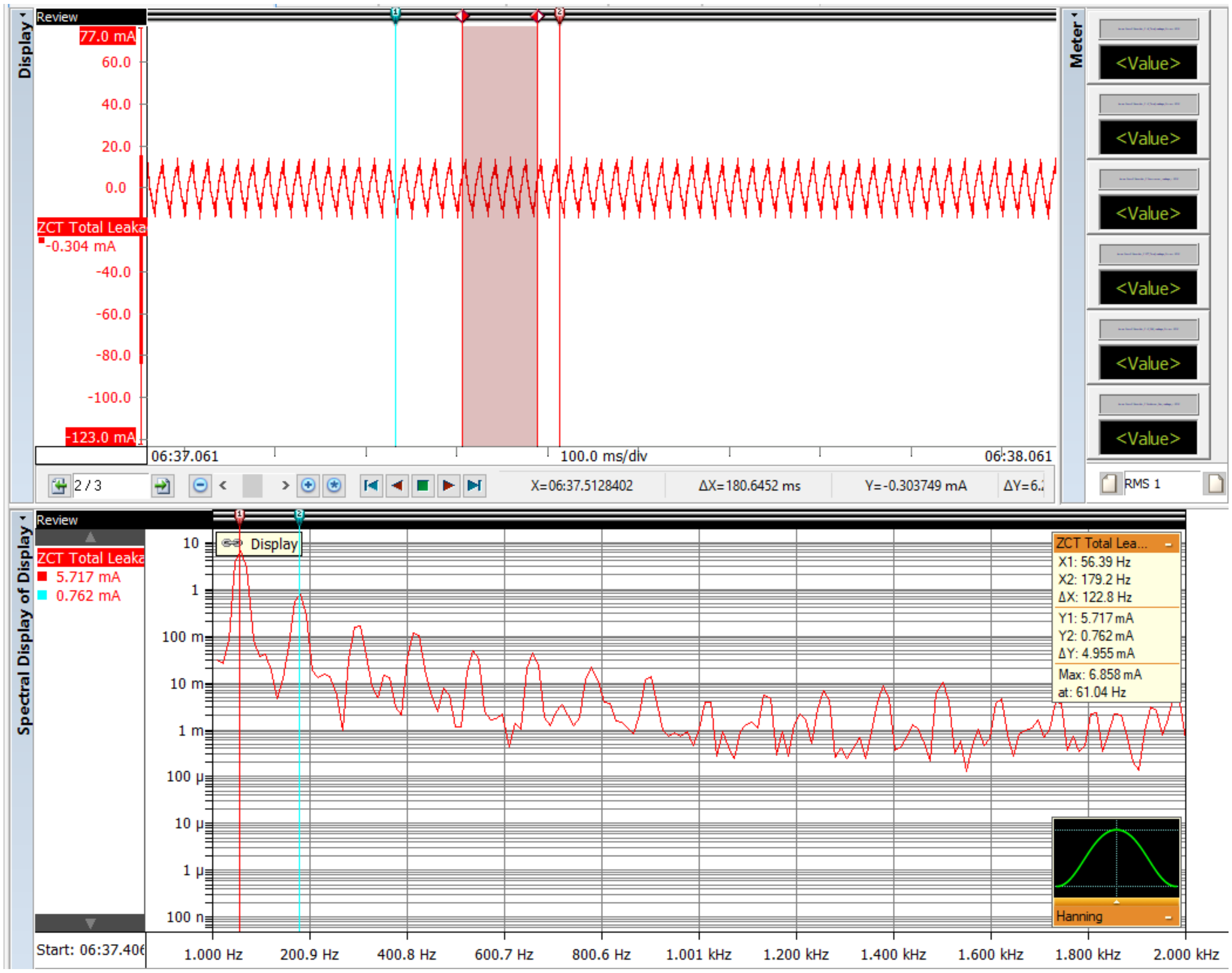


Figure 6-71
FFT of the Nominal Running Current

Test 6 High/Low Voltage Range Test

HVAC systems are installed in real-world residential and commercial power systems. As loading changes on the power grid, so may the nominal voltage. The purpose of this test is to investigate the response of the EUT when operating at the minimum and maximum "acceptable" voltage levels provided in the ANSI C84.1 standard. The test was conducted using a power amplifier to increase and decrease the nominal voltage to 86%, 90%, 95%, and 106%. **Error! Reference source not found.** shows the RMS leakage current measured by the Z-CT for e ach voltage level. All the RMS leakage currents for all the tests may be seen in **Error! Reference source not found.** at the end of this section.

Table 6-26
High/Low Voltage Range Test Maximum Leakage Current

High/Low Voltage Leakage Test	Thermal Temperature Condition	Z-CT Measured Leakage Current (mA) / time	Notes	Outdoor Chamber Humidity
106%	**2**	8.8 mA / 5 min 43 sec	The maximum leakage current ranged between 8.7 and 12 milliamps RMS across the testing. The RMS current was calculated during the 5 minutes the test was run. No GFCI tripping occurred during this test.	23%
95%		12 mA / 4 min 50 sec		
90%		11 mA / 5 min 0 sec		
86%		8.7 mA / 4 min 58 sec		

Figure 6-72 shows all the test levels conducted in one waveform. The four voltage levels were injected into the outdoor unit for approximately 5 minutes at each level with a transition back to 100% voltage for a period of 2 minutes before executing the next voltage test level. The highlighted areas are shown individually in the body of this section of the report. The leakage current during these time periods were analyzed and are discussed in this section of the report. Note: in all the charts, a value appears at left under the name of the leakage current being measured. This is an artifact showing the value registered at the location of the red cursor which may or may not be visible in the chart. This value has no relevance to the measurements of concern.

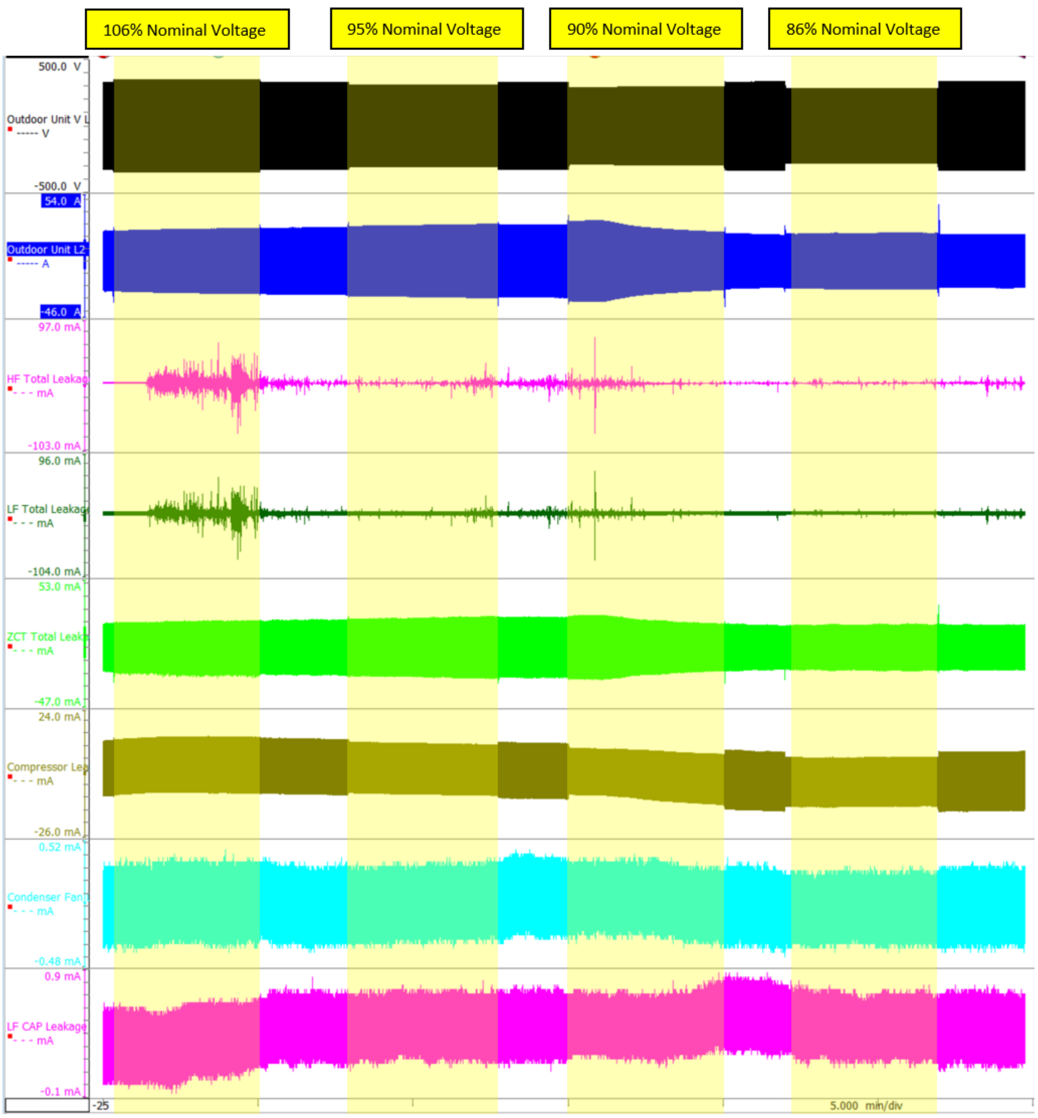


Figure 6-72
High-Low Voltage Range Test

Figure 6-73 shows the waveforms when the nominal voltage was increased to 106%. The waveforms show there is no significant change in the leakage current between 100% voltage and 106% voltage. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

Figure 6-73
106% Voltage Step

Figure 6-74 shows the waveforms when the nominal voltage was decreased to 95%. The waveforms show there is a slight change in the leakage current between 100% voltage and 95% voltage although there is a slight increase in the total current. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

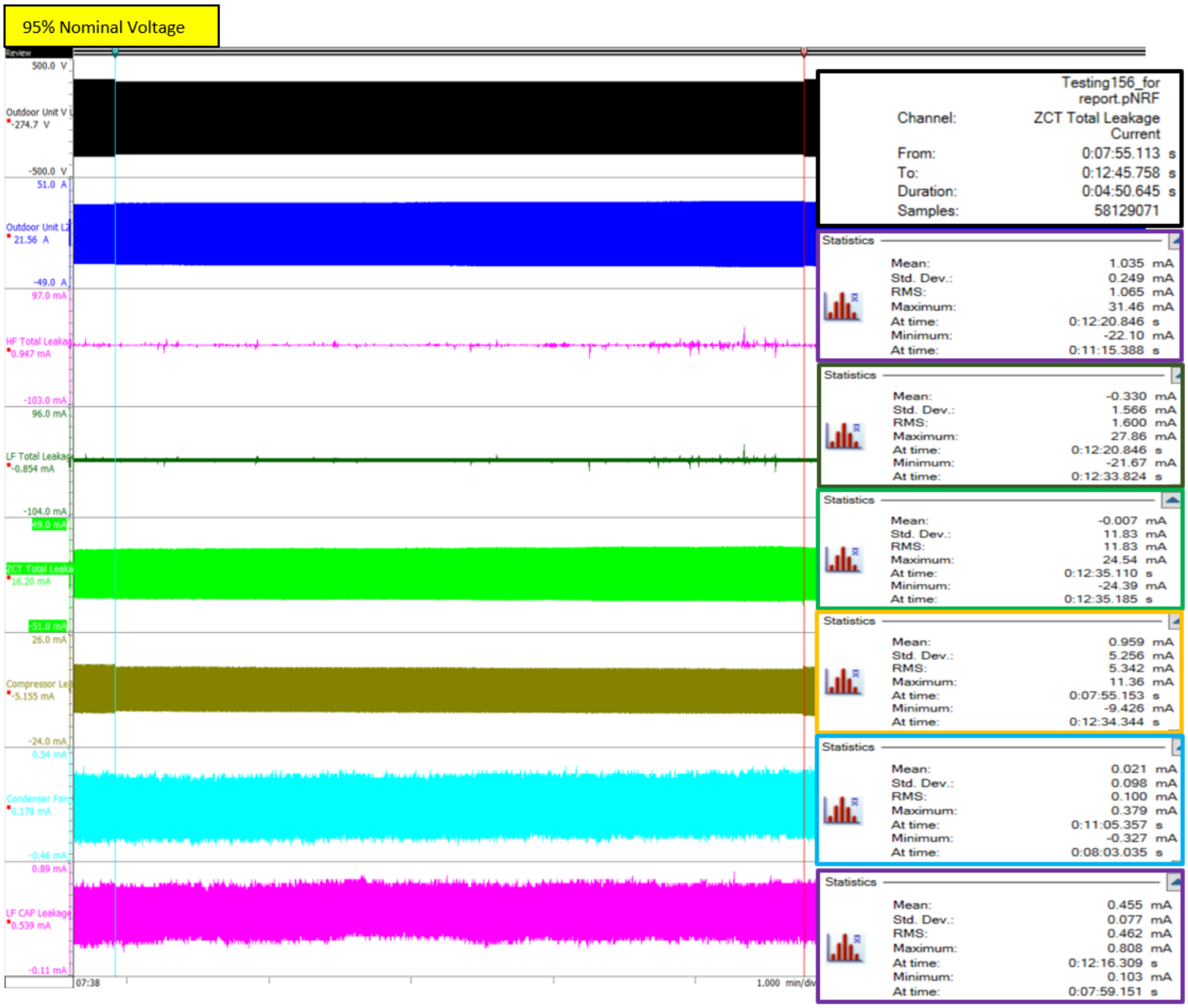


Figure 6-74
95% Voltage Step

Figure 6-75 shows the waveforms when the nominal voltage was decreased to 90%. The Z-CT leakage current waveshape appears to mimic the total current waveshape. The leakage current measured by the Z-CT was above the allowable limits of UL 943; however, the GFCI did not trip. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

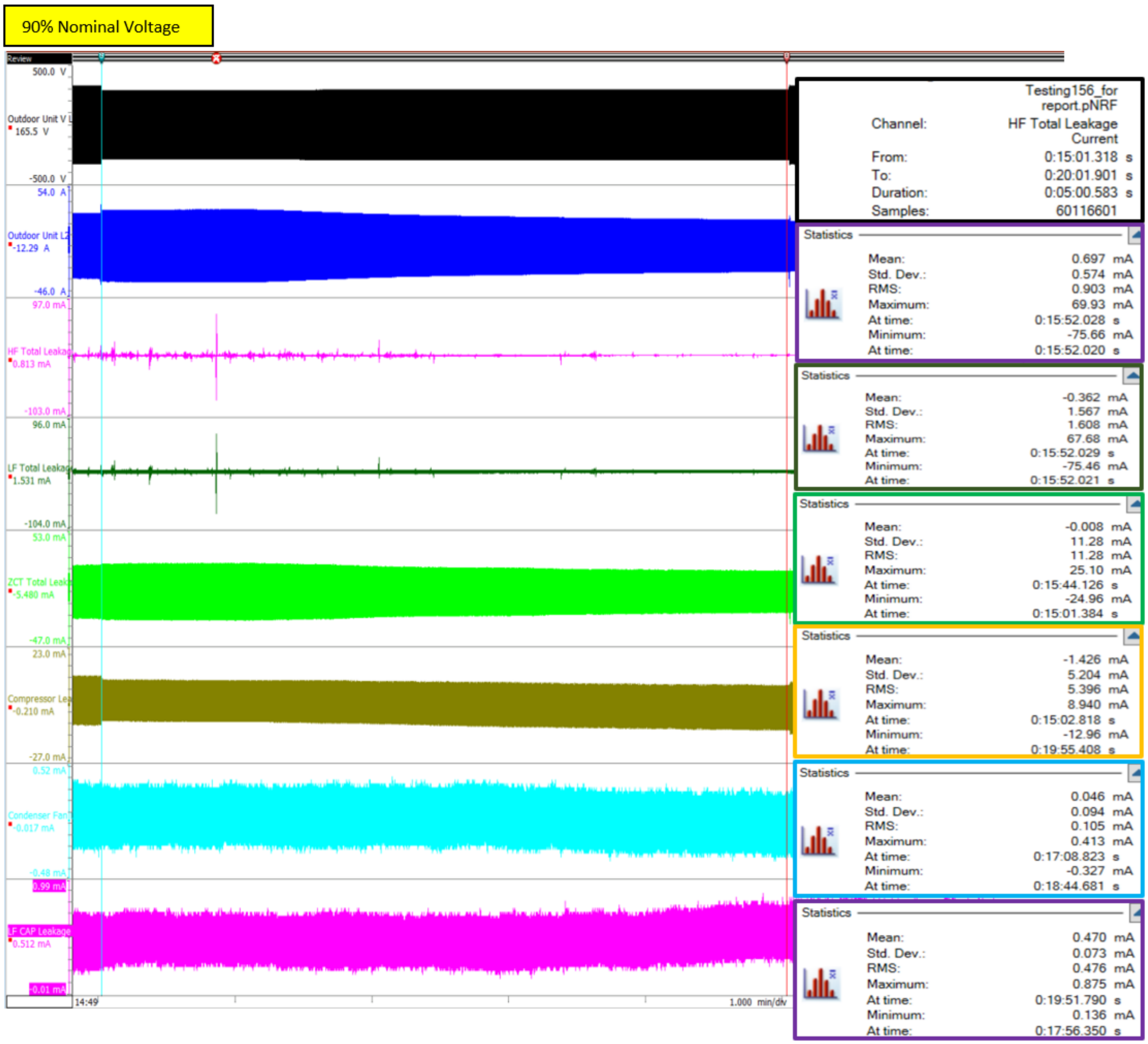


Figure 6-75
90% Step Voltage

Figure 6-76 shows the waveforms when the nominal voltage was decreased to 86%. This was the minimum voltage level for this regime of testing. The leakage current measured by the Z-CT was above the allowable limits of UL 943; however, the GFCI did not trip. A tabular analysis of the RMS leakage current measurements may be seen in **Error! Reference source not found.**.

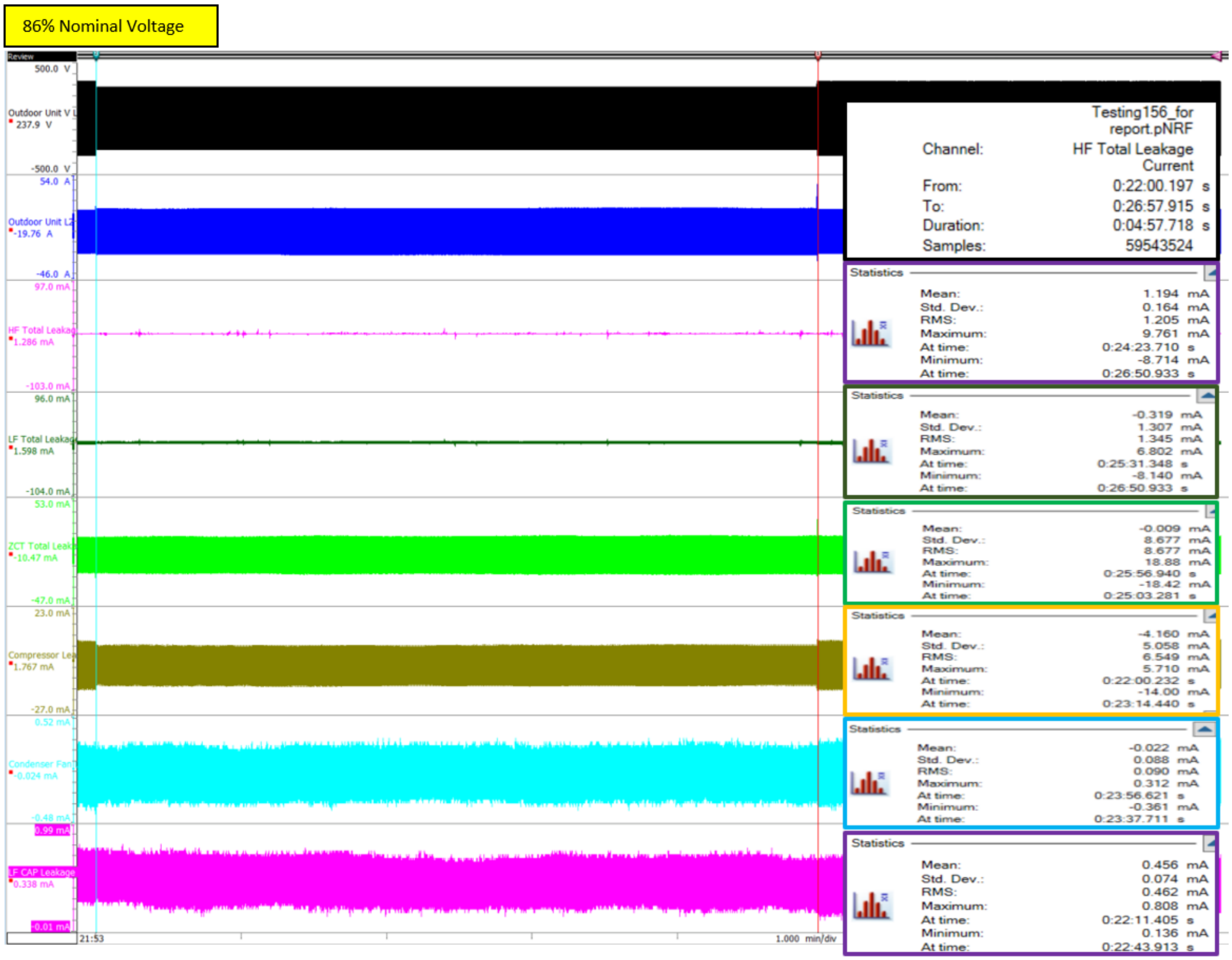


Figure 6-76
86% Step Voltage

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the High/Low Voltage Range Test under full cooling temperature conditions. Four voltage levels were injected into the outdoor unit for approximately 5 minutes at each level with a transition back to 100% voltage for a period of 2 minutes before executing the next voltage test. The tabular data shows the leakage current measured by the Z-CT was always above the UL 943 allowable limits for a 5-minute time period.

Table 6-27
Tabular Data from the High/Low Voltage Range Test

Note: All measurements are represented as RMS	**106%**		**95%**		**90%**		**86%**		
Measurement Time Base	1 min/div		1 min/div		1 min/div		1 min/div		
RMS Measurement Time	4 min 43 sec		4 min 50 sec		5 min 0 sec		4 min 58 sec		
UL 943 Limit	**6 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**6 mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
Z-CT Total Leakage	8.8 mA	No	12 mA	No	11 mA	No	8.7 mA	No	No
Compressor Leakage	6.6 mA	No	5.3 mA	Yes	5.4 mA	Yes	6.5 mA	No	No
Condenser Fan	0.1 mA	Yes	0.1 mA	Yes	0.1 mA	Yes	0.1 mA	Yes	No
Capacitor	0.3 mA	Yes	0.5 mA	Yes	0.5 mA	Yes	0.5 mA	Yes	No
HF Probe Ground Conductor	1.8 mA	Yes	1.1 mA	Yes	0.9 mA	Yes	1.3 mA	Yes	No
LF Probe Ground Conductor	2.1 mA	Yes	1.6 mA	Yes	1.6 mA	Yes	1.4 mA	Yes	No

Test 6 Conclusion

High- and low-voltage tests were conducted between 86% and 106% of the nominal voltage. Leakage current values were reported from the Z-CT. The RMS leakage current values measured during the test appear larger than the acceptable limit of 6 milliamps called out in UL 943, yet the GFCI used to power the outdoor unit did not trip.

7 UNIT 6 TEST RESULTS

Background for Testing HVAC Unit Number 6

As described in Chapter 1, GFCI circuit breakers have tripped when powering HVAC units of various topologies. This chapter will describe the testing of an HVAC system that is primarily controlled by an adjustable speed drive (ASD). Unlike line-start compressors, compressors powered by ASDs may tightly control the speed and acceleration of a motor. ASDs may also allow systems that operate at about a wide range of speeds to operate more efficiently than their line-start counterparts. However, ASDs create nonlinear currents that may result in undesirable conditions such as causing parallel loads to mis-operate, and transformers and conductors to overheat. To combat these conditions many HVAC manufacturers design filters to block the predominantly 3rd and 5th harmonic frequencies. These filters are often referenced to the ground connection.

Test Objectives

The test objective was to discover test conditions that created the highest leakage current. Early in the project, eleven possible tests were proposed that might determine conditions that may create enough leakage current to cause a GCFI to trip. Budget constraints caused the team to reduce the number of tests to seven as shown in **Error! Reference source not found.**. The r esults of these tests are described in the following sections. The remaining tests may be conducted in Phase 2 of this project.

Table 7-1
Test Matrix

Test No.	Test	Procedure	Purpose
0	Power Applied: Extended Off Time	Power down HVAC system overnight, start in the morning to mimic extended off time.	Refrigerants and oils may settle in the compressor. The settling may contribute to additional leakage current – causing GFCI to trip during start-up sequence.
1	Power Applied	Apply power to the compressor at 0-degrees, 45-degrees, and 90-degrees point-on-wave.	VFD-controlled compressors have a DC bus. Current inrush is created when charging the filter capacitors. The magnitude of the inrush current may vary depending on the instantaneous voltage when the AC power is applied.
2	HVAC Running	Monitor the output voltages and current and any suspected leakage current paths while the HVAC is bringing the indoor chamber to the set temperature from a starting temperature to a setpoint.	The purpose of this test is to observe the HVAC unit operating for one hour to see if it trips a GFCI.
3	Thermostat Cycling	Monitor the output voltages and current and any suspected leakage current paths while the HVAC unit is cycled in a 5- minute ON/ 5-minute OFF test pattern for one hour.	Determine if the GFCI trips while the HVAC unit cycles. Chambers to be in condition to cause maximum speed and loading.
4	Defrost Cycling	Monitor the output voltages and current and any suspected leakage current paths with the HVAC operating in thermal condition 3 shown in **Error! Reference s ource not found.**.	The purpose of this test is to monitor the leakage current paths while the HVAC unit is operating in defrost cycling mode. Complete one defrost cycle per test as a minimum.
5	Voltage Interruption	Inject voltage interruptions into the Equipment Under Test (EUT). Observe and document the performance of the EUT. Perform the test with all tap jumpers of the voltage sag generator on the 0% tap and again with the voltage tap jumpers removed	Determine if the response of the HVAC system may cause the GFCI to trip for high impedance voltage interruptions (open circuit) and low impedance voltage interruptions (tap transformer set to 0%).
6	High/Low Voltage Range	Using a power amplifier increases the nominal voltage to the maximum and minimum in three-volt increments until the EUT trips or the C84.1 Range B limits are reached. If the minimum/maximum voltage level is achieved allow the unit to operate for two, 5-minute on/off cycles as described in the thermostat cycling test	Investigate the response of the EUT when operating at the minimum and maximum “acceptable” voltage levels provided in the ANSI C84.1 standard.

The tests shown in **Error! Reference source not found.** were conducted in one or more of the i ndoor and outdoor chamber conditions shown in **Error! Reference source not found.**.

Table 7-2
Test Chamber Temperature Conditions

Test Condition Designation	Outdoor Air Temp (db*)	Indoor Air Temp (db*)	Test Condition Simulates
1	75 °F	75 °F	Nominal Baseline (75 °F)
2	95 °F (Nominal + 20 °F)	75 °F	Full Nominal Cooling Conditions
3	47 °F (Nominal - 28 °F)	75 °F	Full Nominal Heating Conditions

*Dry bulb

Test Setup

This section will describe the test setup for the Unit 6 testing. **Error! Reference source not f ound.** is a collage of photos from the Unit 6 test setup.

Figure 7-1
AHRI Test Unit 6 Setup

The test setup contained HVAC test unit 6, a 45-kVA power amplifier, the 200-amp voltage sag generator, and metering and measurement CTs. A block diagram of the test setup may be seen in Figure 7-2.

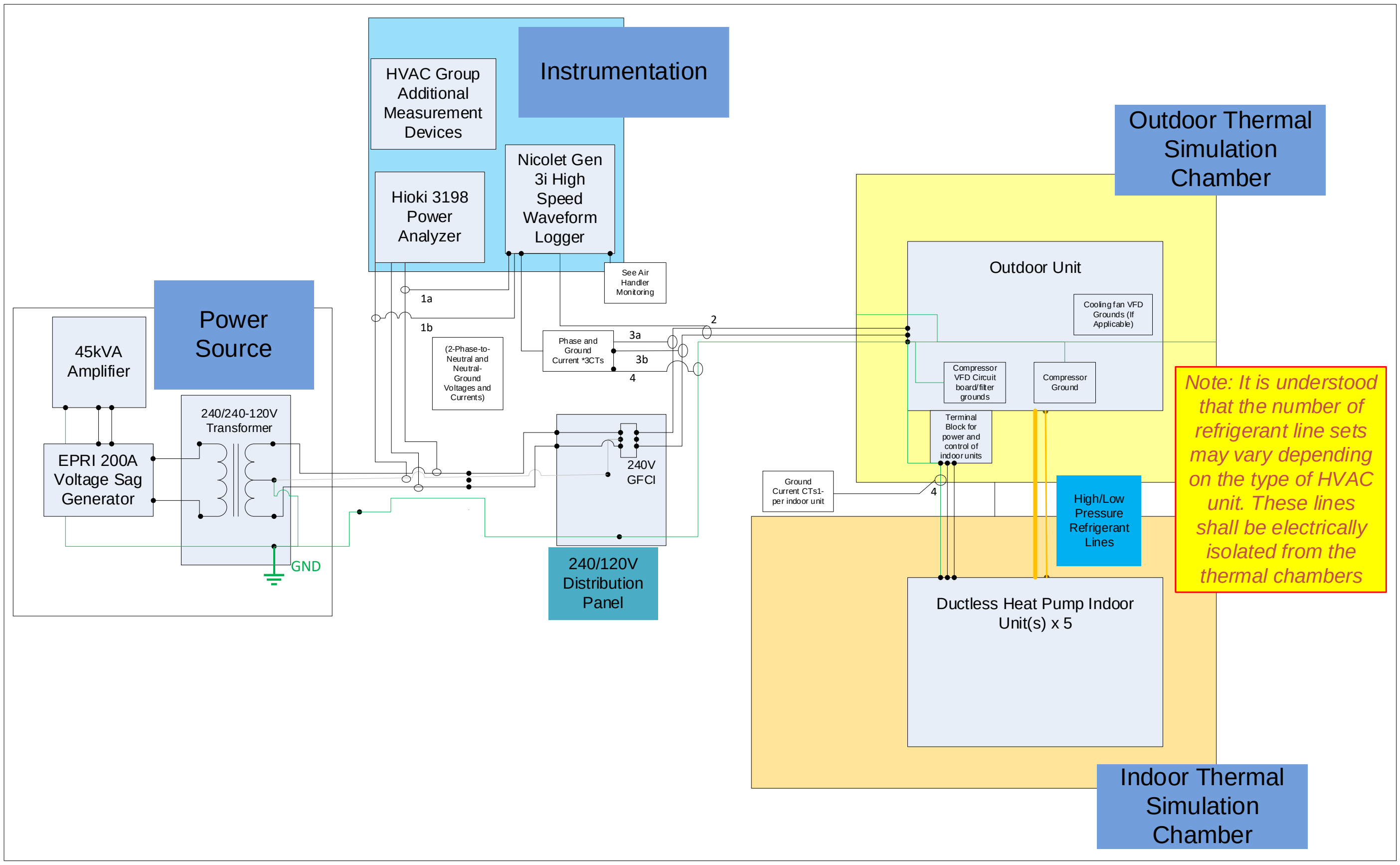


Figure 7-2
Test Setup Diagram

Error! Reference source not found. shows information about the measurement CTs as well as a ssociates the current transformers to the monitoring locations shown in Figure 7-2.

Table 7-3
Current Transformer Data

Current Transformer Data					
Manufacturer	**Model**	**Serial Number**	**Measurement**	**Measurement Description**	**Location in Circuit Figure 7-2**
AEMC	2620	104315WBS	Z-CT	CT Installed around outdoor L1 and L2 input wiring	2
Hioki	CT6700	211230270	HF-GND	Total Ground Current Outdoor Unit: High Frequency Response CT	4
Hioki	3272	220139616	CT6700 Supply	DC Power Supply for Hioki CT	N/A
AEMC	K110	153156WCDV	LF-GND	Total Ground Current Outdoor Unit: Low Frequency CT	4
AEMC	K110	156921WGDV 156929WGDV 156925WGDV 156920WGDV 153155WCDV	Indoor Unit GND A-E	One probe to measure the ground current from each Indoor Unit	5
AEMC	SR661	120174SHDV	L1 Current	Total Current	1a
AEMC	SR661	126241TADV	L2 Current	Total Current	1b
AEMC	SR661	09L29347DV	L1 Current	Total Current	3a
AEMC	SR661	120172HDV	L2 Current	Total Current	3b

Figure 7-3 is a photo of a GFCI that was provided by the manufacturer. This circuit breaker had tripped in some of their laboratory installations. The GFCI was installed in the test circuit and the GFCI tripped spuriously during Test 0 described in **Error! Reference source not found.**. M ore specifically the circuit GFCI tripped occasionally when power was applied to the EUT and when the ASD was enabled. The functional condition and the number of times which the circuit breaker had previously tripped was unknown. The GFCI was removed from the test setup and another circuit breaker was used to in order to learn the maximum leakage current the EUT may create.

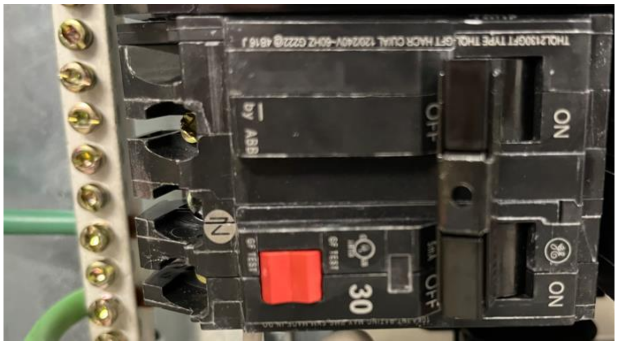


Figure 7-3
Circuit Breaker Provided by HVAC Manufacturer

The objective of this project was to attempt to determine the amount of leakage current the EUT may create and compare the leakage current to the required current limits dictated in UL 943. Therefore, the GFCI shown in Figure 7-3 was removed and the GFCI shown in **Error! Reference source not found.** was installed. Test 0 was conducted again using the replacement GFCI and test 0. This GFCI was used during all the testing conducted in this chapter. This GFCI did not trip during any of the prescribed testing in **Error! Reference source not found.**.

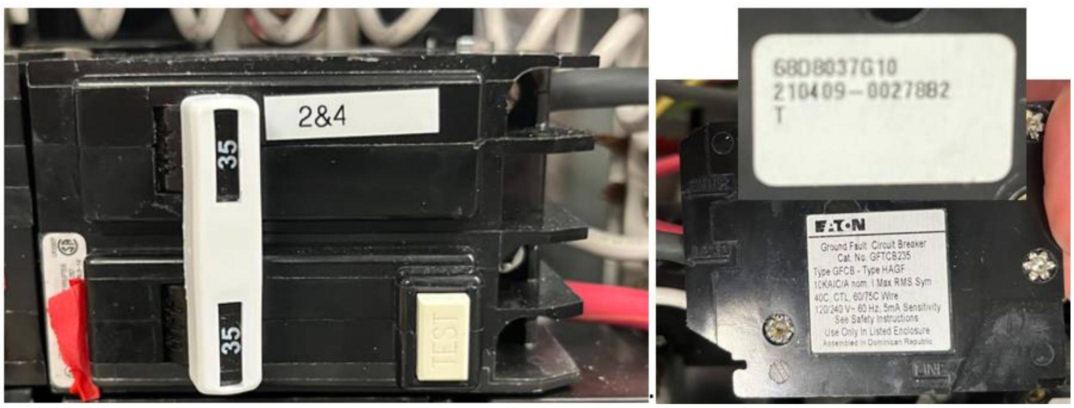


Figure 7-4
GFCI Circuit Breaker Used for all Tests

Test 0 Power Applied Extended Time Off

The purpose of the Extended Off Power Applied test is to determine if refrigerants and oils settling in the compressor during extended periods of no operation may cause an increase in the leakage current at startup. The hypothesis is the leakage current created during startup may result in GFCI tripping. This test was conducted once at each thermal condition shown in **Error! Reference source not found.**.

The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** s hows the periods that produced the maximum and minimum leakage current as well as the maximum RMS leakage current measured by the Z-CT, whether the current level was withing the trip current/time limit shown in UL 943, the relative humidity of the temperature chamber during the test, and whether or not the GFCI tripped.

Table 7-4
Extended Time Off Test Tabular Data

Test Temperature Condition	Lowest Measured Z-CT RMS Current	Highest Measured Z-CT RMS Current	Within UL943 Current/Time Limits?	GFCI Trip?	Outdoor Chamber Humidity
1	File did not have running current; therefore, no data available	$47mA_{RMS}$ Power Applied Measurement Period	Yes	No	45%
2	$14mA_{RMS}$ Compressor Running Measurement Period	$21mA_{RMS}$ Compressor Enabled Measurement Period	No	No	29%
3	$15mA_{RMS}$ Compressor Running Measurement Period	$47mA_{RMS}$ Power Applied Measurement Period	No	No	54% (possible probe error)

Error! Reference source not found. shows that the maximum RMS leakage current ranged b etween 21 mA and 47 mA between the three test scenarios. The highest leakage current was measured when the thermal chambers were configured for thermal condition 3 and power was applied. **Error! Reference source not found.** shows the minimum current was observed after t he compressor had stared and when the EUT was operating nominally. The Z-CT measured 14 milliamps RMS during this time and is above the allowable limits in UL 943. **Error! Reference s ource not found.** through Figure 7-11 Figure 7-10 show the oscillography of each test.

Thermal Condition 1 Testing

Error! Reference source not found. shows the oscillography captured by the waveform data l ogger. The 240-volt power that supplied the EUT, both phase currents, the leakage current measured by the Hioki CT6700, and the leakage current measured by the Z-CT are shown. The figure shows a small rendering of the whole scan with a larger zoomed-in view of the leakage current measured when power was applied. The total scan time was approximately 20 seconds, while the zoomed-in view is 1 millisecond per division. The zoomed view shows that the maximum RMS current measured by the Z-CT was 47 mA for approximately 4 milliseconds.

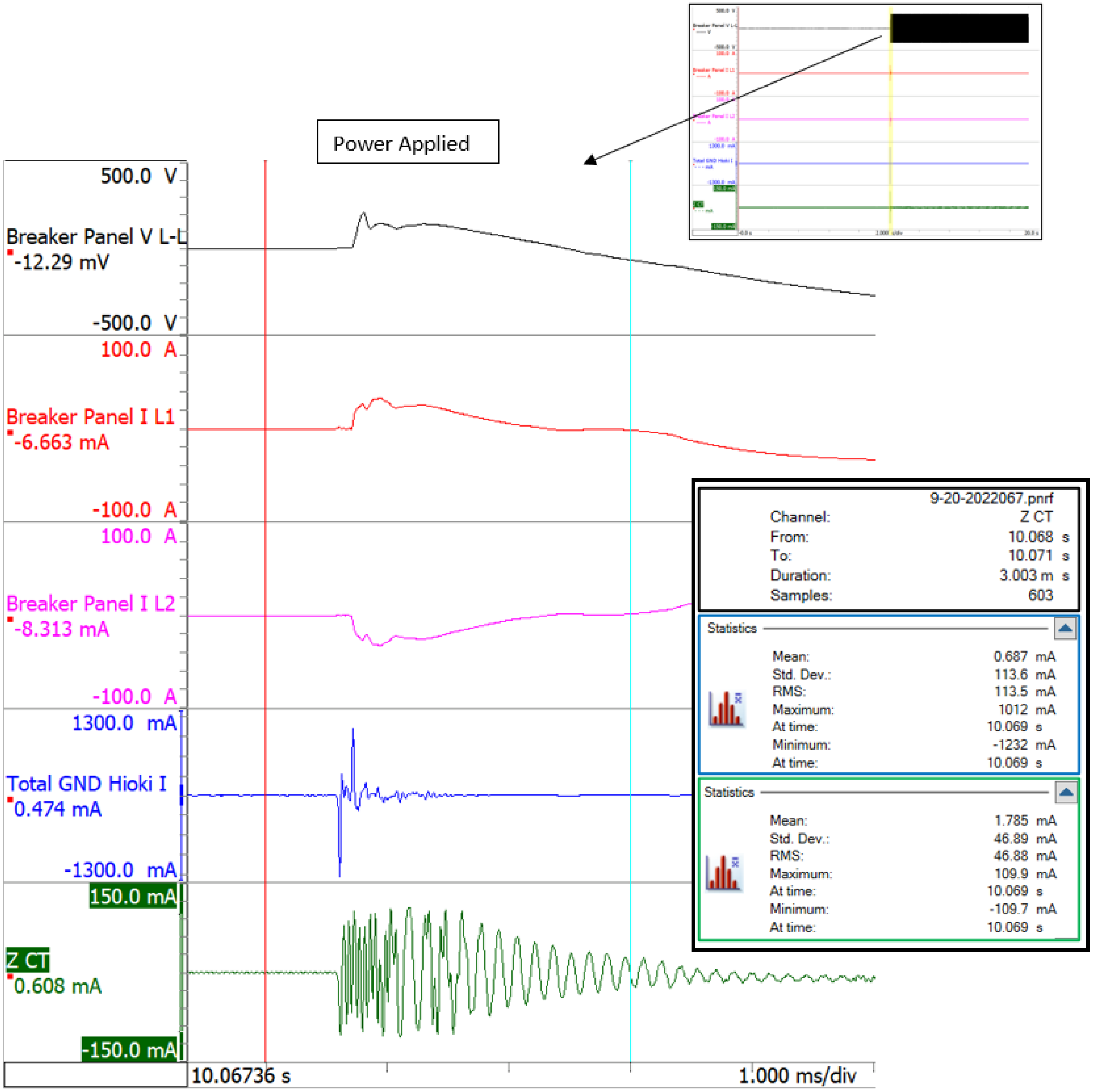


Figure 7-5
Extended Time Off Startup Chamber Condition 1

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the power applied extended time off test while the thermal chamber was set to temperature condition 1. The RMS leakage current measured by the Z-CT during application of power time period was within the time/current limits of UL 943.

Table 7-5
Temperature Condition 1, Extended Time Off Tabular Results

Note: All measurements are represented as RMS	**Application of Power**		
Measurement Time Base	1ms/div		
RMS Measurement Time	3ms		
UL 943 Limit	**1162mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	47mA	Yes	No
Total GND Hioki Leakage Current	114mA	Yes	No

Thermal Condition 2 Testing

Error! Reference source not found. and Figure 7-7 show the oscillography captured by the waveform data logger during testing under Thermal Condition 2. The channel setup is identical to the Chamber Condition 1 test described above. **Error! Reference source not found.** shows a t humbnail rendering of the whole scan with a larger zoomed-in view of the leakage current measured at power up. The total scan time was approximately 11 minutes, and the zoomed-in view is 2 milliseconds per division.

The zoomed view shows the maximum RMS current measured by the Z-CT at application of power was 21 mA. The pulse of current was only present for approximately 3 milliseconds during the application of power.

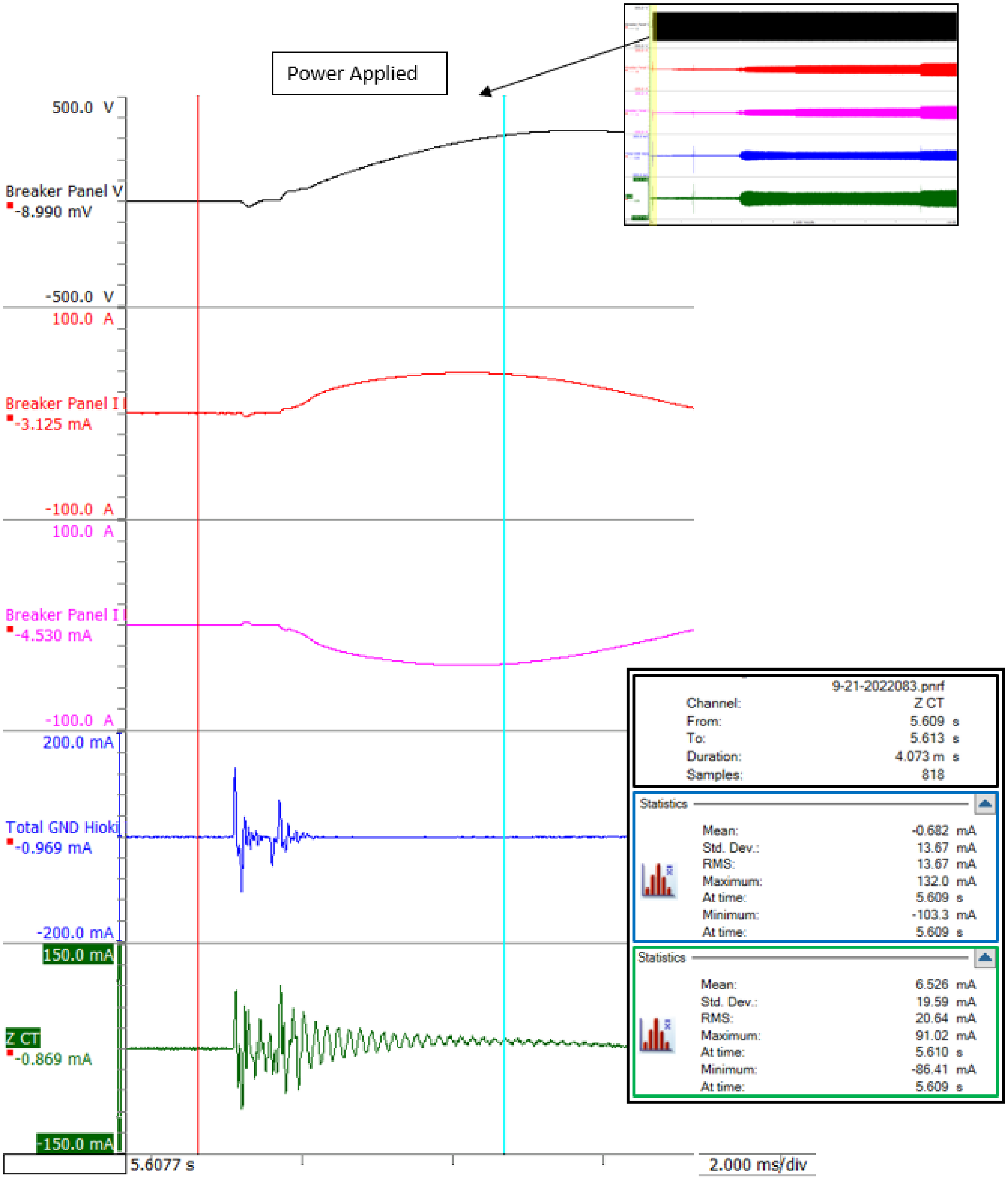


Figure 7-6
Extended Time Off, Startup Chamber Condition 2

Figure 7-7 shows a thumbnail rendering of the whole scan with a larger zoomed-in view of the leakage current measured when the DC bus energized. The total scan time was approximately 11 minutes, and the zoomed-in view is 2 milliseconds per division.

The zoomed view shows the maximum RMS current measured by the Z-CT when the DC bus energized was 21 mA. The figure also shows the leakage current was higher when the DC bus energized than when power was applied. The pulse of current was only present for approximately 4 milliseconds when the DC bus energized. This HVAC system was originally powered through a GFCI circuit breaker that often tripped when the DC bus enabled after sitting unpowered for approximately 12 hours. The circuit breaker was changed to another GFCI to try and determine the maximum current the compressor may produce without tripping prior to this test.

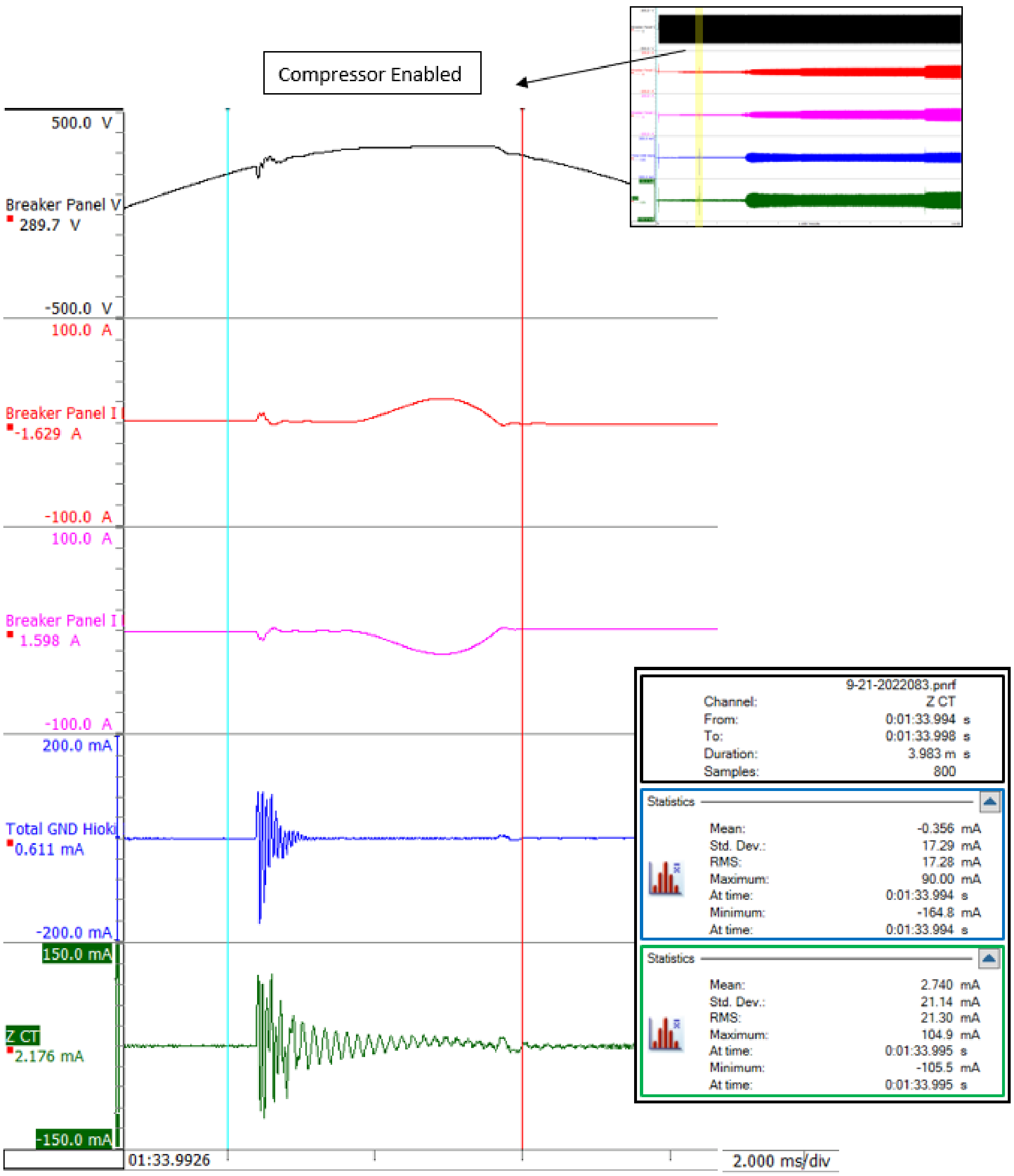


Figure 7-7
Extended time Off, Compressor Enabled Chamber Condition 2

Figure 7-8 shows a thumbnail rendering of the whole scan with a larger zoomed-in view of the leakage current measured when the compressor was running nominally. The total scan time was approximately 11 minutes, and the zoomed-in view is 1 minute per division.

The zoomed view shows the maximum RMS current measured by the Z-CT when the compressor was running nominally was 14 mA. This is lower than the leakage current for either of the other two test points.

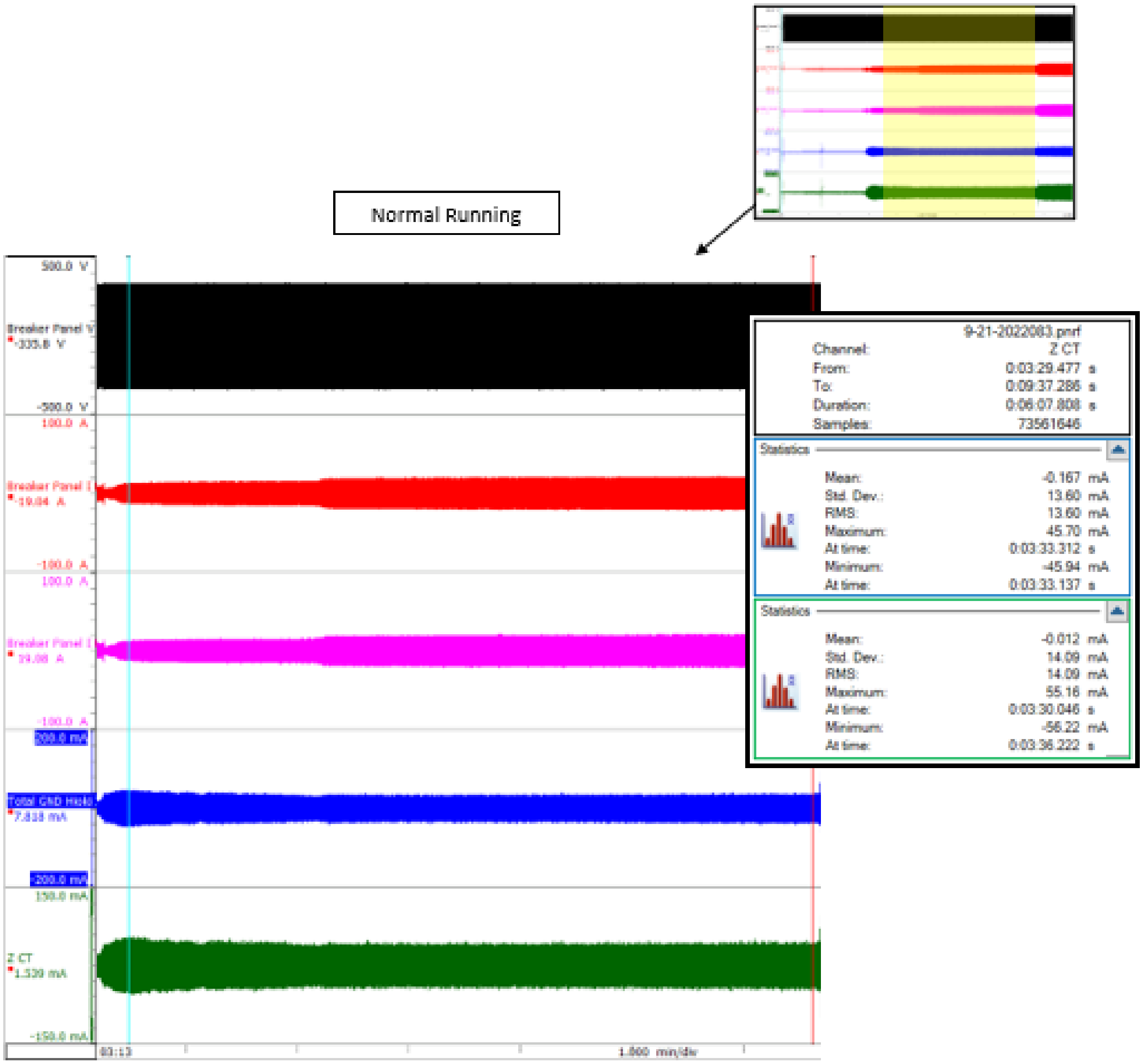


Figure 7-8
Extended time Off, Compressor Running Chamber Condition 2

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the power applied extended time off test while the thermal chamber was set to Temperature Condition 2. The measurements of when power was applied, when the compressor was enabled, and when the compressor was running nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time periods were within the time/current limits of UL 943; however, the RMS current measured by the Z-CT during the nominal running time period was 8 mA above the RMS current limitations of UL 943.

Table 7-6
Temperature Condition 2, Extended Time Off Tabular Results

Note: All measurements are represented as RMS	Application of Power		Compressor Enabled		Normal Running		
Measurement Time Base	2ms/div		2ms/div		1min/div		
RMS Measurement Time	4ms		4ms		6min 8sec		
UL 943 Limit	**950mA**	**Within UL 943 Current/Time Limits?**	**950mA**	**Within UL 943 Current/Time Limits?**	**6mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	21mA	Yes	21mA	Yes	14mA	No	No
Total GND Hioki Leakage Current	14mA	Yes	17mA	Yes	14mA	No	No

Thermal Condition 3 Testing

Error! Reference source not found. and Figure 7-10 show the oscillography captured by the H BM Gen 3i waveform data logger during thermal condition 3. The channel setup is identical to the previous two tests. **Error! Reference source not found.** shows a thumbnail rendering of the w hole scan with a larger, zoomed-in view to show the leakage current in greater detail during power up. The total scan time was approximately 12 minutes and the zoomed-in view at the time power was applied is 2 milliseconds per division. The zoomed view shows the maximum RMS current measured by the Z-CT at application of power was 47 mA for approximately 4 milliseconds.

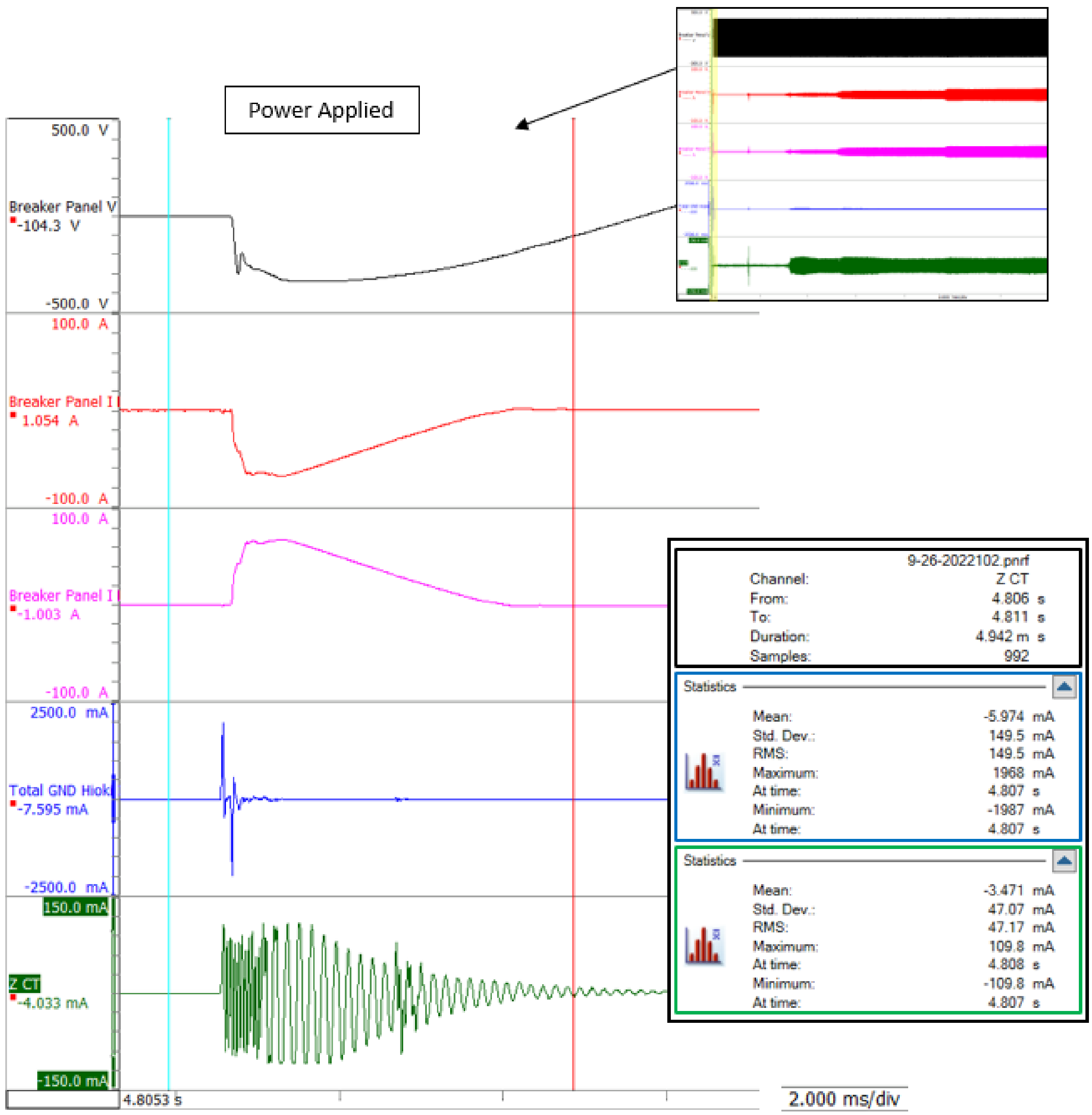


Figure 7-9
Extended Time Off, Startup Chamber Condition 3

Figure 7-10 shows a thumbnail rendering of the whole scan with a larger, zoomed-in view to show the leakage current in greater detail when the DC Bus was enabled. The total scan time was approximately 12 minutes and the zoomed-in view at the time the DC Bus was enabled is 500 microseconds per division. The zoomed view shows the maximum RMS current measured by the Z-CT when the DC Bus was enabled was 38 mA – lower than the current measured when power was applied.

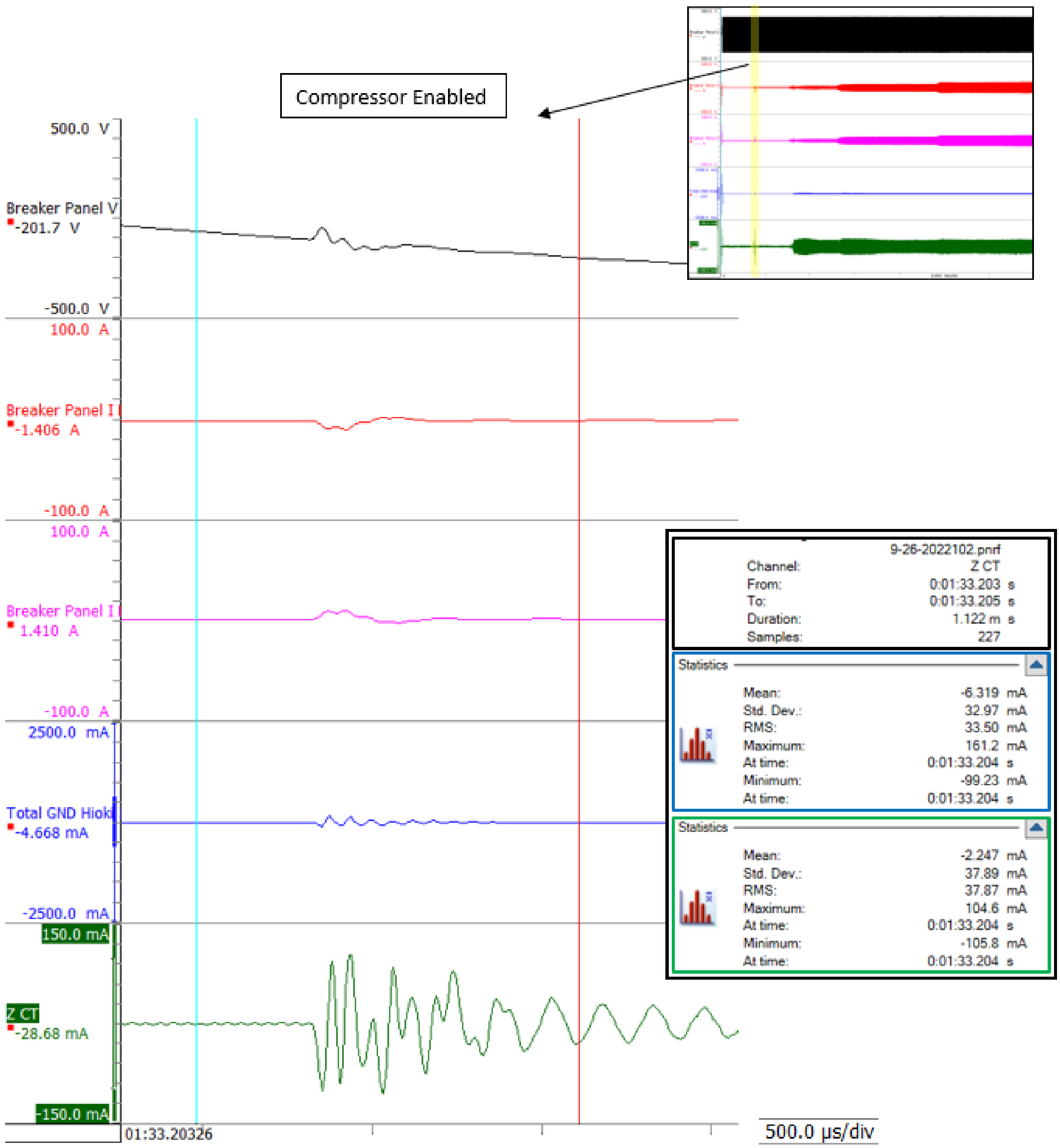


Figure 7-10
Extended Time Off, Compressor Enabled Chamber Condition 3

Figure 7-11 shows a thumbnail rendering of the whole scan with a larger zoomed-in view of the leakage current measured when the compressor was running nominally. The total scan time was approximately 12 minutes, and the zoomed-in view is 2 minutes per division.

The zoomed view shows the maximum RMS current measured by the Z-CT when the compressor was running nominally was 15 mA. This is lower than the leakage current for either of the other two test points.

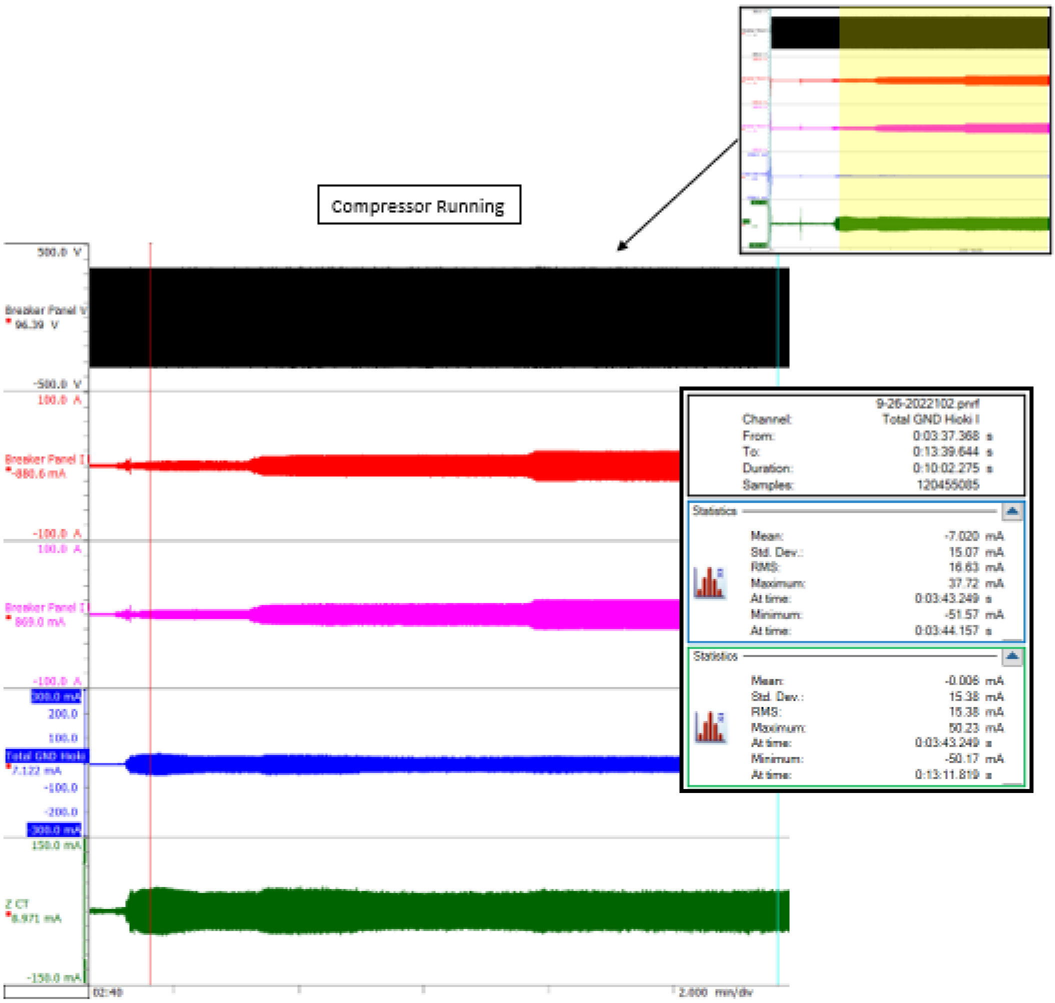


Figure 7-11
Extended Time Off, Compressor Running Chamber Condition 3

Figure 7-12 is a side-by-side comparison at the time when power was applied for each test. The purpose of this figure is to show that the leakage current appears higher when voltage is applied at the positive or negative peak of the voltage than at the zero crossing. The tabular data for each of these tests may be seen in **Error! Reference source not found.** and a zoomed i n rendering of each waveform may be seen in **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**. Inrush current for capacitive loads typically occurred when the voltage was applied at the peak of the sinewave. Capacitors attempted to charge to the maximum voltage instantaneously. Therefore, with the input voltage at a maximum when power is applied—which is worst case at 90 degrees and 270 degrees of the 60-hertz sinewave—maximum inrush current will be supplied. It is believed that the point-on-wave at which power is applied was the cause of the higher leakage current than the thermal conditions of the environment of the units. It is not possible to control the point-on-wave at energization repeatably with a knife switch; however, this might be accomplished with a semiconductor switch such as a silicon-controlled rectifier (SCR).

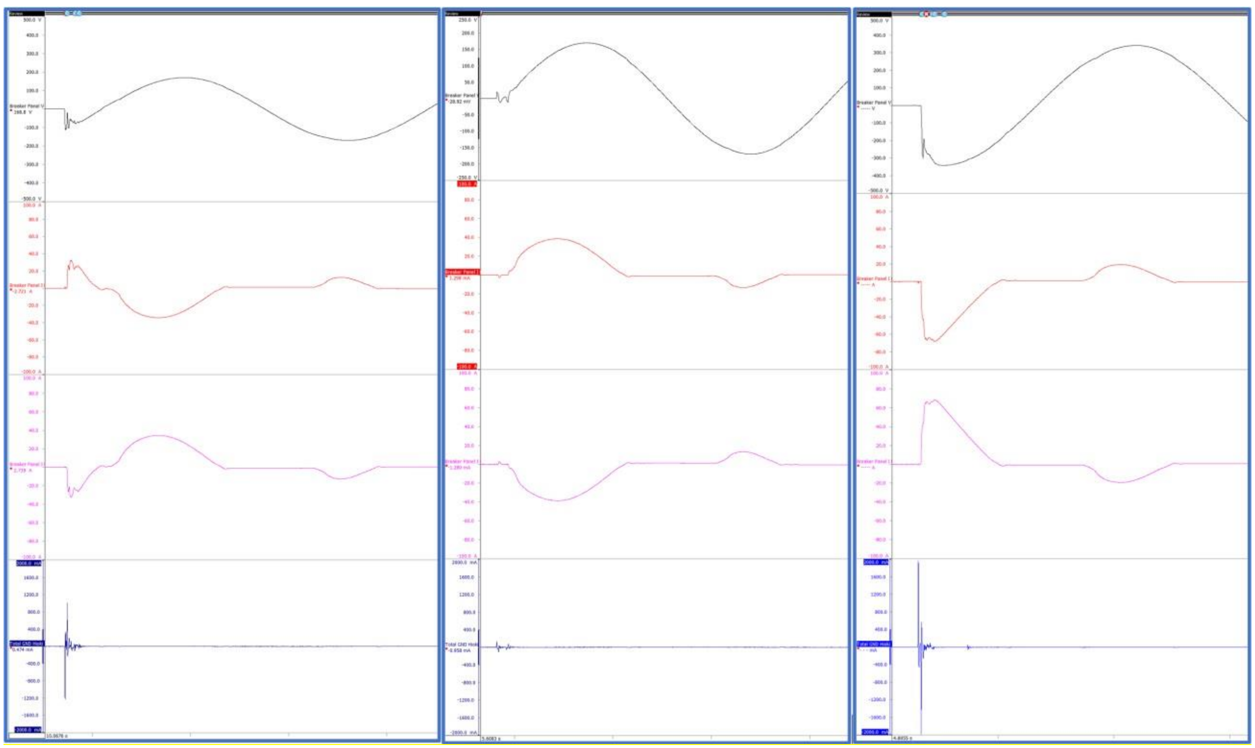


Figure 7-12
Point-on-Wave Vs. Leakage Current

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the power applied extended time off test while the thermal chamber was set to temperature condition 3. The measurements when power was applied, when the compressor was enabled, and when the compressor was running nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time periods were within the time/current limits of UL 943; however, the RMS current measured by the Z-CT during the nominal running time period was 9 mA above the RMS current limitations of UL 943.

Table 7-7
Temperature Condition 3, Extended Time Off Tabular Results

Note: All measurements are represented as RMS	Application of Power		Compressor Enabled		Normal Running		
Measurement Time Base	2ms/div		500µs/div		2min/div		
RMS Measurement Time	5ms		1ms		10min 2sec		
UL 943 Limit	813mA	Within UL 943 Current/Time Limits?	2506mA	Within UL 943 Current/Time Limits?	6mA	Within UL 943 Current/Time Limits?	GFCI Trip?
ZCT Total Leakage Current	47mA	Yes	38mA	Yes	15mA	No	No
Total GND Hioki Leakage Current	150mA	Yes	34mA	Yes	17mA	No	No

Test 0 Conclusion

Power was applied to the HVAC unit after allowing the unit to dwell without power for at least 12 hours. The first test conducted each day was to energize the HVAC system to measure the leakage current. Initially, a GFCI shown in Figure 7-3 was installed in the circuit that was known to trip. Initial testing revealed that this GFCI tripped most of the time when the DC Bus was enabled; however, rarely did the GFCI trip when power was initially supplied. The GFCI was changed to a more robust circuit breaker shown in **Error! Reference source not found.** to a ttempt to measure the maximum leakage current that might occur when the HVAC was energized after settling for at least 12 hours. The testing was conducted as per the test protocol while the thermal chambers were set to the each of the temperature modes shown in **Error! R eference source not found.**. The GFCI circuit breaker did not trip for any of the tests. Maximum leakage current was observed when the test chambers were set for Test 3, Full Nominal Heating Mode. However, the leakage current may have been the result of the point-on-wave when the voltage was applied and not the thermal condition of the test chambers. The purpose of this test was to determine if the leakage current values at the time power is applied remains within the boundaries of the time/current curve within UL 943. The test data shows the EUT remained within the bounds of UL 943; however, the EUT was permitted to operate until the compressor enabled, and the compressor was allowed to operate for a few minutes. During the compressor running time it was discovered the Z-CT and the High Fidelity CT both measured RMS current levels around 14 milliamps regardless of the thermal conditions of the temperature chambers. The current measured 8 milliamps above the allowable limit of 6 milliamps for longer than a few seconds. An FFT analysis was conducted within the normal running time period for approximately 6-minutes of the Thermal Condition 2 test as shown in Figure 7-14.

A spectral analysis of the RMS current measured by the Z-CT was conducted. **Error! Reference source not found.** shows the area shaded in red shows where the frequency spectrum of the Z-CT and the HF Ground current probe was analyzed using the spectral analysis module of the HBM Gen3i data recorder.

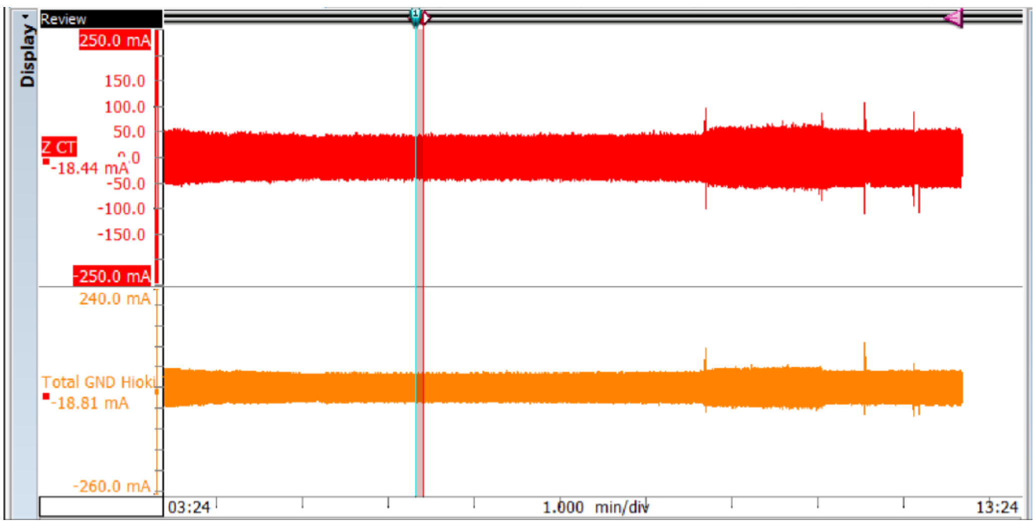


Figure 7-13
Time Period FFT was Captured

Figure 7-14 shows the Z-CT measured 3 milliamps RMS current at 60 Hz and 8.5 milliamps, at 5.9 kHz. The High-Fidelity Leakage Probe measured 0.5 milliamps at 60 Hz and 5.6 milliamps at 5.9 kHz. Therefore, both meters agree that the majority of the leakage current resides at a frequency higher than the fundamental frequency. The Z-CT measured leakage current below the maximum requirements in UL 943, and the GFCI may not respond to currents created at 5.9 kHz.

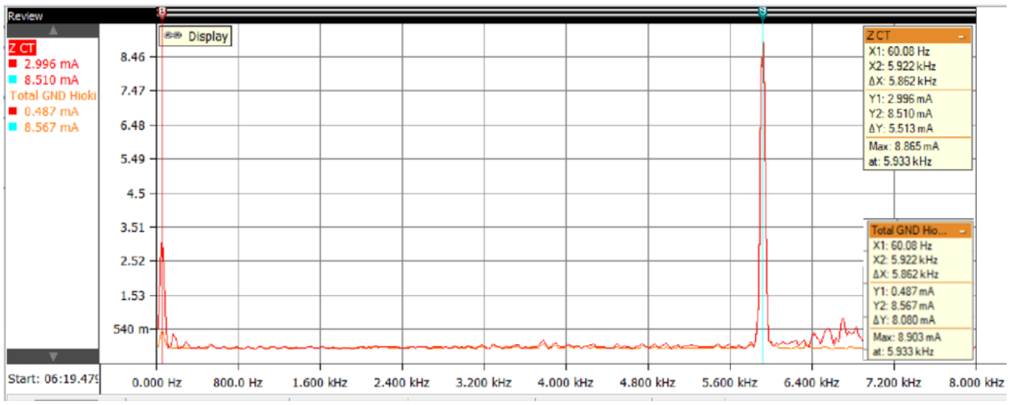


Figure 7-14
FFT Showing the values of the ZCT and Total Ground HF CT

Test 1 Power Applied

VFD-controlled compressors have a DC bus. Current inrush is created when the DC bus capacitors are initially charging the filter capacitors. The magnitude of the inrush current may vary depending on the instantaneous voltage when the AC power is applied. The instantaneous voltage is determined by the point-on-wave (POW) of the sinusoidal AC voltage. The purpose of the Power Applied test is to determine if the instantaneous magnitude of the voltage when power is applied to the HVAC system affects the magnitude of the leakage current. This test was conducted once at each thermal condition shown in **Error! Reference source not found.**. V oltage was applied at 0-degrees POW, 45-degrees POW, and 90-degrees POW at the primary of the 240/240-120-volt transformer with a 7-minute power off time between events to allow the DC bus capacitors to discharge. The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** shows the maximum RMS current measured by the Z-CT during each test, the relative humidity of the temperature chamber during the test, and some general observation notes.

Table 7-8
Power Applied Tabular Data

Chamber Temperature Condition	Highest Measured ZCT Current (mA_{RMS})	Notes	Within UL943 Current/Time Limits?	GFCI Trip?	Outdoor Chamber Humidity
1	0-degrees POW 13 mA_{RMS} 45-degrees POW 21 mA_{RMS} 90-degrees POW 21 mA_{RMS}	The sag generator pulsed on for approximately 300 microseconds, two seconds prior to the expected start of each test. This may be the reason for the difference in leakage current between the extended time off and the power applied results	Yes	No	45%
2	0-degrees POW 12mA_{RMS} 45-degrees POW 30 mA_{RMS} 90-degrees POW 23 mA_{RMS}		Yes	No	29%
3	0-degrees POW 17 mA_{RMS} 45-degrees POW 29 mA_{RMS} 90-degrees POW 24 mA_{RMS}		Yes	No	72% (possible probe error)

Error! Reference source not found. also shows leakage current values were lower when power w as applied at 0 degrees POW. Leakage current values for 45 degrees POW and 90 degrees POW were typically twice the value at 0 degrees POW. The RMS leakage current ranged between 21 milliamps and 30 milliamps at 45 degrees POW and between 21 milliamps and 24 milliamps at 90 degrees POW between the three temperature conditions. For 0 degrees POW, the RMS leakage current never exceeded 17 milliamps between the three temperature conditions. **Error! Reference source not found.** through Figure 7-26 show the oscillography of each test, including the entire scan of each temperature condition as well as zoomed in views at 0 degrees, 45 degrees, and 90 degrees point on wave to show greater detail of the leakage current for each temperature condition.

Thermal Condition 1 Testing

Error! Reference source not found. shows the oscillography captured by the waveform data l ogger for all three tests while the chambers were configured for the nominal baseline test shown in **Error! Reference source not found.**. The total scan time was approximately 15 m inutes. The 240-volt power that supplied the EUT, both phase currents, the leakage current measured by the Hioki CT6700, and leakage current measured by the Z-CT were measured.

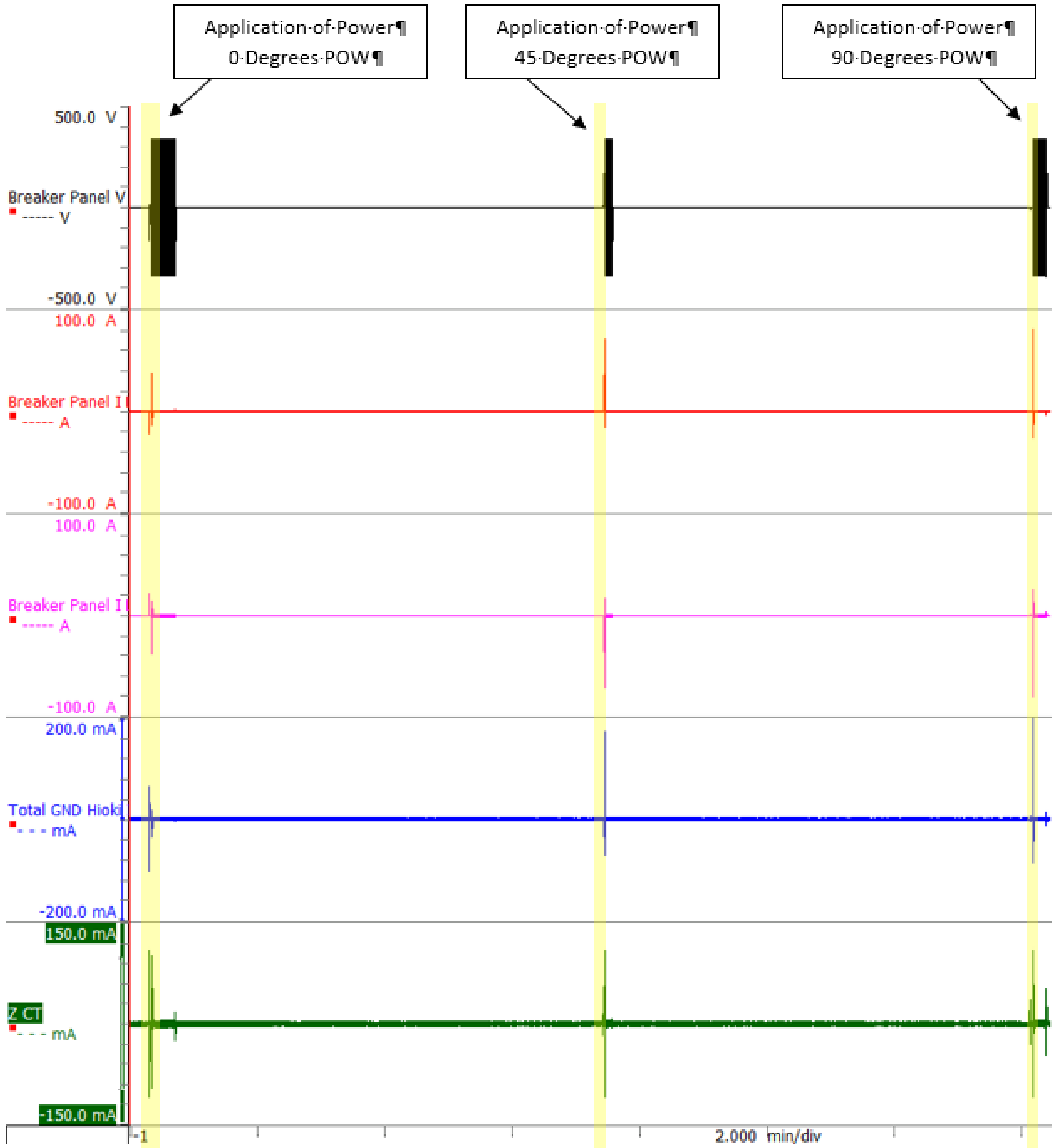


Figure 7-15
Power Applied Chamber Condition 1

Figure 7-16 through Figure 7-18 show the zoomed-in view of the leakage current at 5 milliseconds per division when power was applied at 0 degrees, 45 degrees, and 90 degrees POW sequentially. The waveforms show the maximum leakage current was the highest during the 45-degree POW test—21.19 milliamps RMS. Maximum leakage current was only present for approximately 5 milliseconds which may explain why the GFCI circuit breaker did not trip since this measured current is within the boundaries of the time/current limits of UL 943.

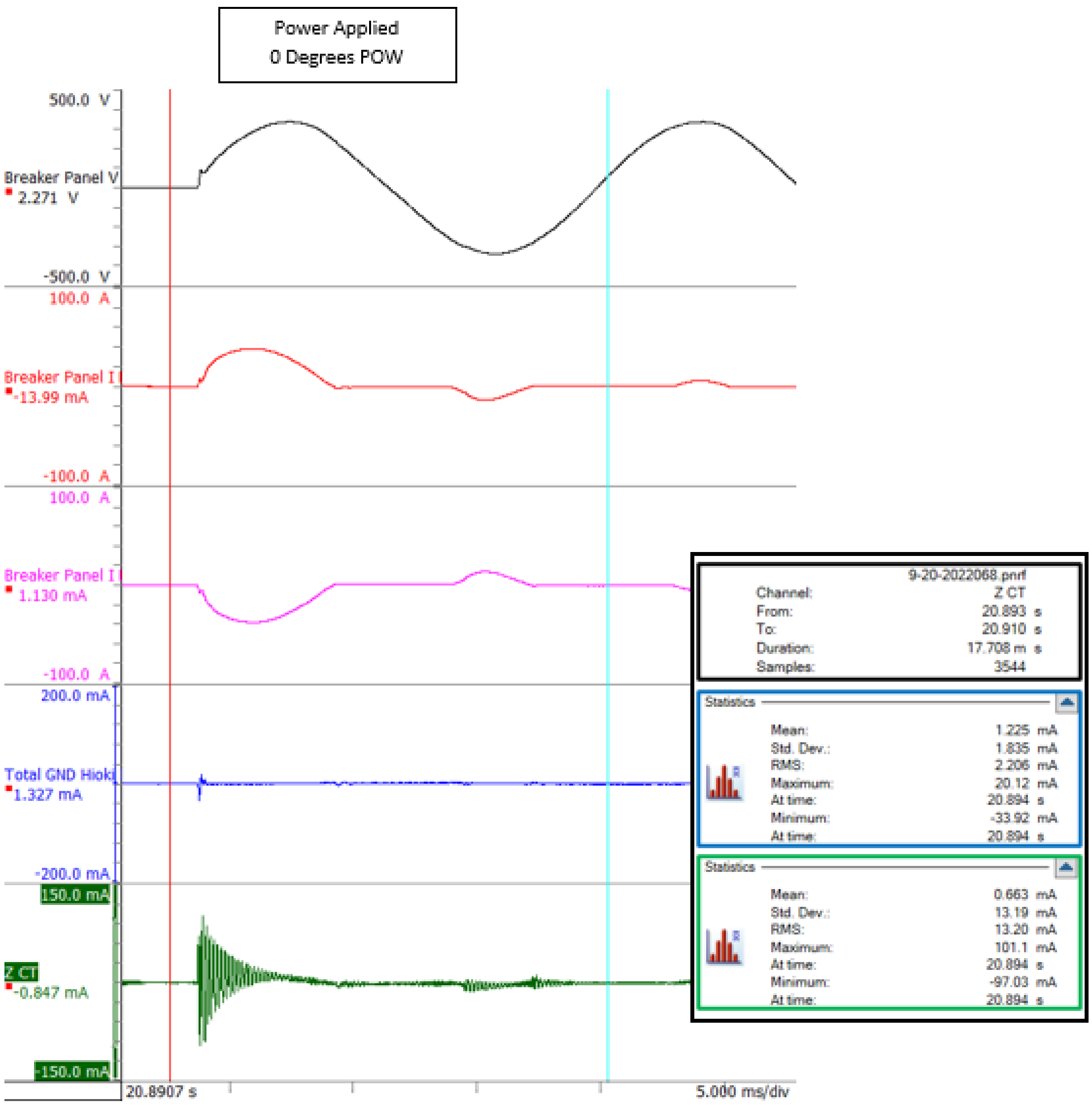


Figure 7-16
Zoomed 0 Degree POW Applied Power Chamber Condition 1

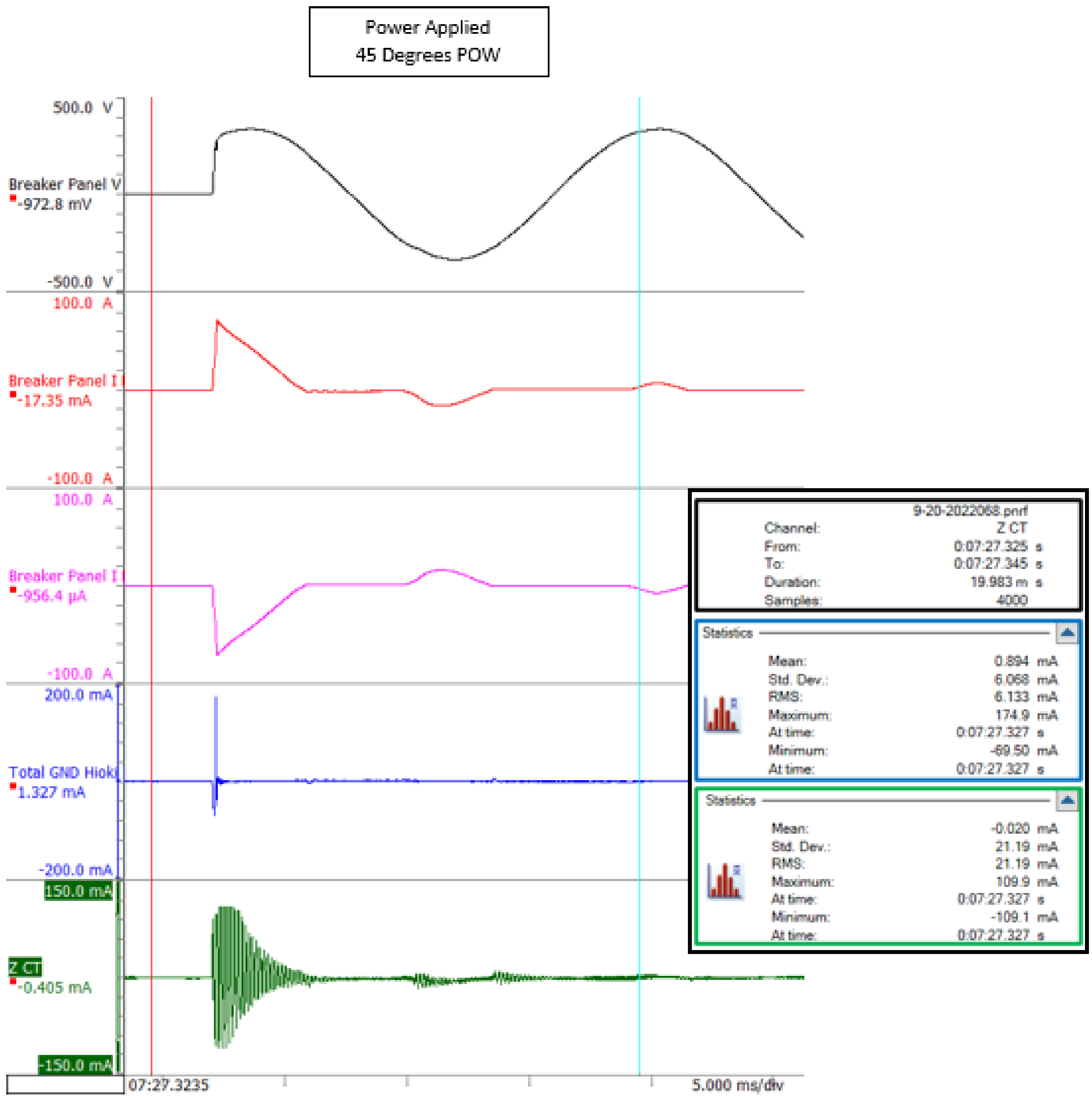


Figure 7-17
Zoomed 45 Degree POW Applied Power Chamber Condition 1

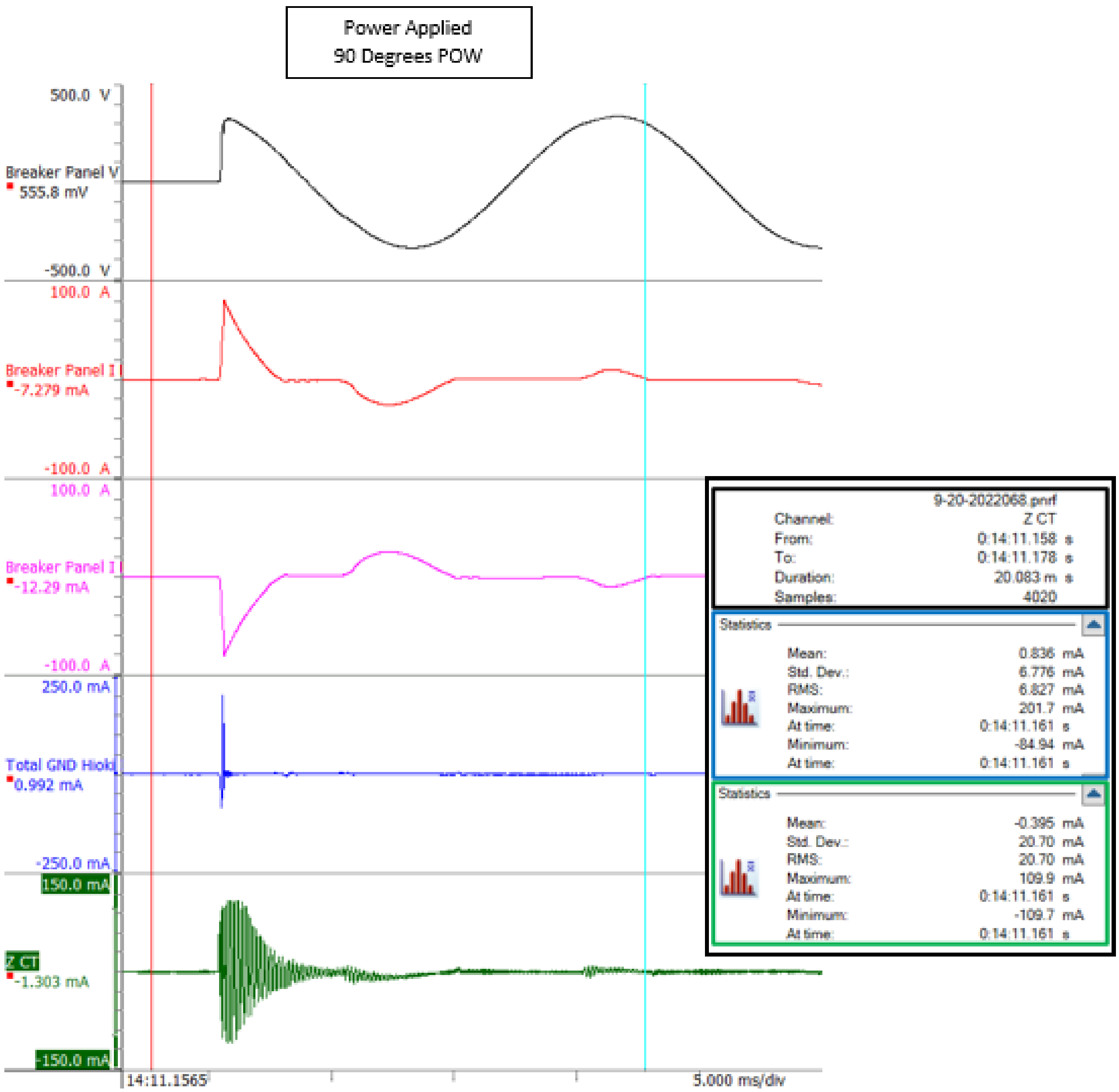


Figure 7-18
Zoomed 90 Degree POW Applied Power Chamber Condition 1

Error! Reference source not found. shows the RMS current values during the time that power w as applied to the circuit when testing was conducted at 0 degrees, 45 degrees, and 90 degrees POW. The data shows the circuit breaker did not trip at any time during the test and the Z-CT, and the measurements did not exceed the maximum current limits as per UL 943.

Table 7-9
Thermal Condition 1, Power Applied POW Tabular Results

Note: All measurements are represented as RMS	**0 Degrees POW**		**45 Degrees POW**		**90 Degrees POW**		
Measurement Time Base	5ms/div		5ms/div		5ms/div		
RMS Measurement Time	18ms		20ms		20ms		
UL 943 Limit	**332mA**	**Within UL 943 Current/Time Limits?**	**308mA**	**Within UL 943 Current/Time Limits?**	**308mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	13mA	Yes	21mA	Yes	21mA	Yes	No
Total GND Hioki Leakage Current	2mA	Yes	6mA	Yes	7mA	Yes	No

Thermal Condition 2 Testing

Error! Reference source not found. shows the oscillography captured by the waveform data l ogger for all three tests while the chambers were configured for the full-nominal cooling condition shown in **Error! Reference source not found.**. The total scan time was approximately 1 9 minutes. The 240-volt power that supplied the EUT, both phase currents, the leakage current measured by the Hioki CT6700, and leakage current measured by the Z-CT were recorded.

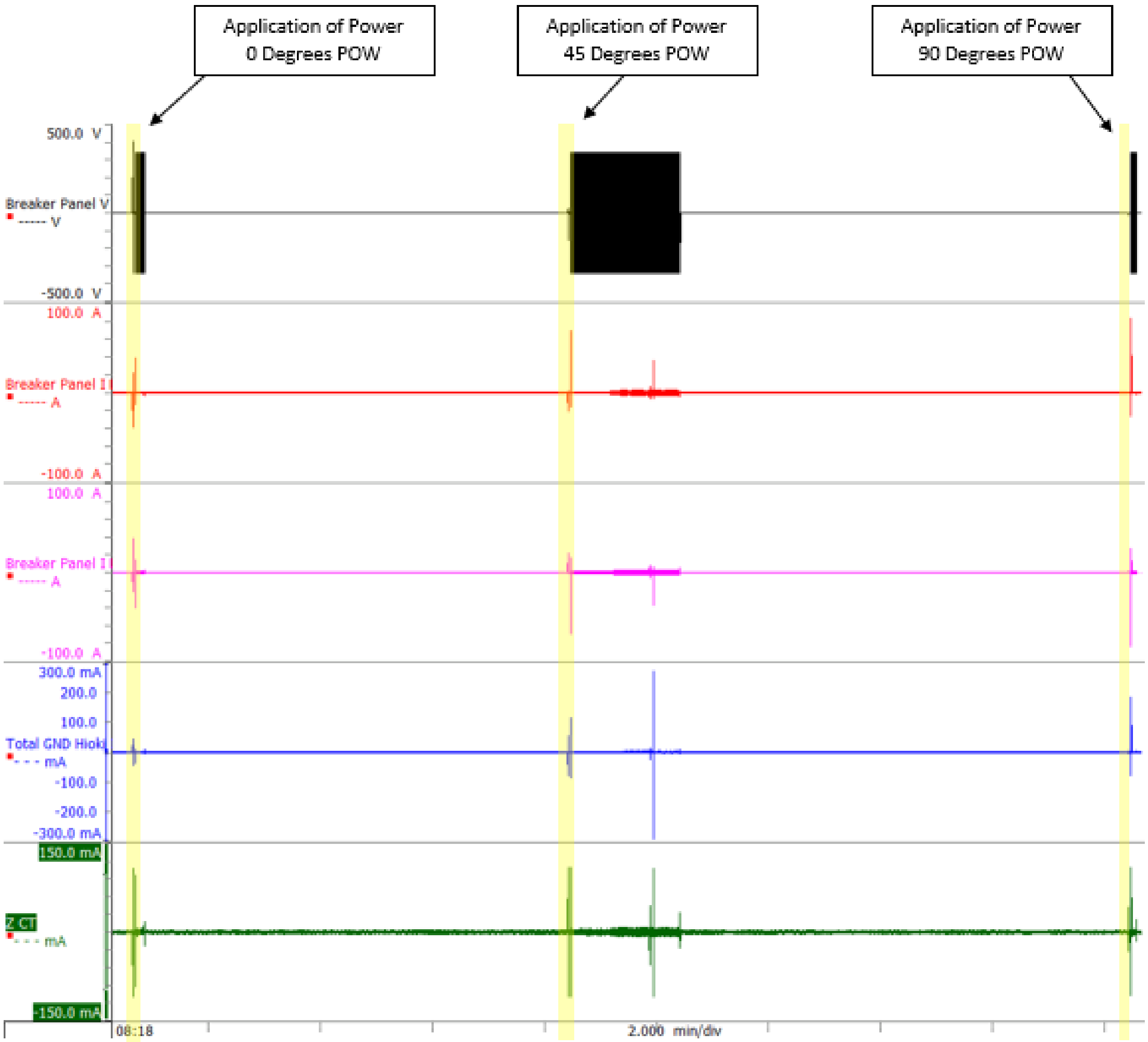


Figure 7-19
Power Applied Chamber Condition 2

Figure 7-20 through Figure 7-22 show the zoomed-in view of the leakage current at 5 milliseconds per division when power was applied at 0 degrees, 45 degrees, and 90 degrees POW sequentially. The zoomed view shows the maximum leakage current was highest during the 45-degree POW test—30 milliamps. The leakage current was present for approximately 5 milliseconds, which may explain why the GFCI circuit breaker did not trip. Some GFCIs are programmed to follow Dalziel's curve; therefore, they may ignore this pulse of current.

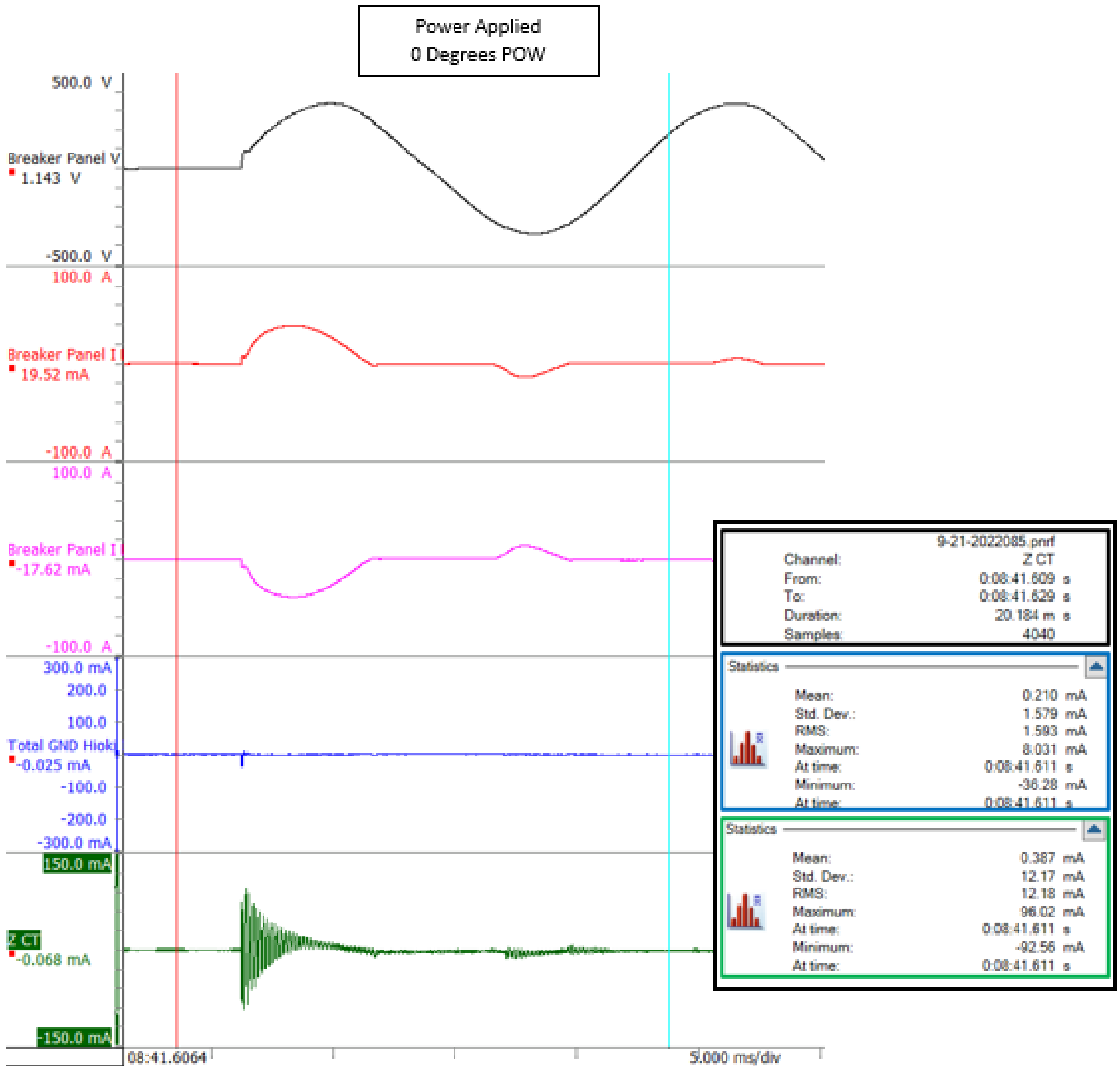


Figure 7-20
Zoomed 0 Degree POW Power Applied Chamber Condition 2

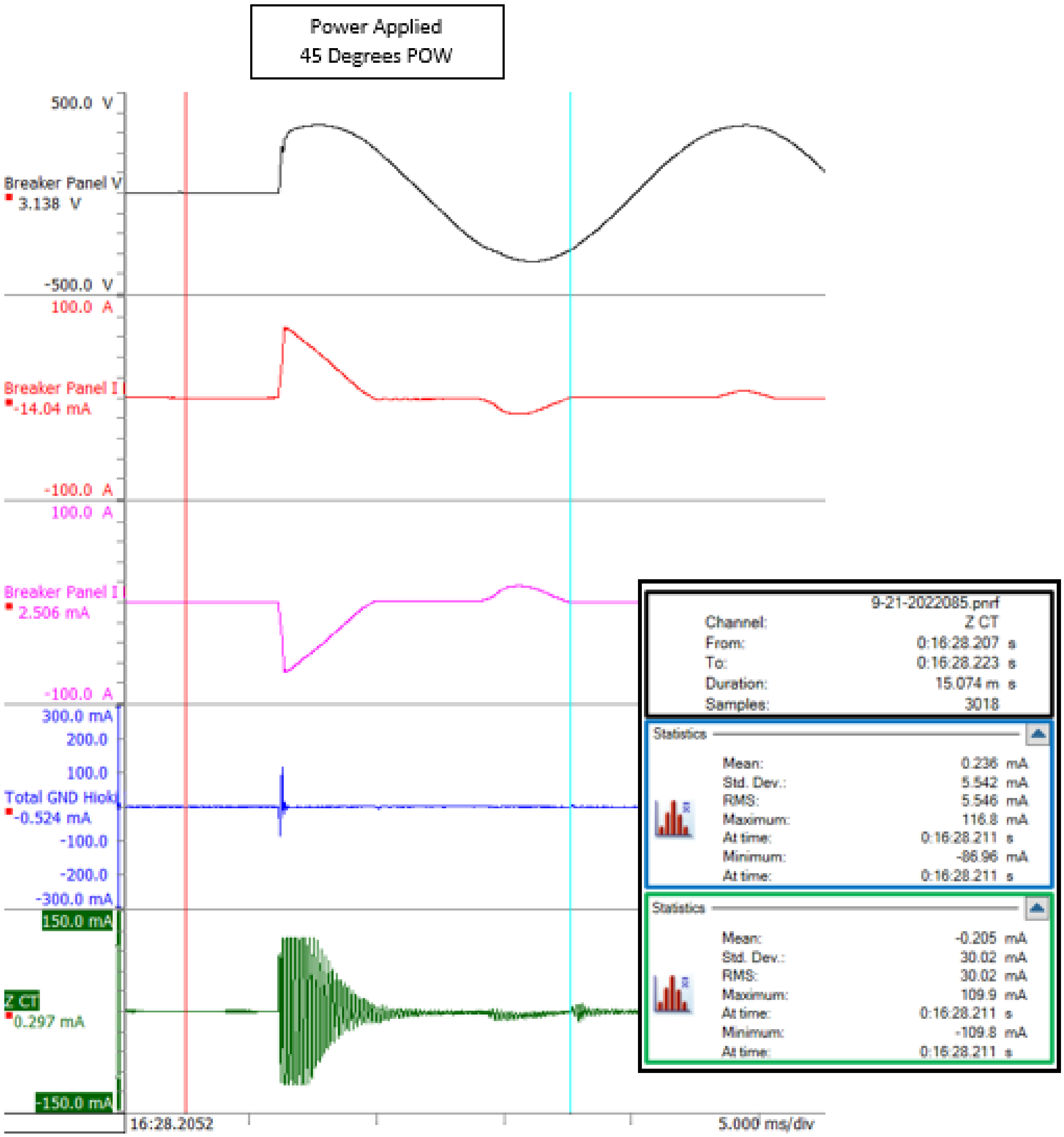


Figure 7-21
Zoomed 45 Degree POW Power Applied Chamber Condition 2

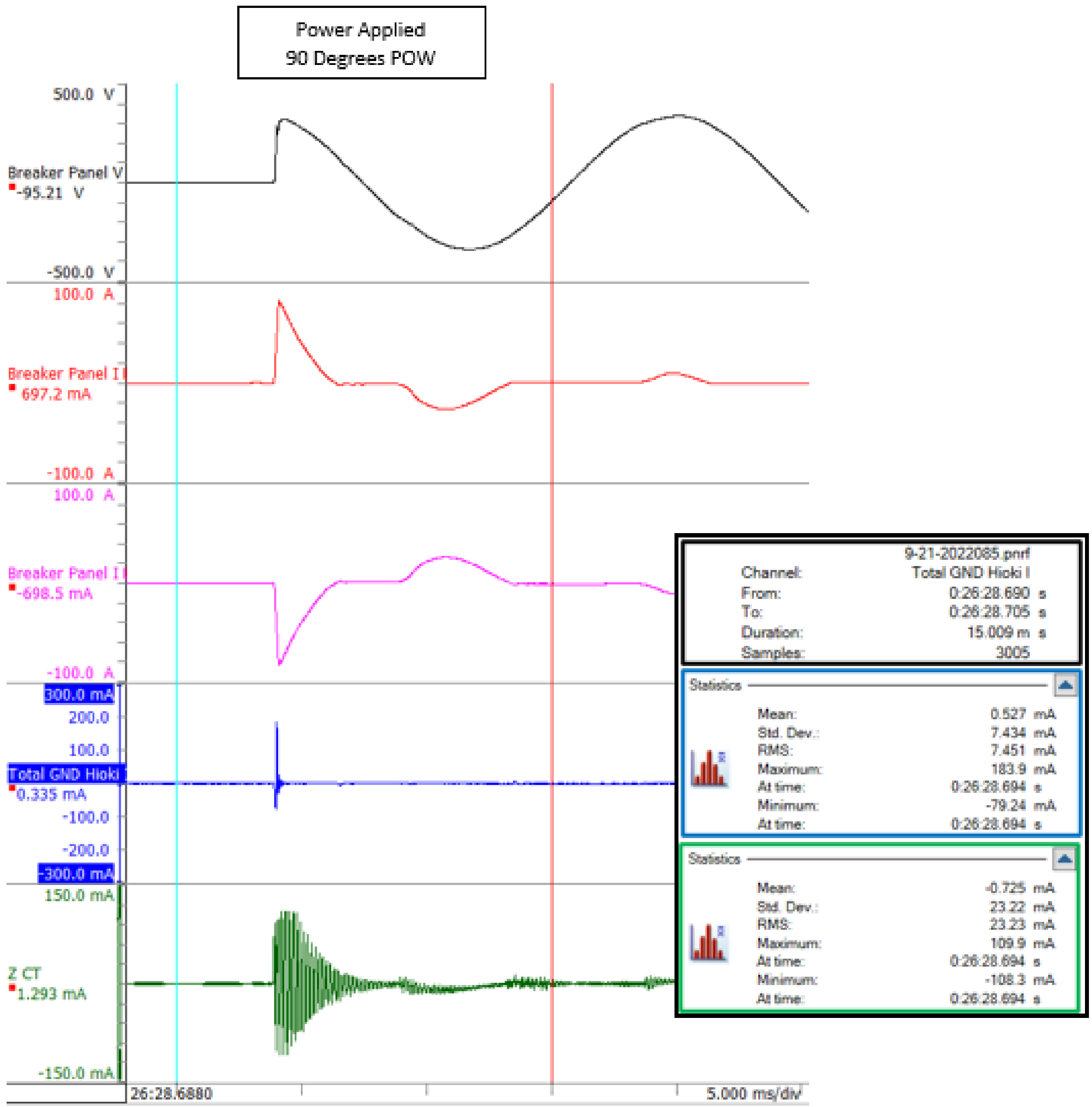


Figure 7-22
Zoomed 90 Degree POW Power Applied Chamber Condition 2

Error! Reference source not found. shows the RMS current values during the time that power w as applied to the circuit when testing was conducted at 0 degrees, 45 degrees, and 90 degrees POW. The data shows the circuit breaker did not trip at any time during the test and the Z-CT, and the measurements did not exceed the maximum current limits as per UL 943.

Table 7-10
Thermal Condition 2, Power Applied POW Tabular Results

Note: All measurements are represented as RMS	**0 Degrees POW**		**45 Degrees POW**		**90 Degrees POW**		
Measurement Time Base	5ms/div		5ms/div		5ms/div		
RMS Measurement Time	20ms		15ms		15ms		
UL 943 Limit	**308mA**	**Within UL 943 Current/Time Limits?**	**377mA**	**Within UL 943 Current/Time Limits?**	**377mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	12mA	Yes	30mA	Yes	23mA	Yes	No
Total GND Hioki Leakage Current	2mA	Yes	6mA	Yes	7mA	Yes	No

Thermal Condition 3 Testing

Error! Reference source not found. shows the oscillography captured by the waveform data l ogger for all three tests while the chambers were configured for the full nominal heating condition shown in **Error! Reference source not found.**. The total scan time was approximately 1 7 minutes. The 240-volt power that supplied the EUT, both phase currents, the leakage current measured by the Hioki CT6700, and leakage current measured by the Z-CT were recorded.

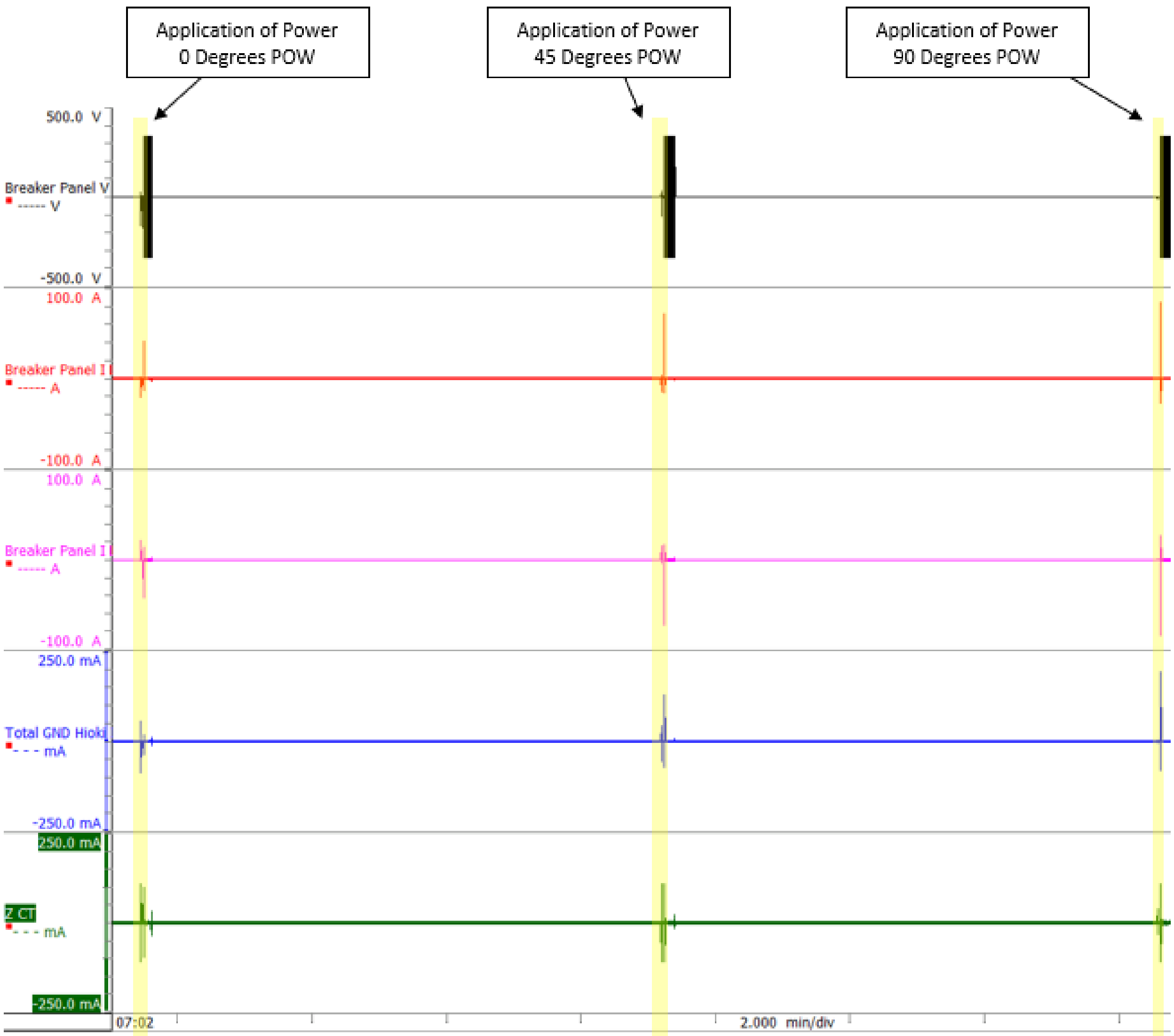


Figure 7-23
Power Applied Chamber Condition 3

Figure 7-24 through Figure 7-26 show the zoomed-in view of the leakage current at 5 milliseconds per division when power was applied at 0 degrees, 45 degrees, and 90 degrees POW sequentially. The zoomed view shows the maximum leakage current was the highest during the 45-degree POW test—29 milliamps. The leakage current was present for less than 5 milliseconds, which may explain why the GFCI circuit breaker did not trip. Some GFCIs are programmed to follow Dalziel's curve; therefore, they may ignore this impulse of current.

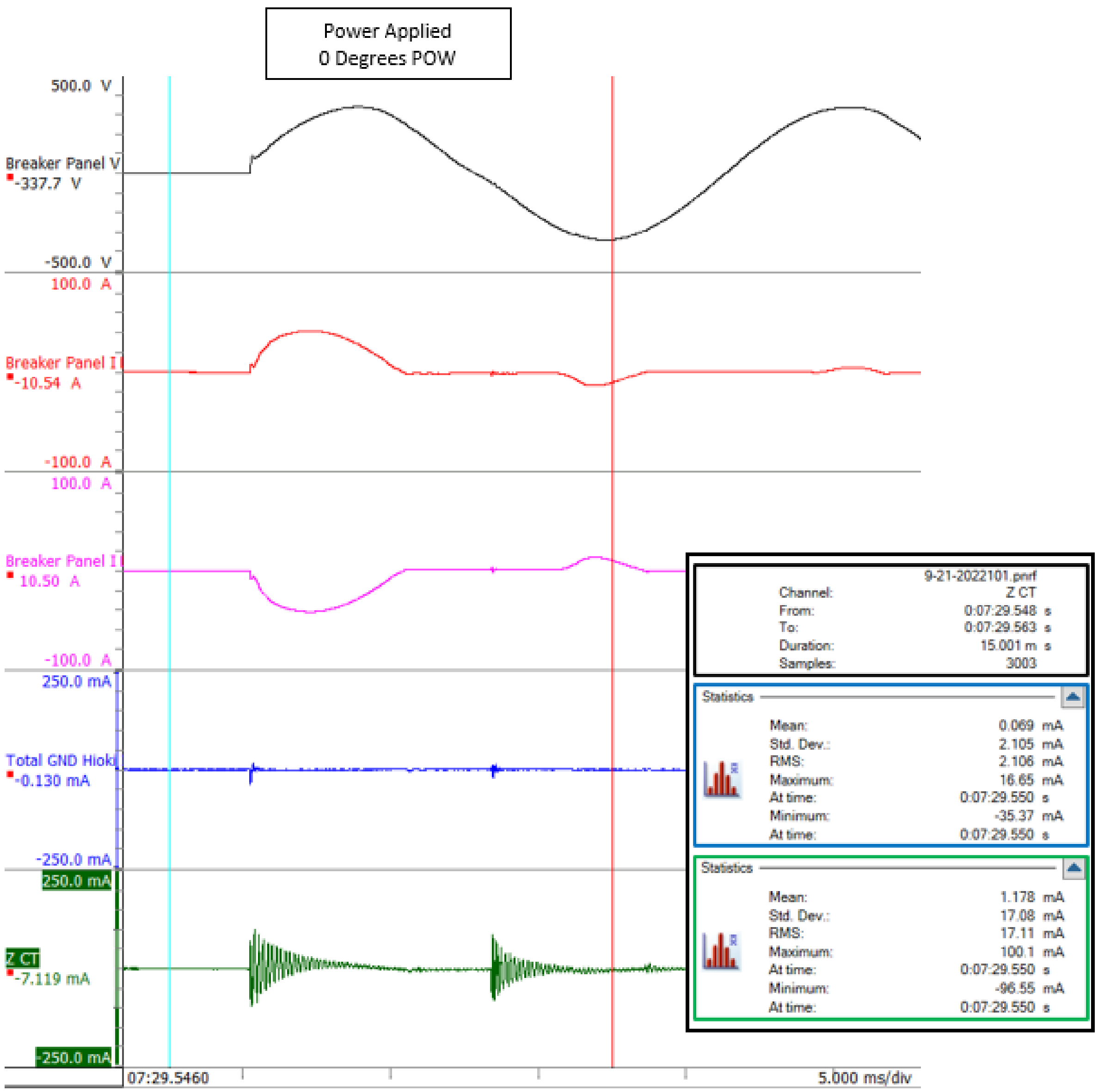


Figure 7-24
Zoomed 0 Degree POW Power Applied Chamber Condition 3

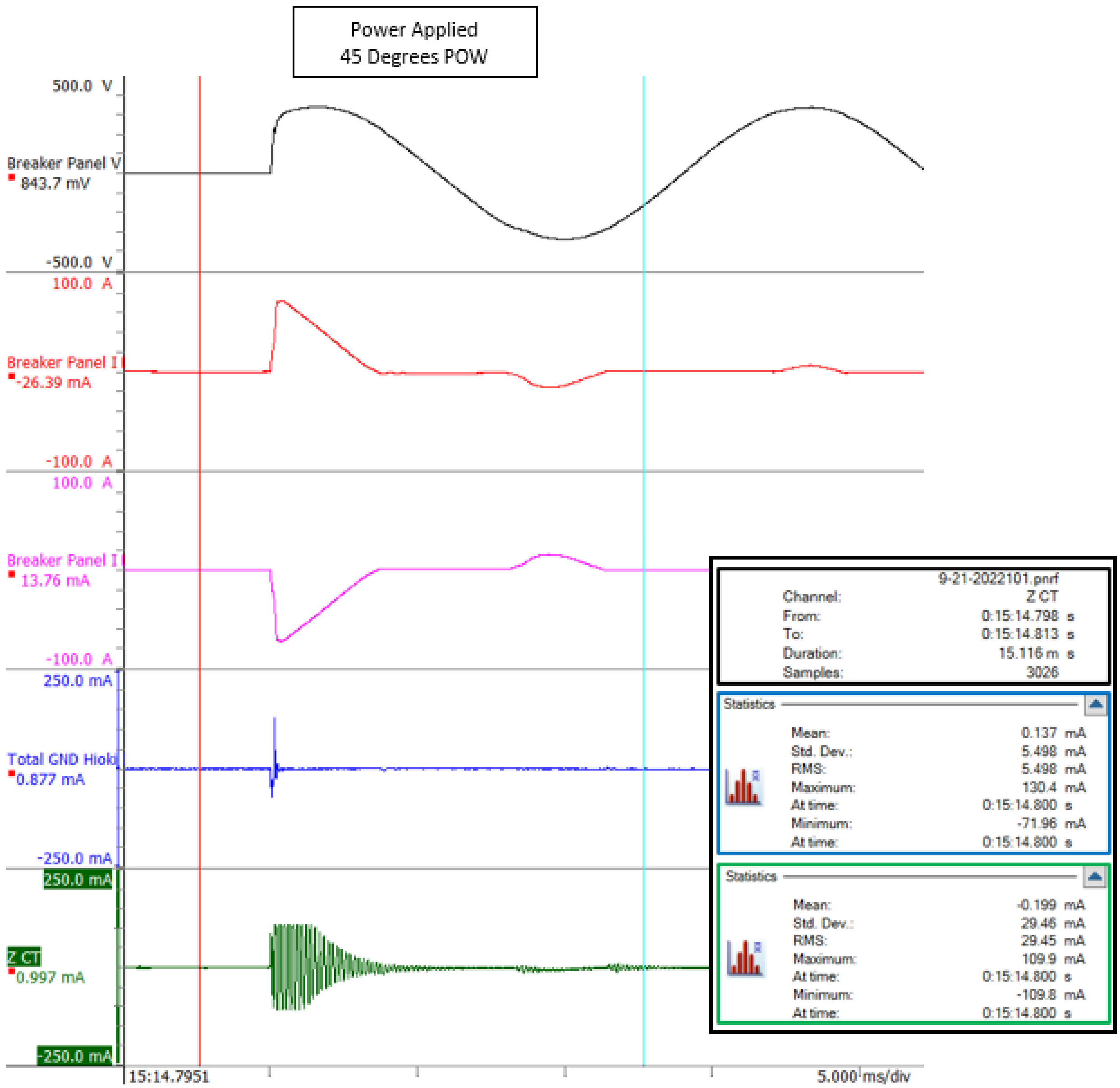


Figure 7-25
Zoomed 45 Degree POW Power Applied Chamber Condition 3

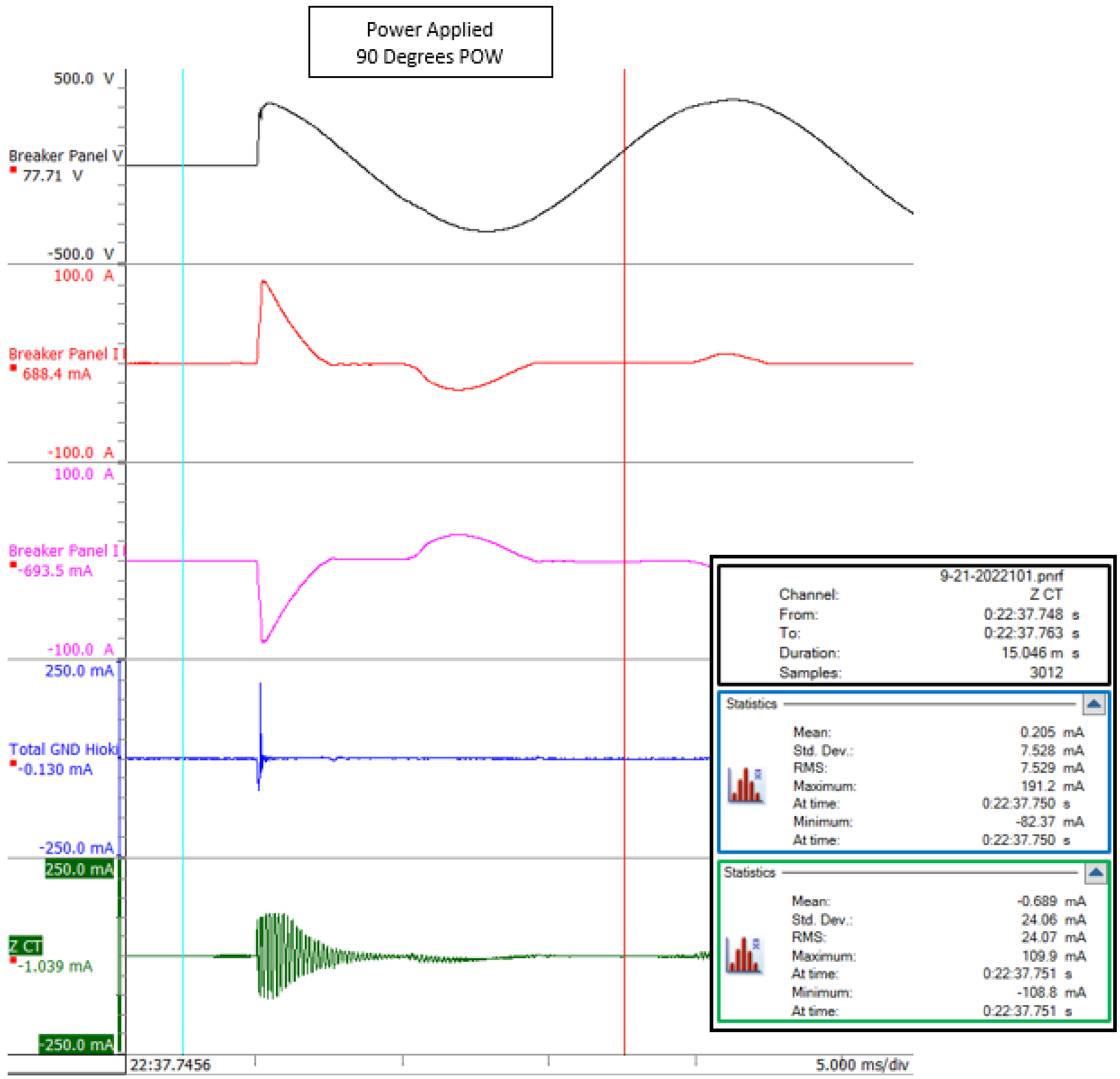


Figure 7-26
Zoomed 90 Degree POW Power Applied Chamber Condition 3

Error! Reference source not found. shows the RMS current values during the time that power w as applied to the circuit when testing was conducted at 0 degrees, 45 degrees, and 90 degrees POW. The data shows the circuit breaker did not trip at any time during the test and the Z-CT, and the measurements did not exceed the maximum current limits as per UL 943.

Table 7-11
Thermal Condition 3, Power Applied POW Tabular Results

Note: All measurements are represented as RMS	**0 Degrees POW**		**45 Degrees POW**		**90 Degrees POW**		
Measurement Time Base	5ms/div		5ms/div		5ms/div		
RMS Measurement Time	15ms		15ms		15ms		
UL 943 Limit	**377mA**	**Within UL 943 Current/Time Limits?**	**377mA**	**Within UL 943 Current/Time Limits?**	**377mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	17mA	Yes	29mA	Yes	24mA	Yes	No
Total GND Hioki Leakage Current	2mA	Yes	5mA	Yes	8mA	Yes	No

Test 1 Conclusion

The purpose of the Power Applied test was to determine if the amount of leakage current changes based on when power was applied. Power was applied at 0 degrees POW, 45 degrees POW, and 90 degrees POW using the voltage sag generator, allowing 7 minutes between tests. The voltage sag generator was connected between the power amplifier and the primary of the split-phase transformer. The testing was conducted as per the test protocol while the thermal chambers were set to each of the temperature modes shown in **Error! Reference source not f ound.**. The GFCI circuit breaker did not trip for any of the tests. Maximum leakage current between 21 milliamps RMS and 30 milliamps RMS was measured by the Z-CT when power was applied at 45-degrees POW The data shows leakage current was higher when voltage was applied at 45-degrees POW and 90-degrees POW than 0-degress POW. The test data also shows the chamber temperature did not appear to affect the leakage current when power was applied.

Test 2 HVAC Running

It is important to understand the power profile of the EUT throughout a cycle from nominal temperature to arrival at a set temperature. The purpose of this test was to determine the maximum leakage current from the time power is applied to the EUT and while the unit operates for one-hour. This test was conducted while the thermal chambers were configured to condition 1 shown in **Error! Reference source not found.**. The monitoring was conducted while t he HBM Gen 3i was configured to collect data at 250 kilo samples per second; therefore, the measurement was collected across three separate files to reduce the size per file. The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** shows the m aximum RMS leakage current measured by the Z-CT recorded during each test, whether the current was within UL 943 limits, if the GFCI tripped, and the relative humidity of the temperature chamber during the test.

Table 7-12
ZCT Leakage Current Data from HVAC Running Test

Acquisition File (one per 20 minutes for 1 hour)	ZCT Leakage Current (mA_{RMS}/time)	Within UL943 Current/Time Limits?	GFCI Trip?	Outdoor Chamber Humidity
1	Compressor Enabled Start $24mA_{RMS}$/1.17ms	Yes	No	38%
2	Compressor Step Change $34mA_{RMS}$/2.01ms	Yes	No	38%
3	Compressor Step Change $28mA_{RMS}$/2.21ms	Yes	No	38%

First 20-Minute Time Segment

Error! Reference source not found. shows the voltage, current, leakage current measured by t he Hioki CT6700, and leakage current measured by the Z-CT of the EUT during the first 20 minutes of the 1-hour test run. Power was applied and 3 minutes later, the compressor was enabled.

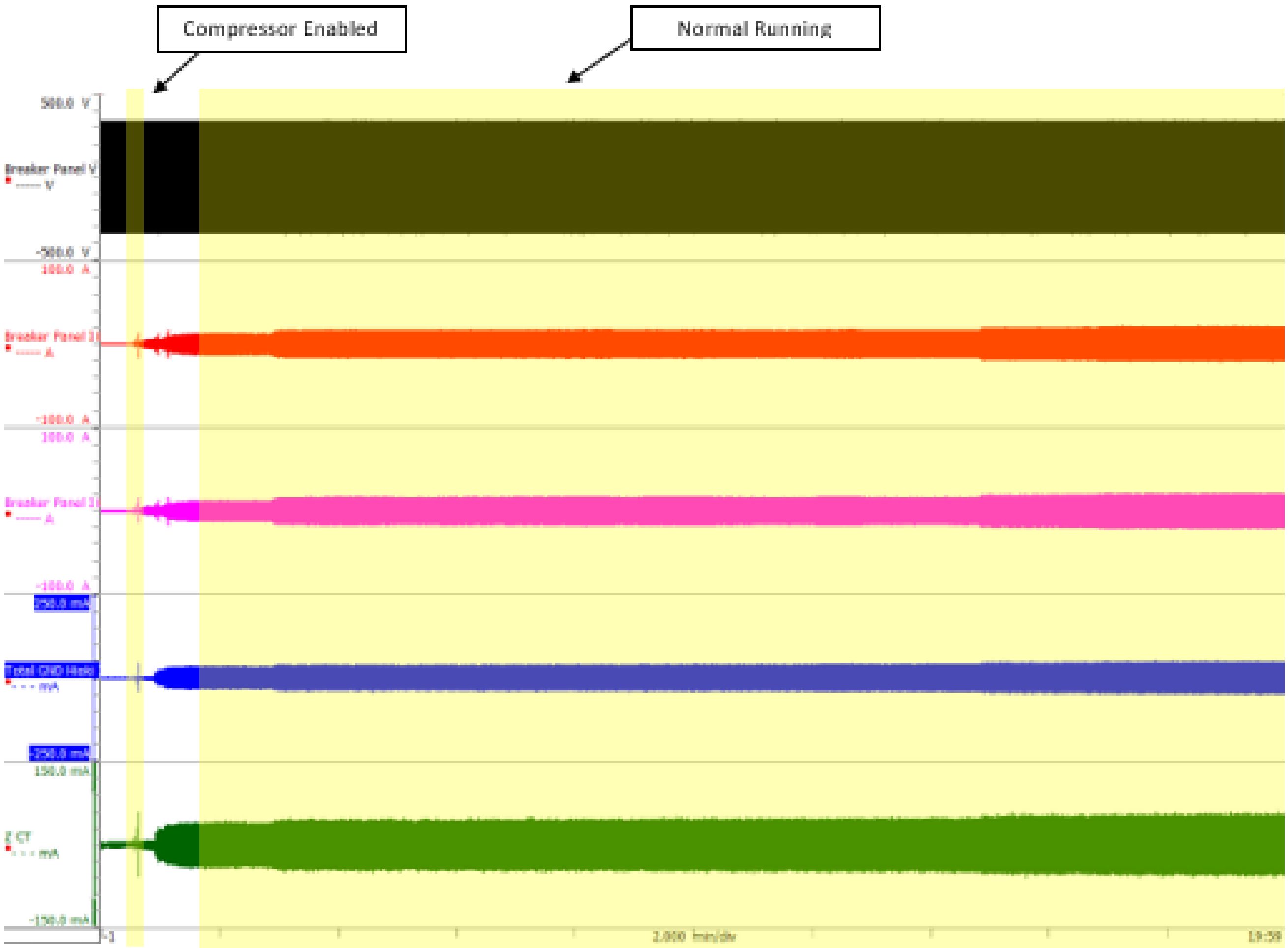


Figure 7-27
First 20 Minutes of HVAC Running Test

Figure 7-28 shows maximum RMS leakage current measured by the Z-CT was 24 milliamps for approximately 1 millisecond when the DC bus was enabled.

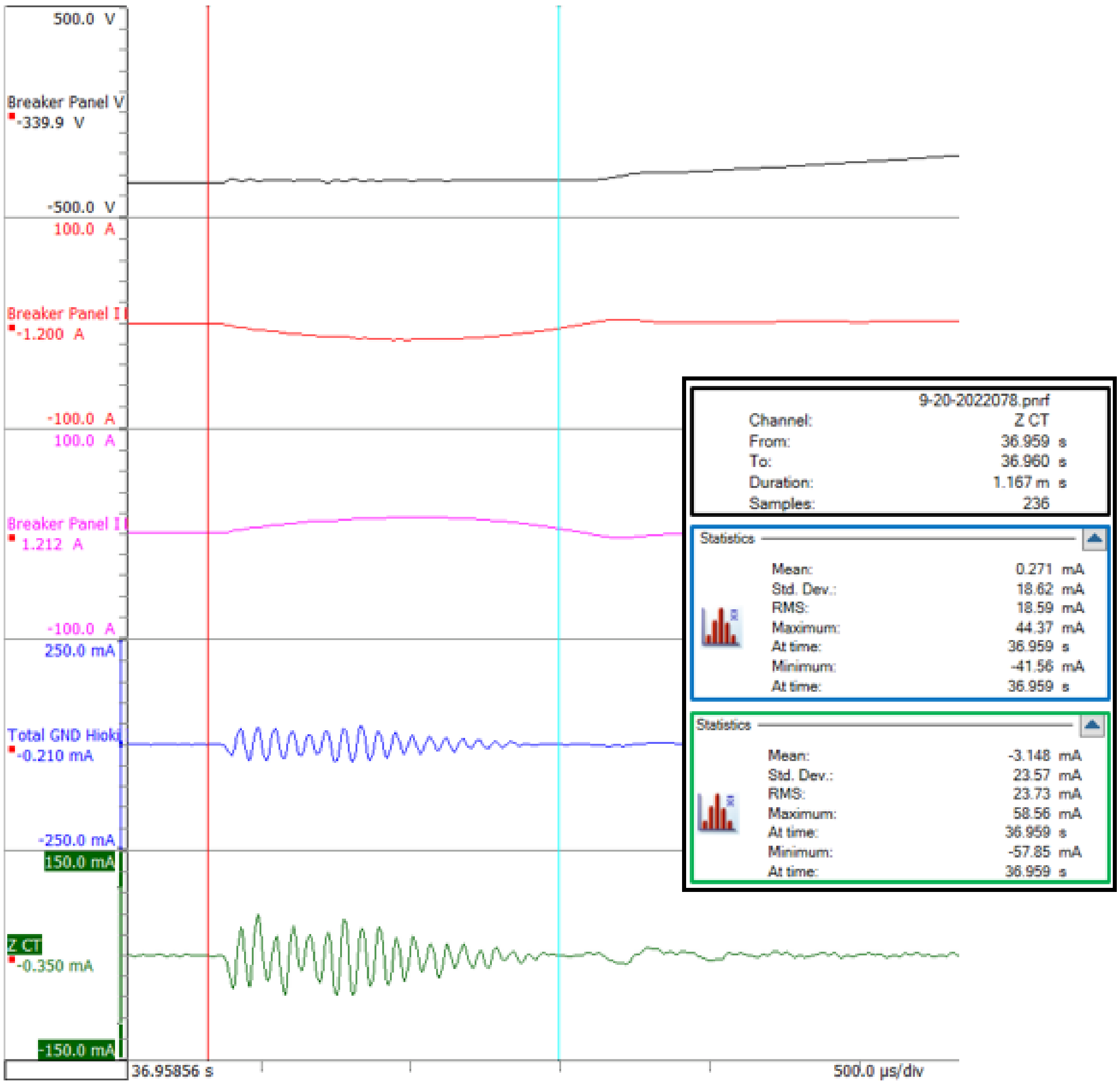


Figure 7-28
Leakage Current at DC Bus Enable

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the first 20-minute time segment of the HVAC Running test. Note that the leakage current was higher during the compressor enable phase of the test verses the normal running leakage current. The leakage current was higher for a very short time period during the compressor enable time period; therefore, it falls within the acceptable current levels of the UL 943 time/current curve. Although the RMS leakage current was lower during the normal running segment of the test, the leakage current was much higher than the UL 943 allowable limits. The GFCI may not have tripped because a very small portion of the current measured by the Z-CT was 60 Hz while the majority of the leakage current was in the 6 kHz range. The GFCI may not react to the high frequency current. This is discussed in greater detail in the conclusion section of Test 0.

Table 7-13
Tabular Data: First 20 Minutest HVAC Running Test

Note: All measurements are represented as RMS	**Compressor Enabled**		**Normal Running**		
Measurement Time Base	500µs/div		2min/div		
RMS Measurement Time	1.17ms		19min 7sec		
UL 943 Limit	**2245mA**	**Within UL 943 Current/Time Limits?**	**6mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	24mA	Yes	15mA	No	No
Total GND Hioki Leakage Current	19mA	Yes	15mA	No	No

Middle 20 Minute Time Segment

Error! Reference source not found. shows the voltage, current, leakage current measured by t he Hioki CT6700, and leakage current measured by the Z-CT of the EUT during the second 20 minutes of the 1-hour test run. The maximum leakage current during this segment appears to have occurred when the compressor made a step change in speed thus increasing the nominal current.

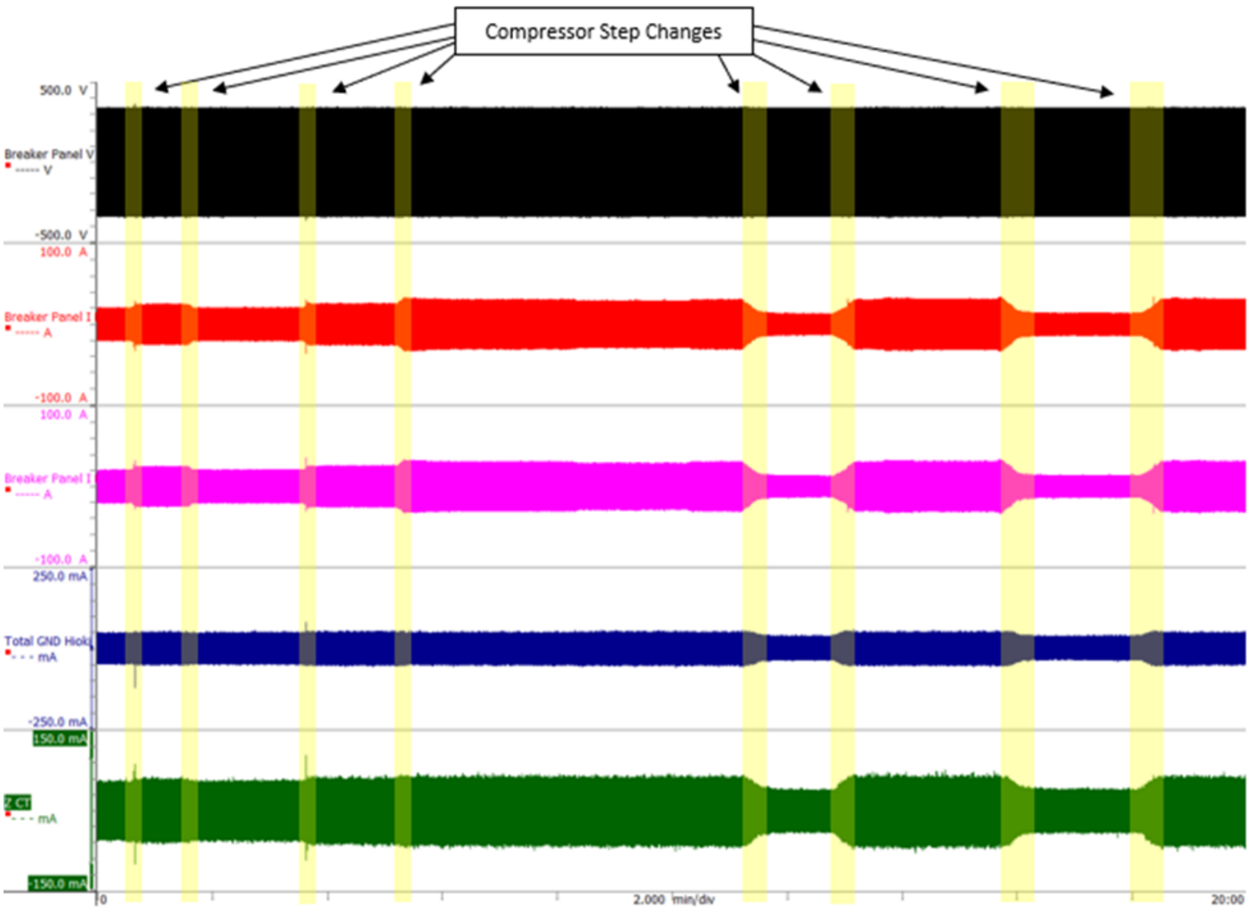


Figure 7-29
Second 20 Minute Segment of HVAC Running Test

Figure 7-30 shows the RMS leakage current measured by the Z-CT increased to 34 milliamps when the compressor made a step change. The leakage current quickly decreased approximately 2 milliseconds after the step change.

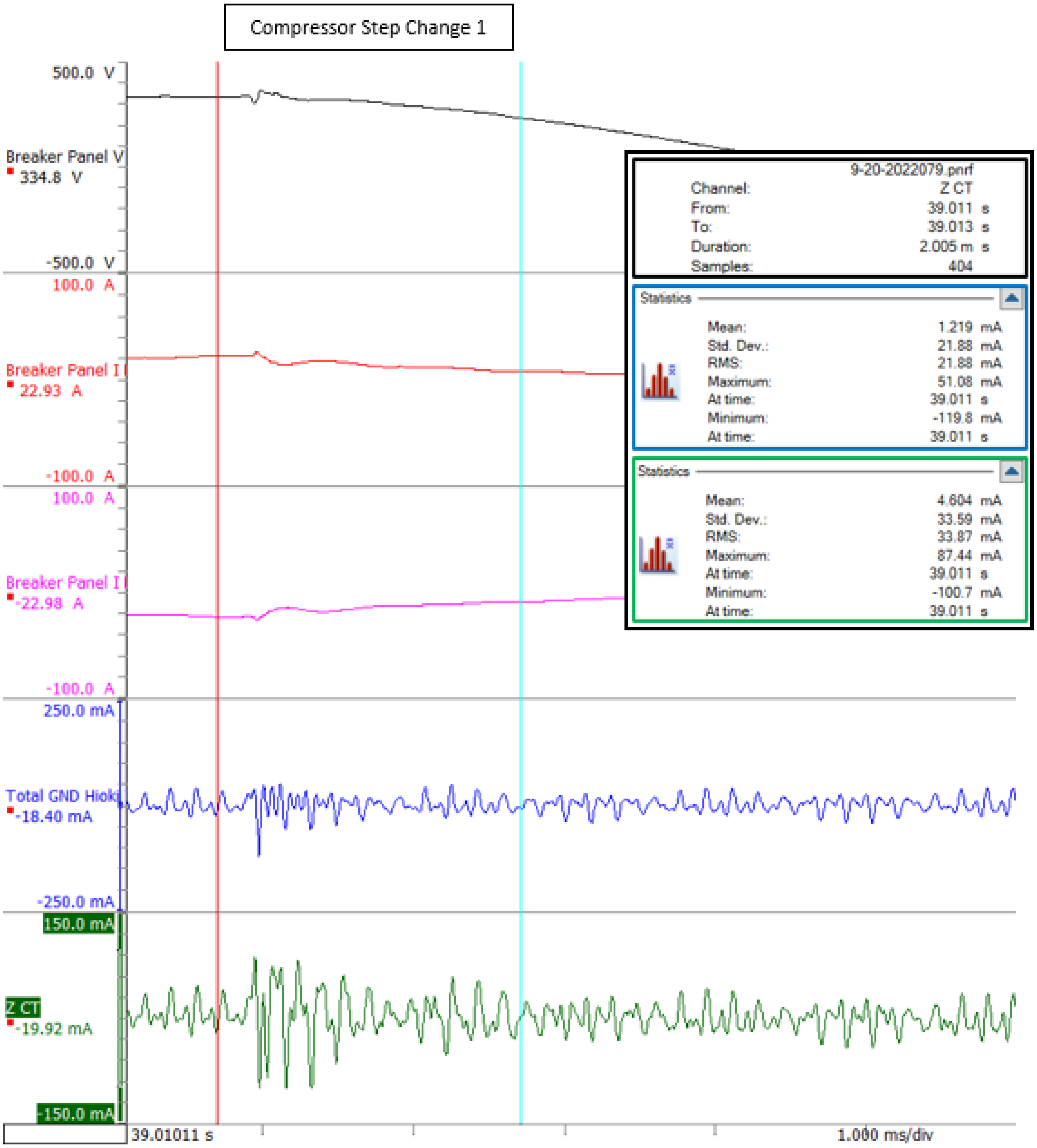


Figure 7-30
Leakage Current at Compressor Step Change 1

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the middle 20-minute time segment of the HVAC Running test.

Table 7-14
Tabular Data: Middle 20 Minutest HVAC Running Test

Note: All measurements are represented as RMS	Step Change 1	Step Change 2	Step Change 3	Step Change 4	Step Change 5	Step Change 6	Step Change 7	Step Change 8		
RMS Measurement Time	2.01ms	4.37sec	2.06sec	6.16sec	15.9sec	18.0sec	21.1sec	15.4sec		
UL 943 Limit	1538 mA	7 mA	12 mA	6 mA	6 mA	6 mA	6 mA	6 mA	Within UL943 Current/ Time Limits?	GFCI Trip?
ZCT Total Leakage Current	34mA	16mA	17mA	17mA	17mA	16mA	17mA	17mA	No	No
Total GND Hioki Leakage Current	22mA	16mA	16mA	16mA	16mA	16mA	16mA	16mA	No	No

Final 20-Minute Time Segment

Error! Reference source not found. shows the voltage, current, leakage current measured by t he Hioki CT6700, and leakage current measured by the Z-CT of the EUT during the final 20-minutes of the 1-hour test run. The maximum leakage current during appears to have occurred when the compressor made a step change in speed thus increasing the nominal current.

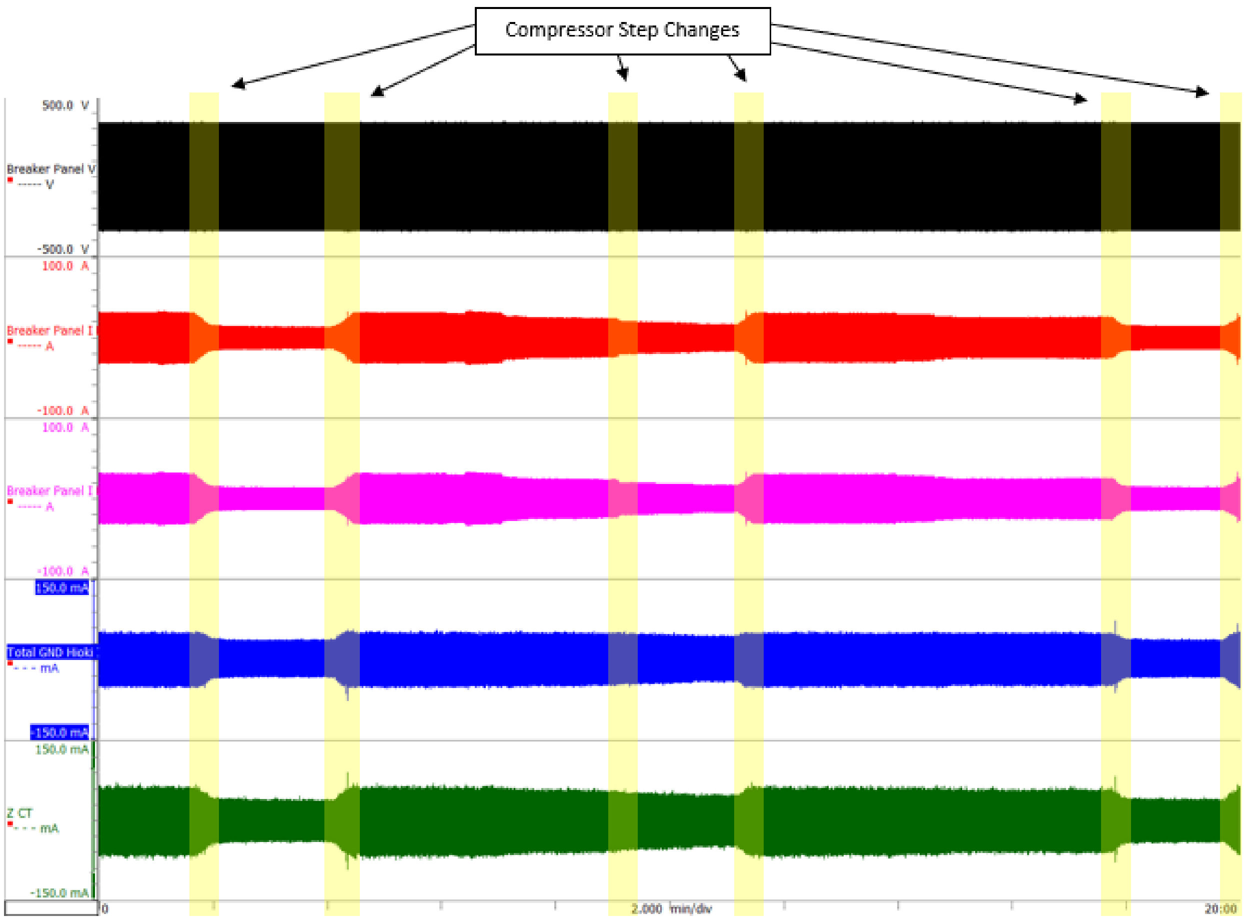


Figure 7-31
Final 20 Minute Segment of HVAC Running Test

Figure 7-32 shows the RMS leakage current measured by the Z-CT increased to 28 milliamps when the compressor made another step change. The leakage current quickly decreased after approximately 2 milliseconds.

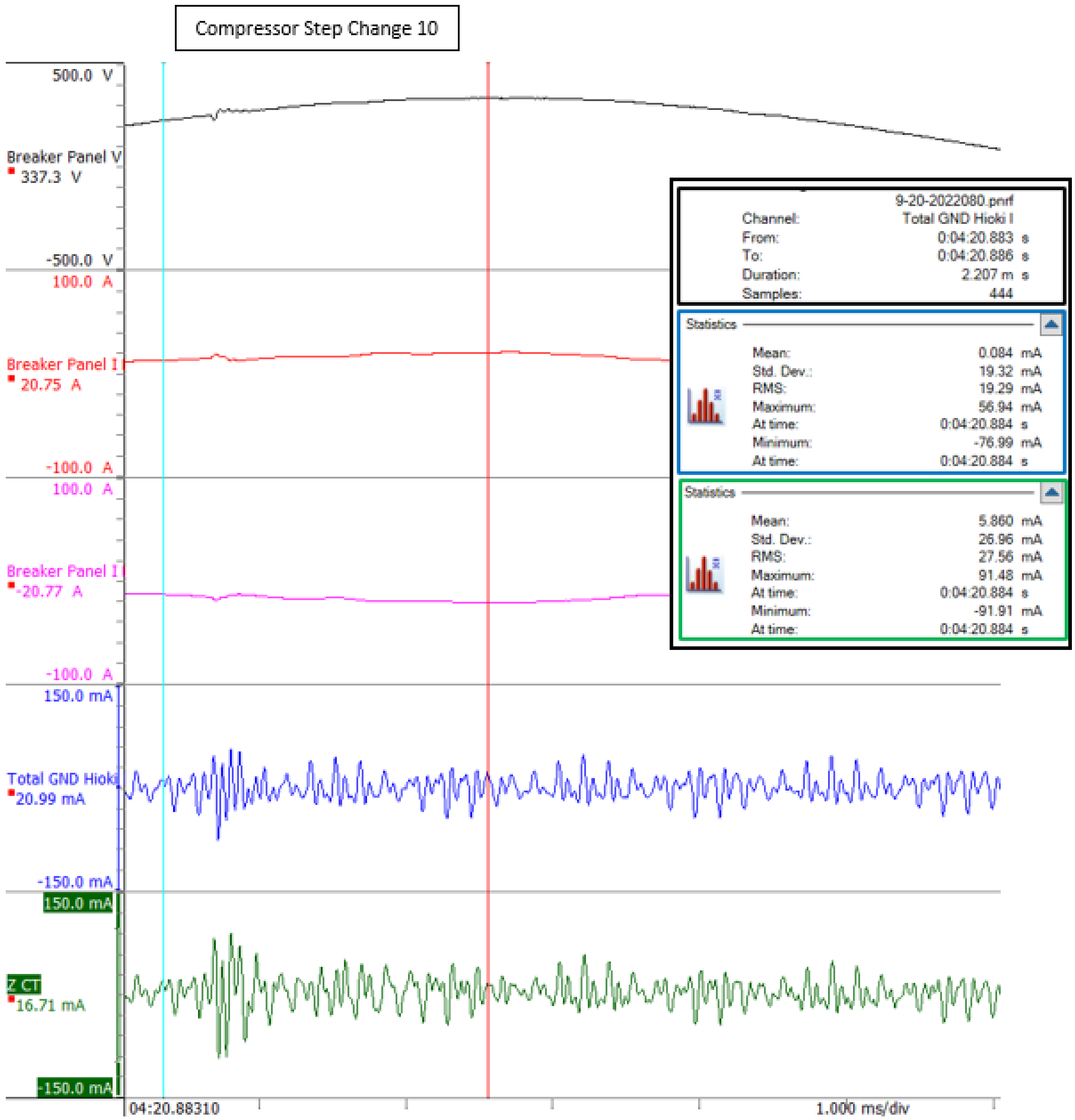


Figure 7-32
Leakage Current at Compressor Step Change 2

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the final 20-minute time segment of the HVAC Running test.

Table 7-15
Tabular Data: Final 20 Minutest HVAC Running Test

Note: All measurements are represented as RMS	Step Change 9	Step Change 10	Step Change 11	Step Change 12	Step Change 13	Step Change 14		
RMS Measurement Time	14.4ms	2.21ms	2.316sec	13.4sec	8.22sec	15.7sec		
UL 943 Limit	6 mA	1439 mA	11 mA	6 mA	6 mA	6 mA	Within UL943 Current/ Time Limits?	GFCI Trip?
ZCT Total Leakage Current	17mA	28mA	16mA	17mA	16mA	16mA	No	No
Total GND Hioki Leakage Current	15mA	19mA	15mA	15mA	15mA	15mA	No	No

Test 2 Conclusion

The purpose of the HVAC Running test was to measure the power profile and leakage current during a normal operating cycle. Power was applied to the system for one hour and the system was operated with the thermal chambers operating in the nominal baseline mode (Thermal Condition 1). The data was captured in three 20-minute chunks as the file size was very large. The data shown in **Error! Reference source not found.** shows maximum leakage current of 23 m illiamps was observed when the DC Bus was enabled or the compressor experienced step changes. Although the leakage current was greater than 6 milliamps the current was only present for 1.7 milliseconds, therefore; the current was at an acceptable level as per the time/current curve of UL 943. The EUT was permitted to operate for one hour in which the EUT was permitted to cool or heat depending on the thermal condition of the test chambers. During this time, the Z-CT measured 15 milliamps of RMS leakage current for about 15 minutes which is above the allowable limits in UL 943 of 6 milliamps. The FFT shown in Figure 7-14 located in the conclusion section of Test 0 shows the majority of the leakage current when the EUT is running lies in the 6 kHz range while the leakage current at 60 Hz is only about 4 mA which is within the limits of UL 943.

Test 3 Thermostat Cycling

HVAC systems do not typically operate continuously as they cycle on and off as needed to maintain the temperature setpoint. The purpose of the thermostat cycling test is to determine the maximum leakage current when the HVAC unit cycles on and off. The HVAC system that was tested contained 5 zones. These zones were manually toggled on and off once every 5 minutes for a one-hour period. This test was conducted once at each thermal condition shown in **Error! Reference source not found.**. The monitoring was conducted while the HBM Gen 3i w as configured to collect data at 250 kilo samples per second; therefore, the measurement was collected across three separate files to reduce the size per file. The detailed test procedures may be seen in Appendix A. **Error! Reference source not found.** shows the maximum RMS l eakage current measured by the Z-CT recorded during each test, whether the current was within UL 943 limits, if the GFCI tripped, and the relative humidity of the temperature chamber during the test.

Table 7-16
Tabular Data from Thermostat Cycling Test

Temperature Chamber Condition	Highest Measured ZCT Leakage Current (mA_{RMS}/time)	Within UL943 Current/Time Limits?	GFCI Trip?	Outdoor Chamber Humidity
1	Application of Power 27mA_{RMS}/5.36ms (1) DC Bus Enable 28mA_{RMS}/3.99ms (2) Compressor Step Change 26mA_{RMS}/4.11ms (3)	Yes	No	39%
2	DC Bus Enable 27mA_{RMS}/4.69ms (1) DC Bus Enable 41mA_{RMS}/6.23ms (2) DC Bus Enable 33mA_{RMS}/9ms (3)	Yes	No	23%
3	Application of Power 40mA_{RMS}/8.50ms (1) DC Bus Enable 21mA_{RMS}/4.00ms(2) DC Bus Enable 15mA_{RMS}/6.71ms (3)	Yes	No	56% (possible probe error)

Nominal Baseline Condition Testing

The first test was conducted with the thermal chambers configured for condition one, or Nominal Baseline. The waveforms show the voltage, current, and leakage current measured by the Hioki CT6700, and leakage current measured by the Z-CT while the thermal chambers were operating in the nominal baseline configuration. Figure 7-33 shows the first 20 minutes of the thermostat cycling test with nominal baseline conditions.

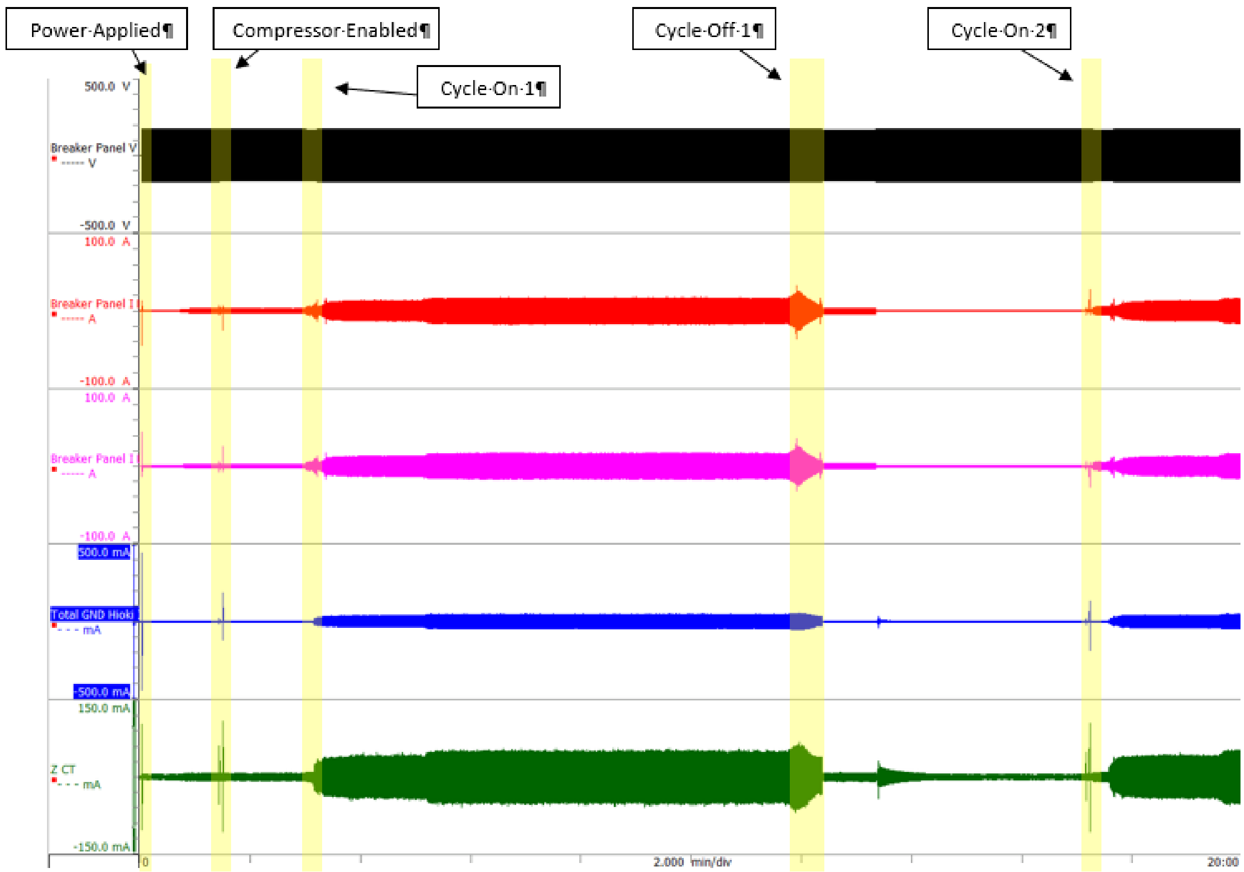


Figure 7-33
Nominal Baseline, First 20 Minutes, Thermostat Cycling Test

Figure 7-34 shows the greatest leakage current during the first 20 minutes, which occurred when power was applied by turning on power through the knife-switch. The maximum RMS leakage current measured by the Z-CT was 26 milliamps for 5 milliseconds.

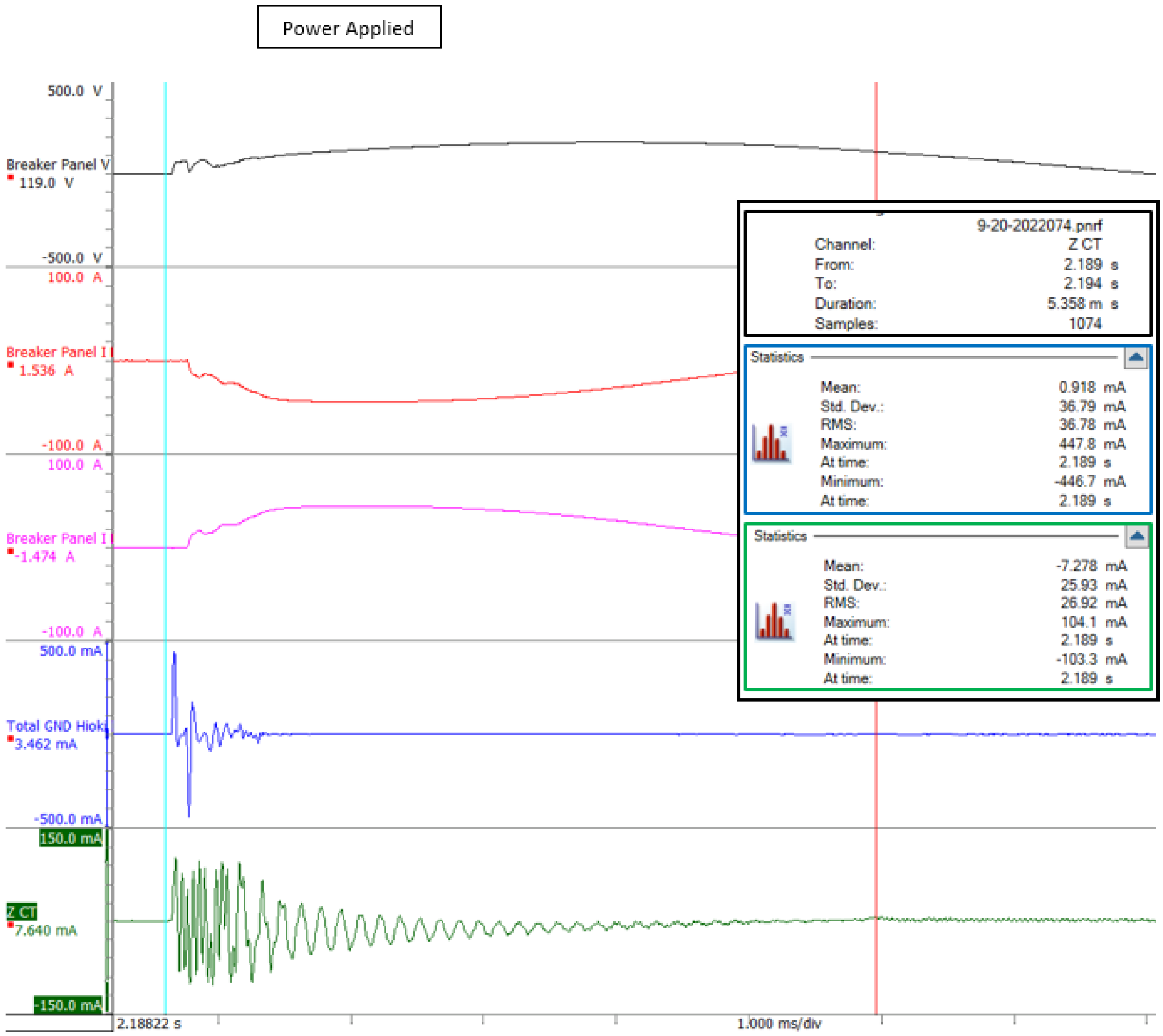


Figure 7-34
Highest Leakage Current, Nominal Baseline, First 20 Minutes, Thermostat Cycling Test

The second 20-minute span of the test is shown in Figure 7-35. The waveform shows the greatest leakage current during the second 20 minutes occurred when the compressor turned on after being off for a 5-minute period.

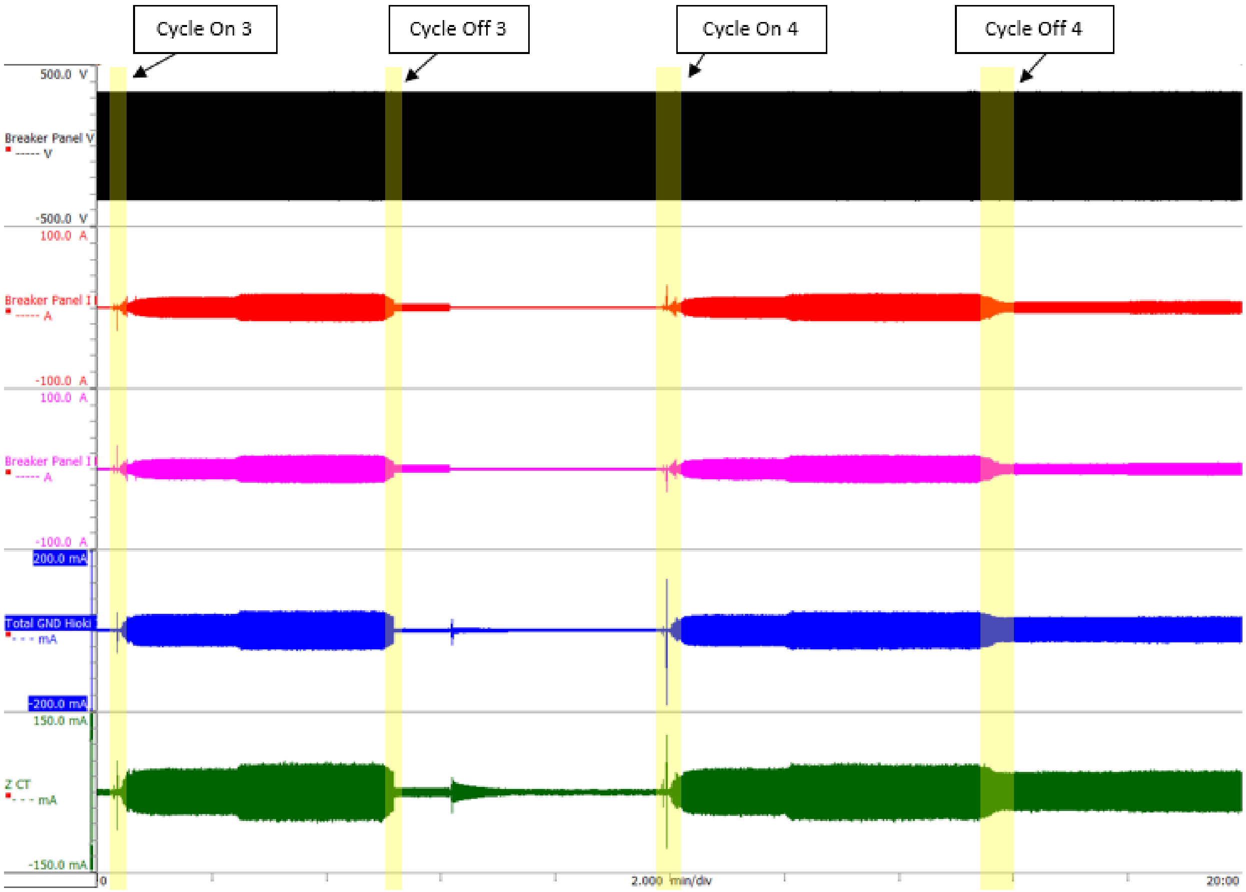


Figure 7-35
Nominal Baseline, Second 20 Minutes, Thermostat Cycling Test

Figure 7-36 shows the maximum RMS leakage current measured by the Z-CT was 28 milliamps for approximately 4 milliseconds.

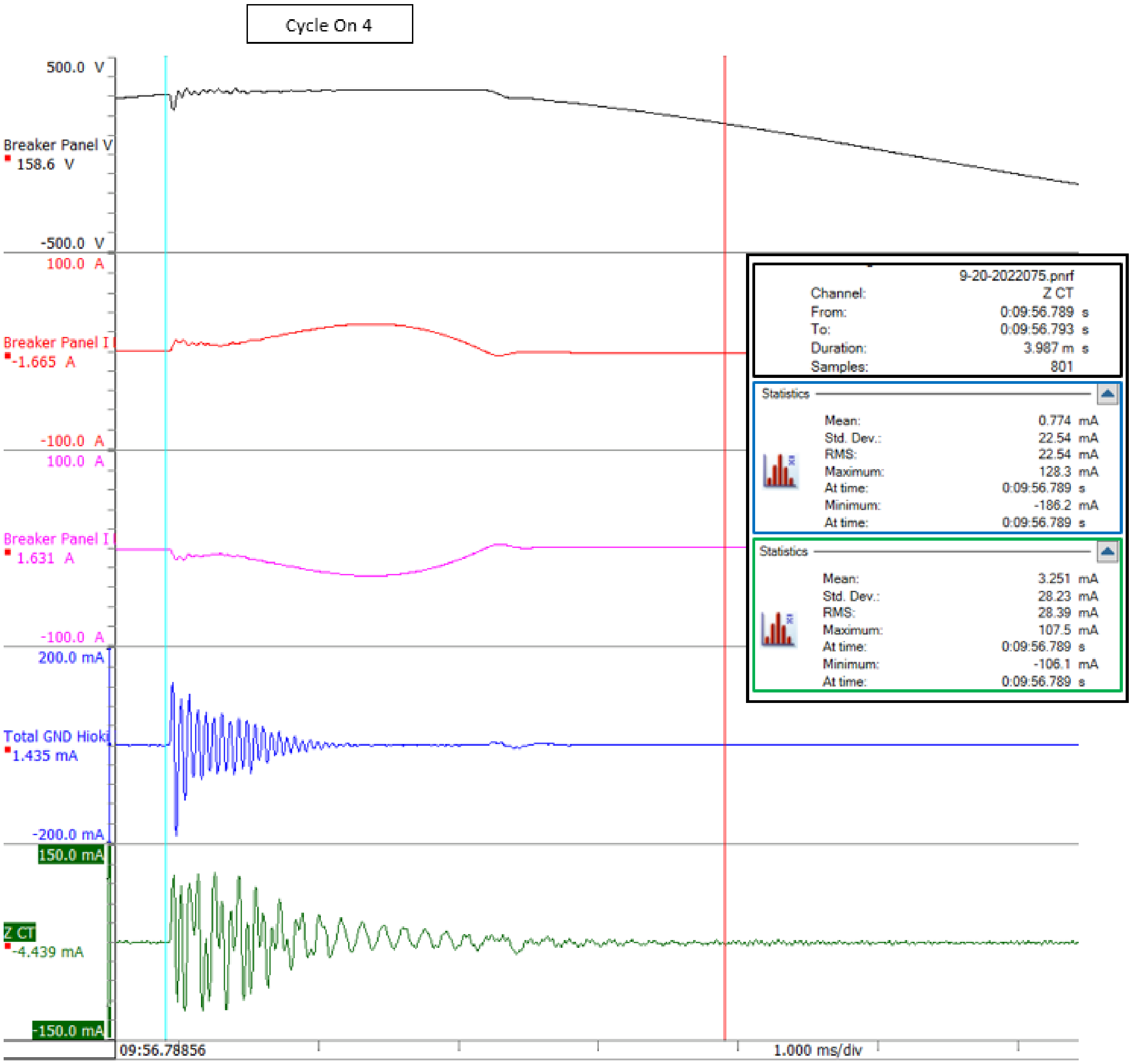


Figure 7-36
Highest Leakage Current, Nominal Baseline, Second 20 Minutes, Thermostat Cycling Test

Figure 7-37 shows the final 20 minutes of the thermostat cycling test with nominal baseline conditions. The greatest RMS leakage current measured by the Z-CT during the final 20 minutes occurred when the compressor made a step change (turned off) after being on for a 5-minute period.

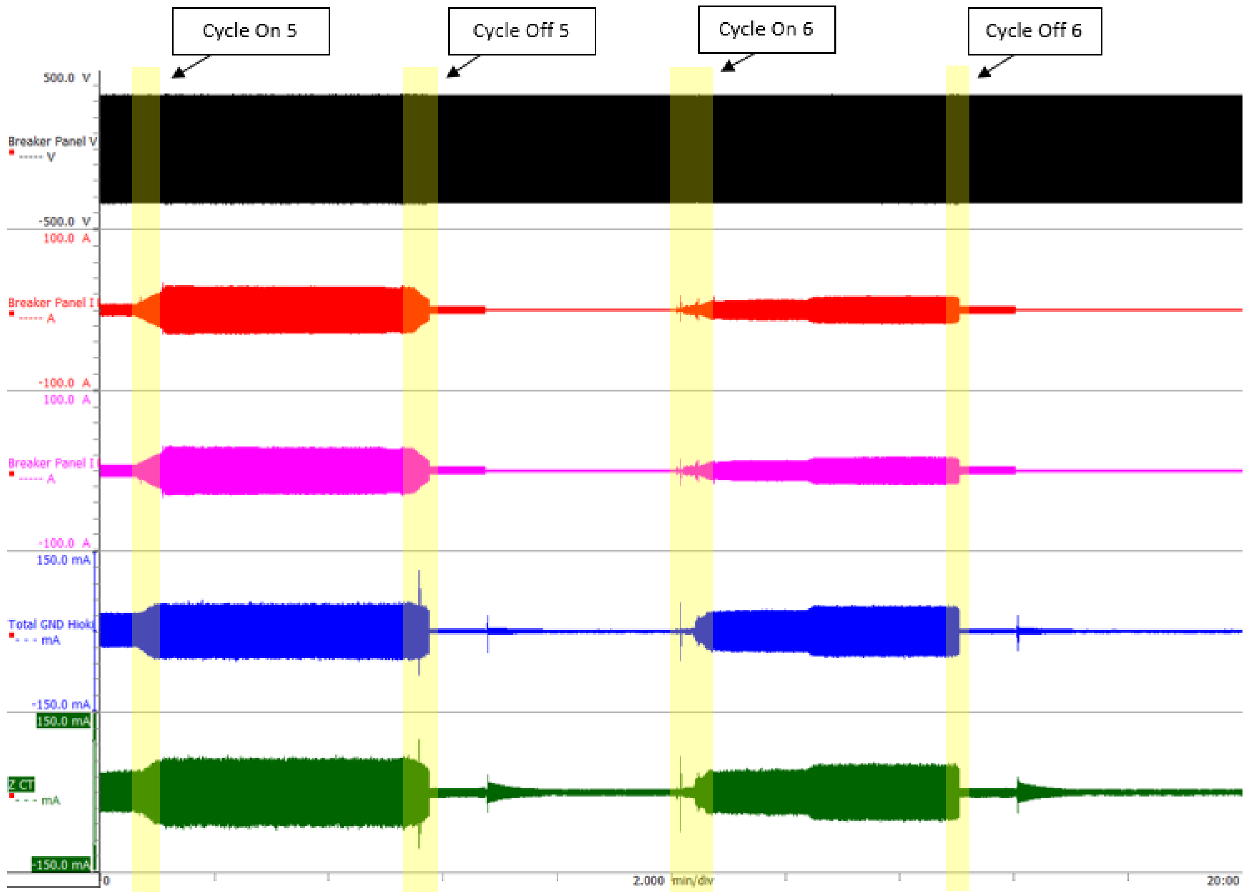


Figure 7-37
Nominal Baseline, Last 20 Minutes, Thermostat Cycling Test

Figure 7-38 shows the maximum RMS leakage current measured by the Z-CT was 26 milliamps for approximately 4 milliseconds.

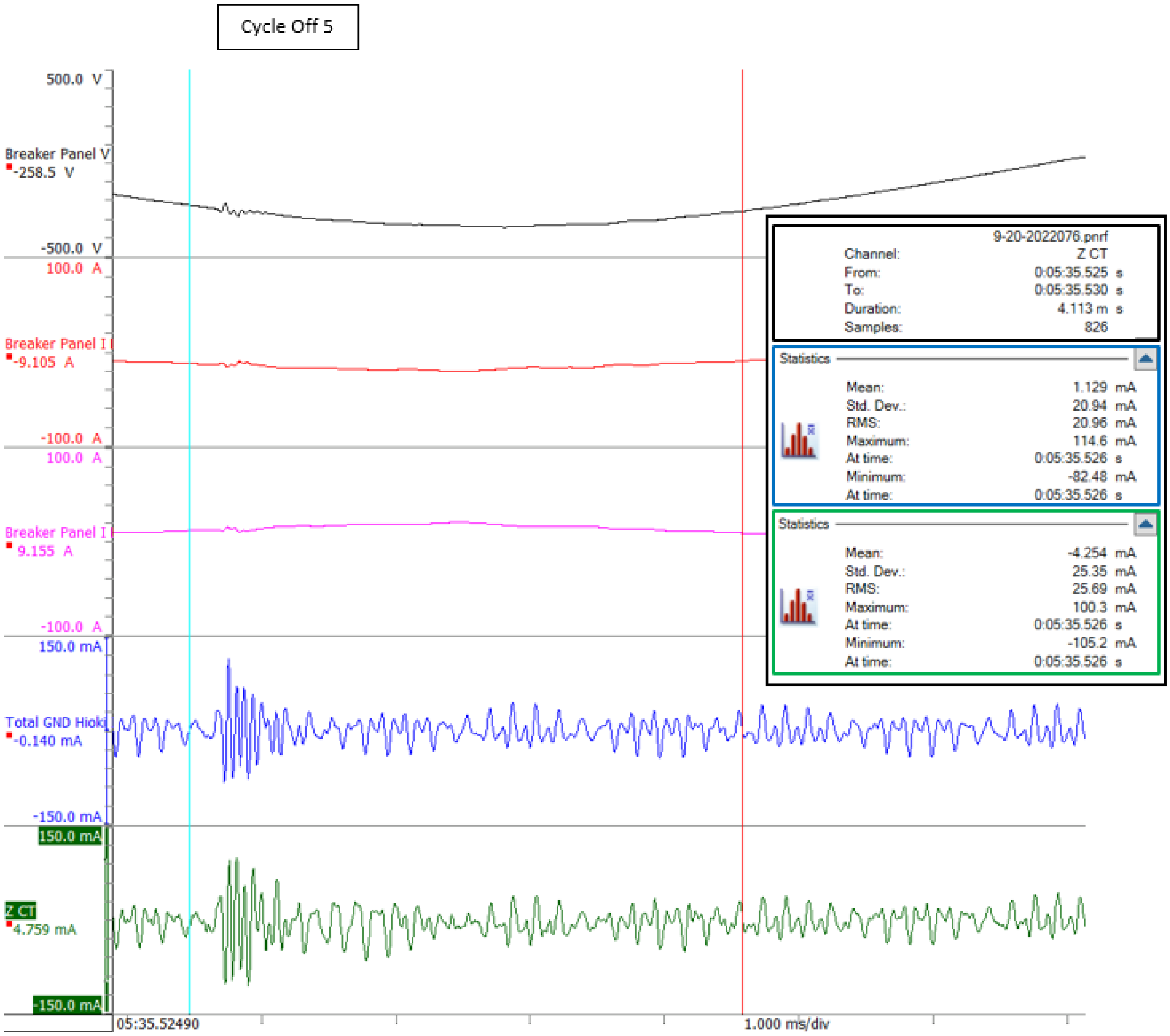


Figure 7-38
Highest Leakage Current, Nominal Baseline, Last 20 Minutes, Thermostat Cycling Test

Full Nominal Cooling Condition Testing

The second test was conducted with the thermal chambers configured for condition two, or the Full Nominal Cooling condition. The waveforms show the voltage, current, and leakage current measured by the Hioki CT6700, and leakage current measured by the Z-CT while the thermal chambers were operating in full nominal cooling condition. Figure 7-39 shows the first 20 minutes of operation under full nominal cooling conditions.

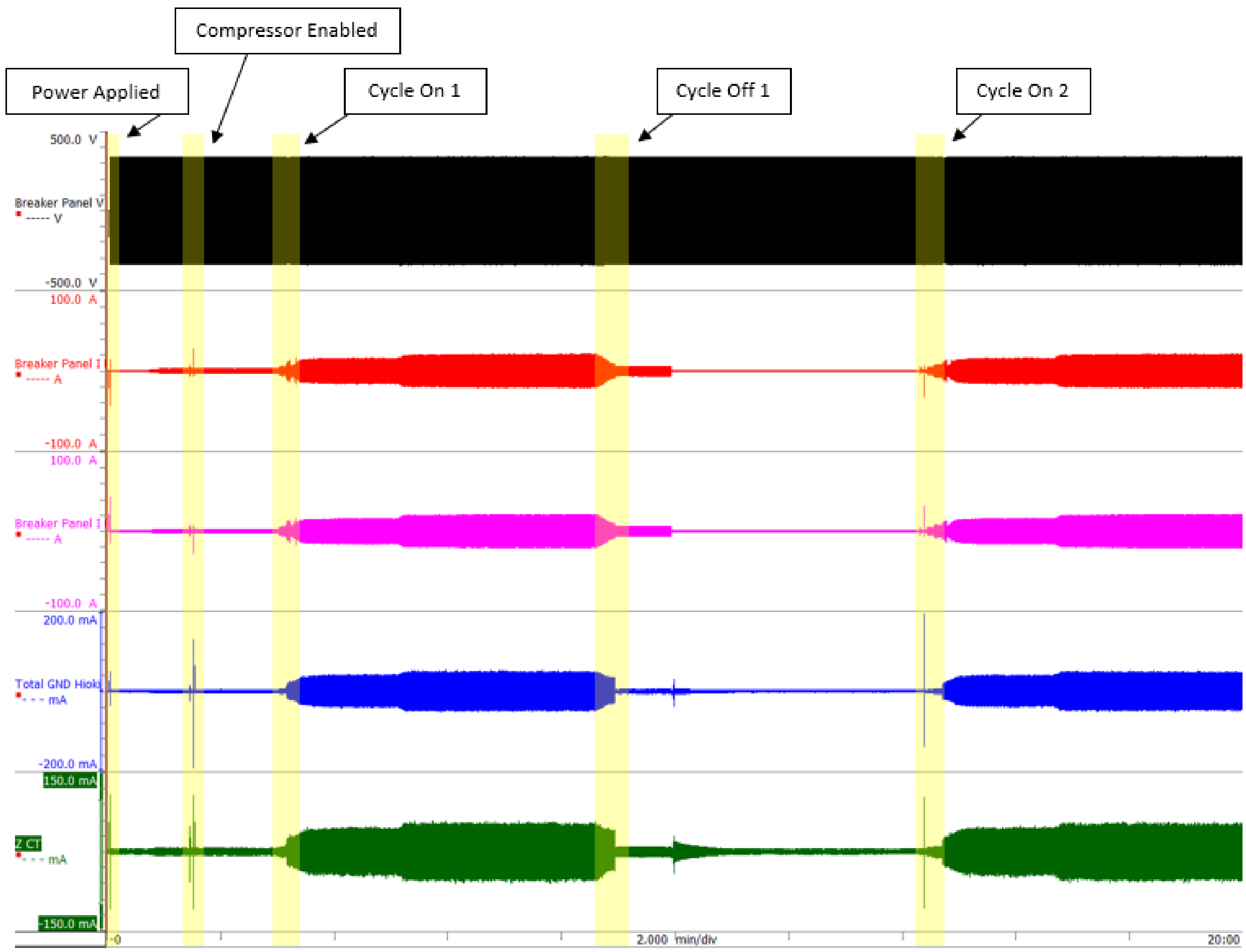


Figure 7-39
Full Nominal Cooling, First 20 Minutes, Thermostat Cycling Test

Figure 7-40 shows the greatest RMS leakage current measured by the Z-CT during the first 20 minutes occurred when the compressor turned on after being off for a 5-minute period. The maximum RMS leakage current measured by the Z-CT was 27 milliamps for approximately 5 milliseconds.

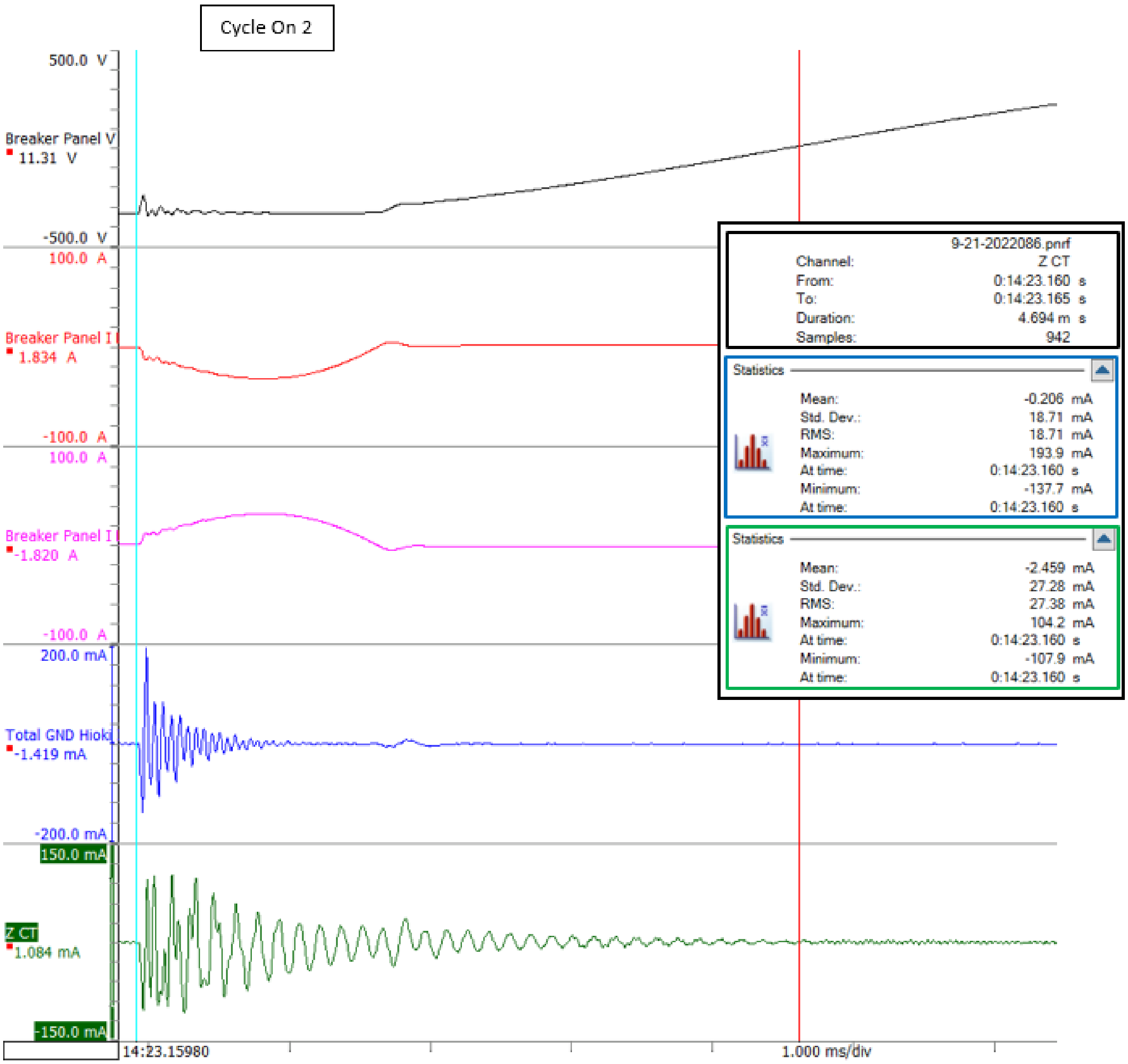


Figure 7-40
Highest Leakage Current, Full Nominal Cooling, First 20 Minutes, Thermostat Cycling Test

The second 20-mintute span of the test is shown in Figure 7-41. The waveform shows the greatest RMS leakage current measured by the Z-CT during the second 20 minutes occurred when the compressor turned on after being off for a 5-minute period.

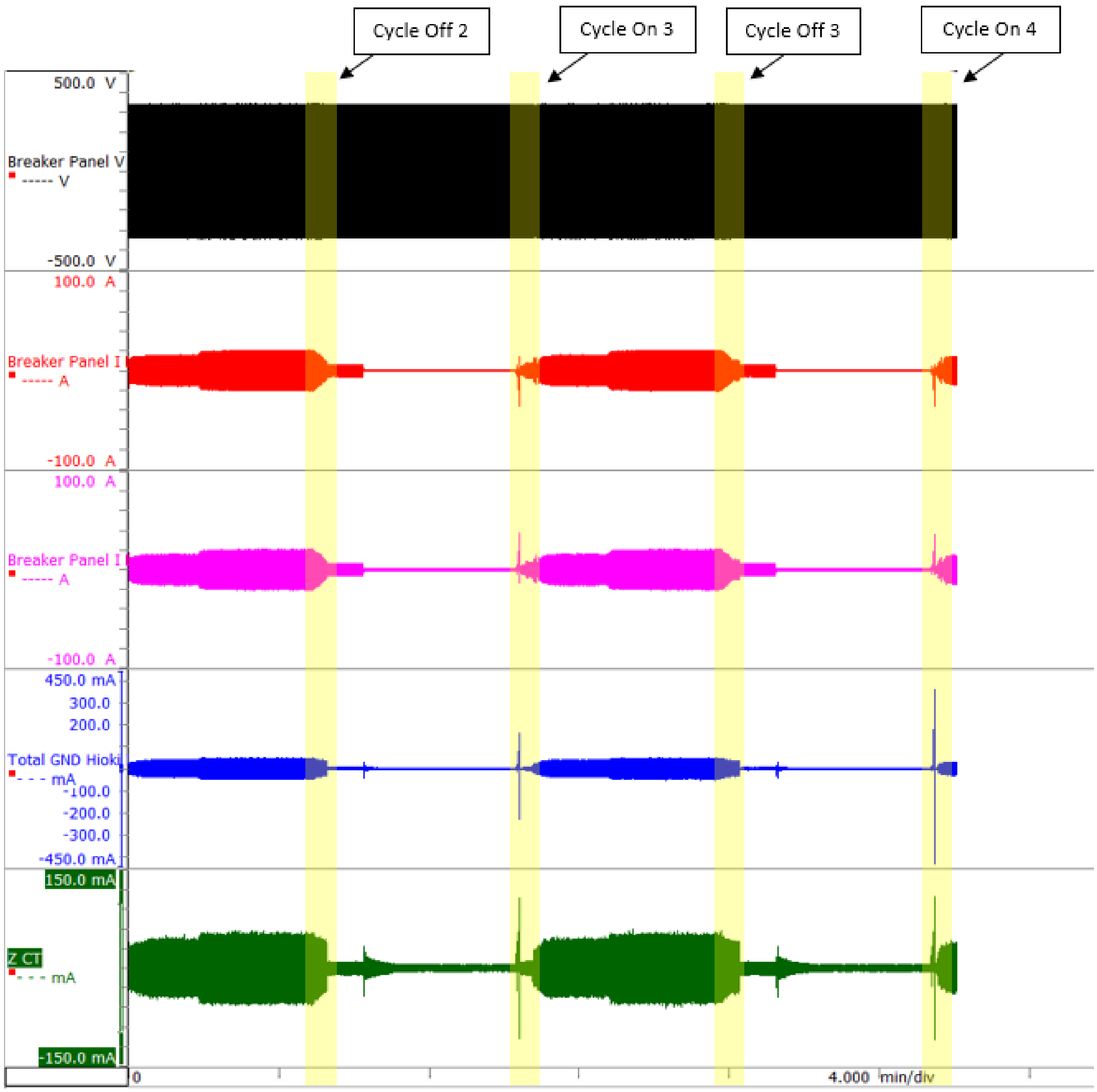


Figure 7-41
Full Nominal Cooling, Second 20 Minutes, Thermostat Cycling Test

Figure 7-42 shows the maximum RMS leakage current measured by the Z-CT was 41 milliamps for approximately 6 milliseconds.

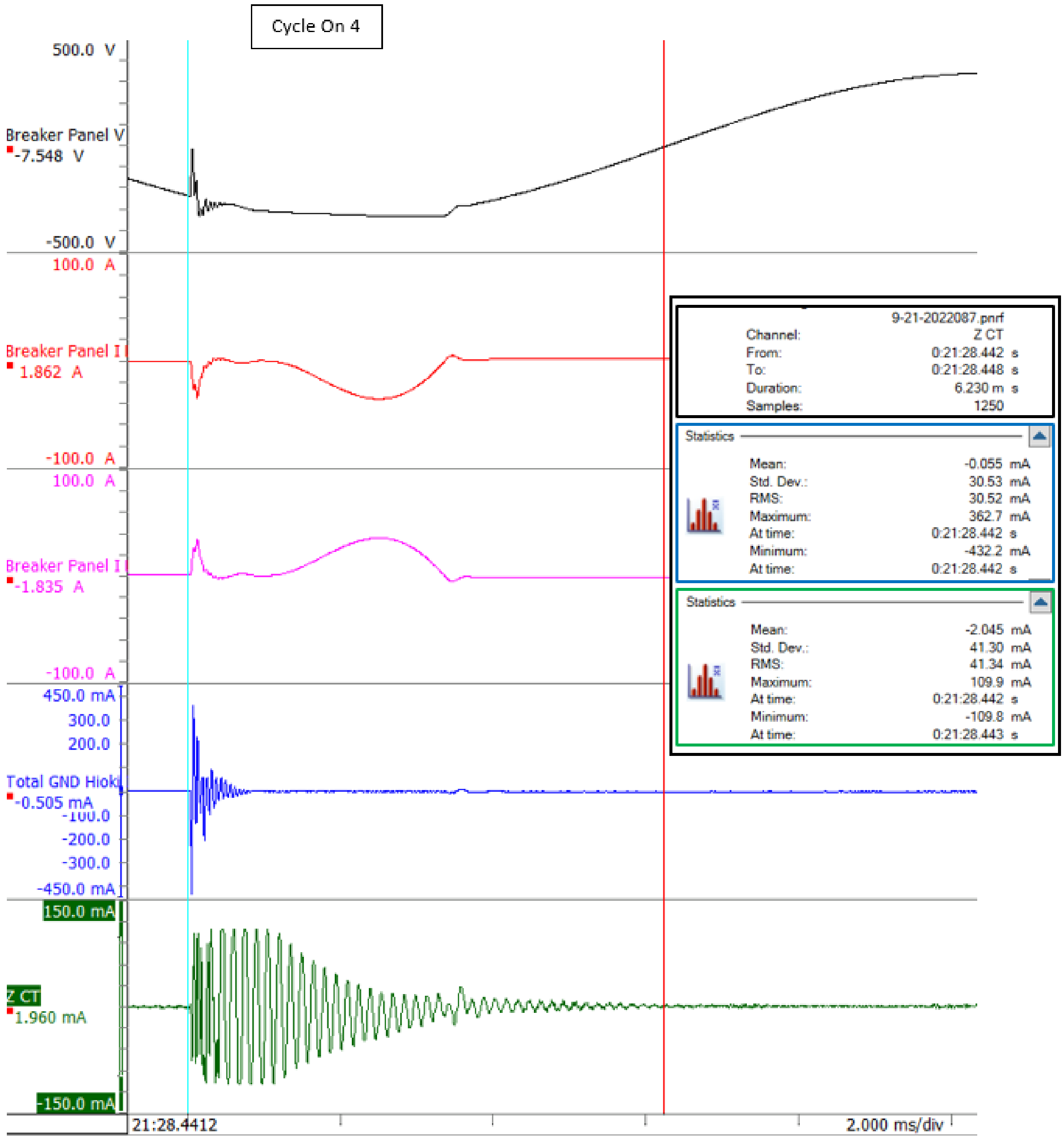


Figure 7-42
Highest Leakage Current, Full Nominal Cooling, Second 20 Minutes, Thermostat Cycling Test

Figure 7-43 shows the final 20 minutes of the thermostat cycling test while configured for full nominal cooling. The greatest RMS leakage current measured by the Z-CT occurred during the final 20 minutes when the compressor turned back on after being off for a 5-minute period.

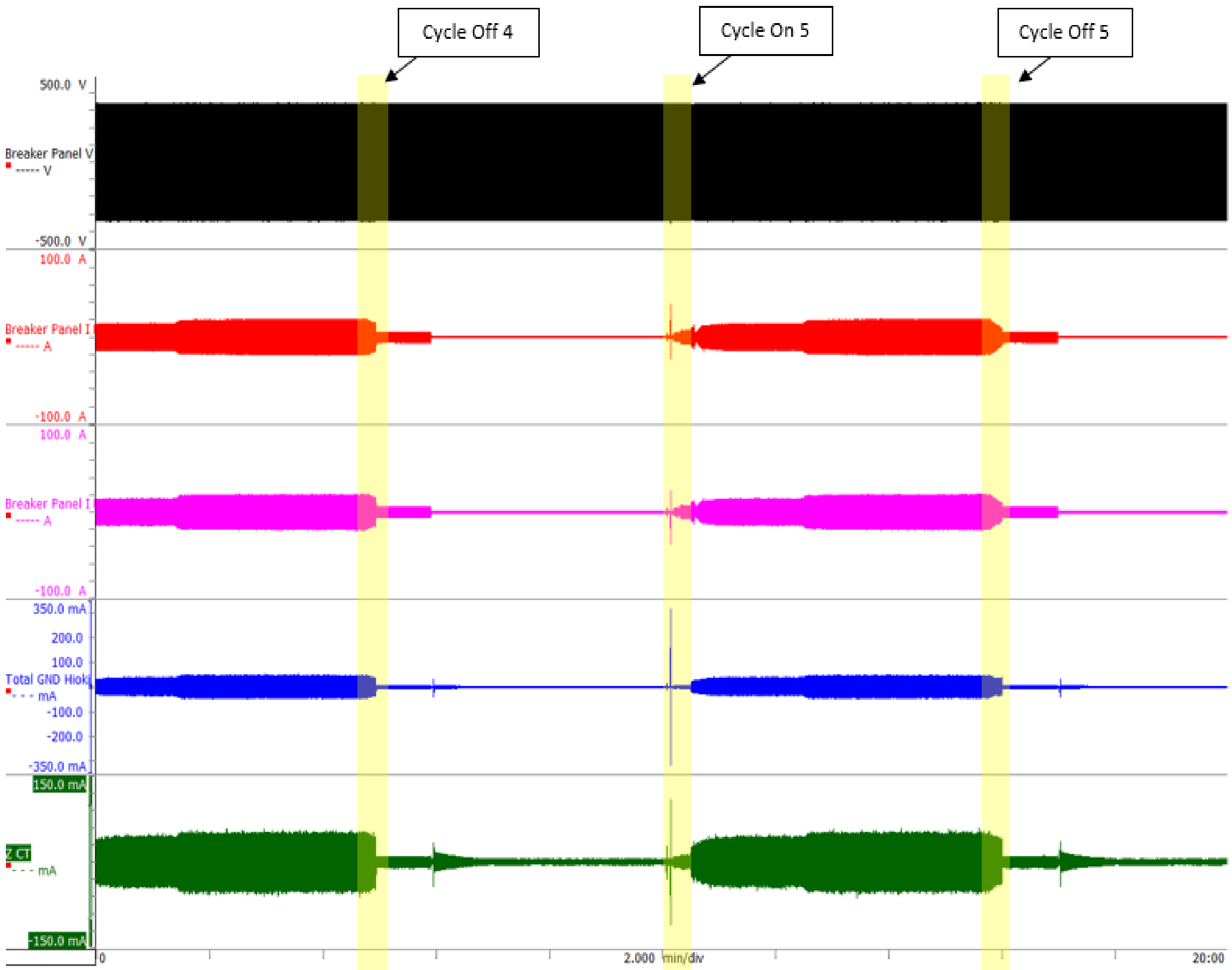


Figure 7-43
Full Nominal Cooling, Final 20 Minutes, Thermostat Cycling Test

Figure 7-44 shows the maximum RMS leakage current measured by the Z-CT was 33 milliamps for approximately 9 milliseconds.

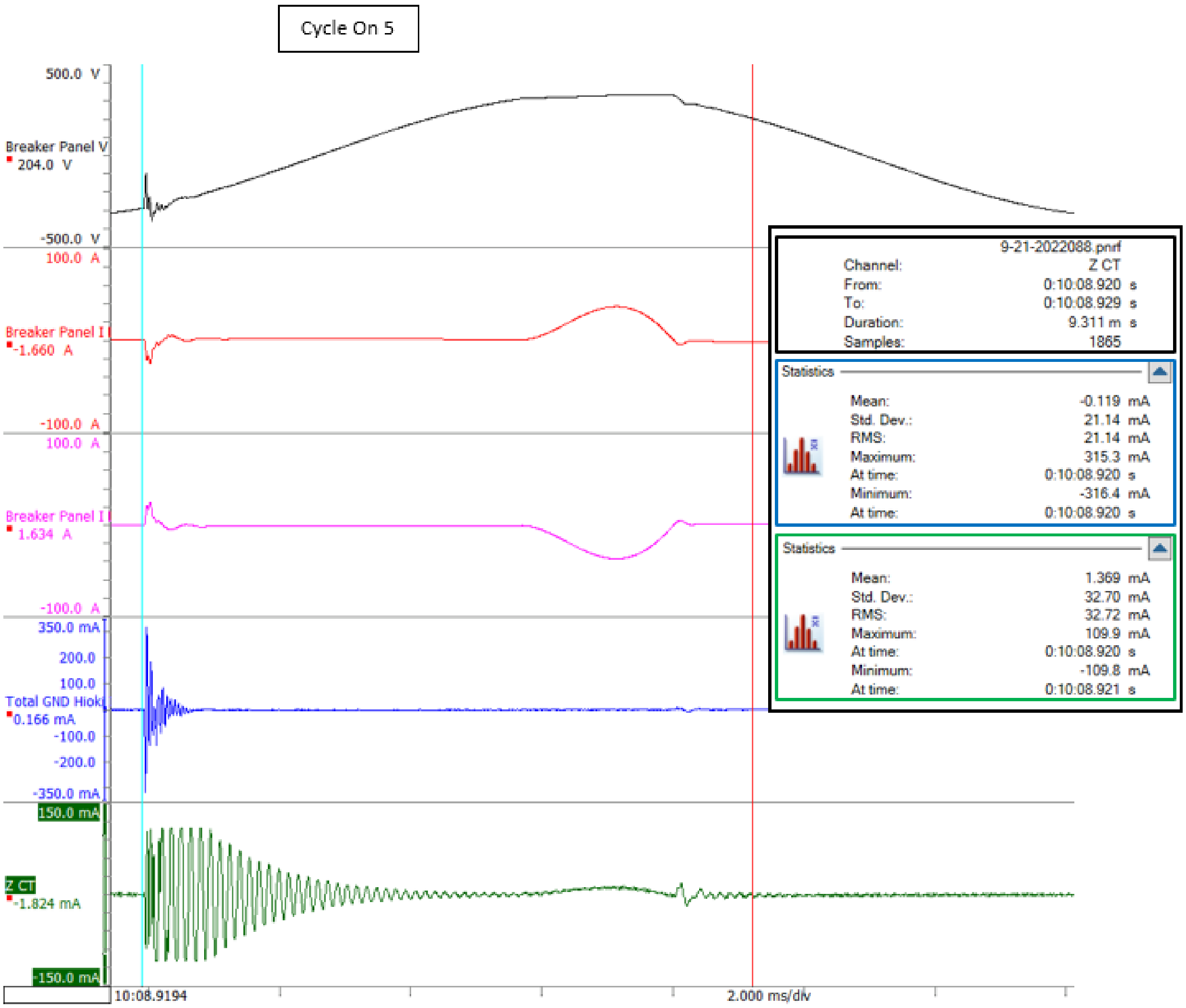


Figure 7-44
Highest Leakage Current, Full Nominal Cooling, Final 20 Minutes, Thermostat Cycling Test

Full Nominal Heating Condition Testing

The third test was conducted with the thermal chambers configured for condition three, or the Full Nominal Heating condition. The waveforms show the voltage, current, and leakage current measured by the Hioki CT6700, and leakage current measured by the Z-CT while the thermal chambers were operating in full nominal heating condition.

Figure 7-45 shows the greatest RMS leakage current measured by the Z-CT occurred during the first 20 minutes when power was applied to the circuit.

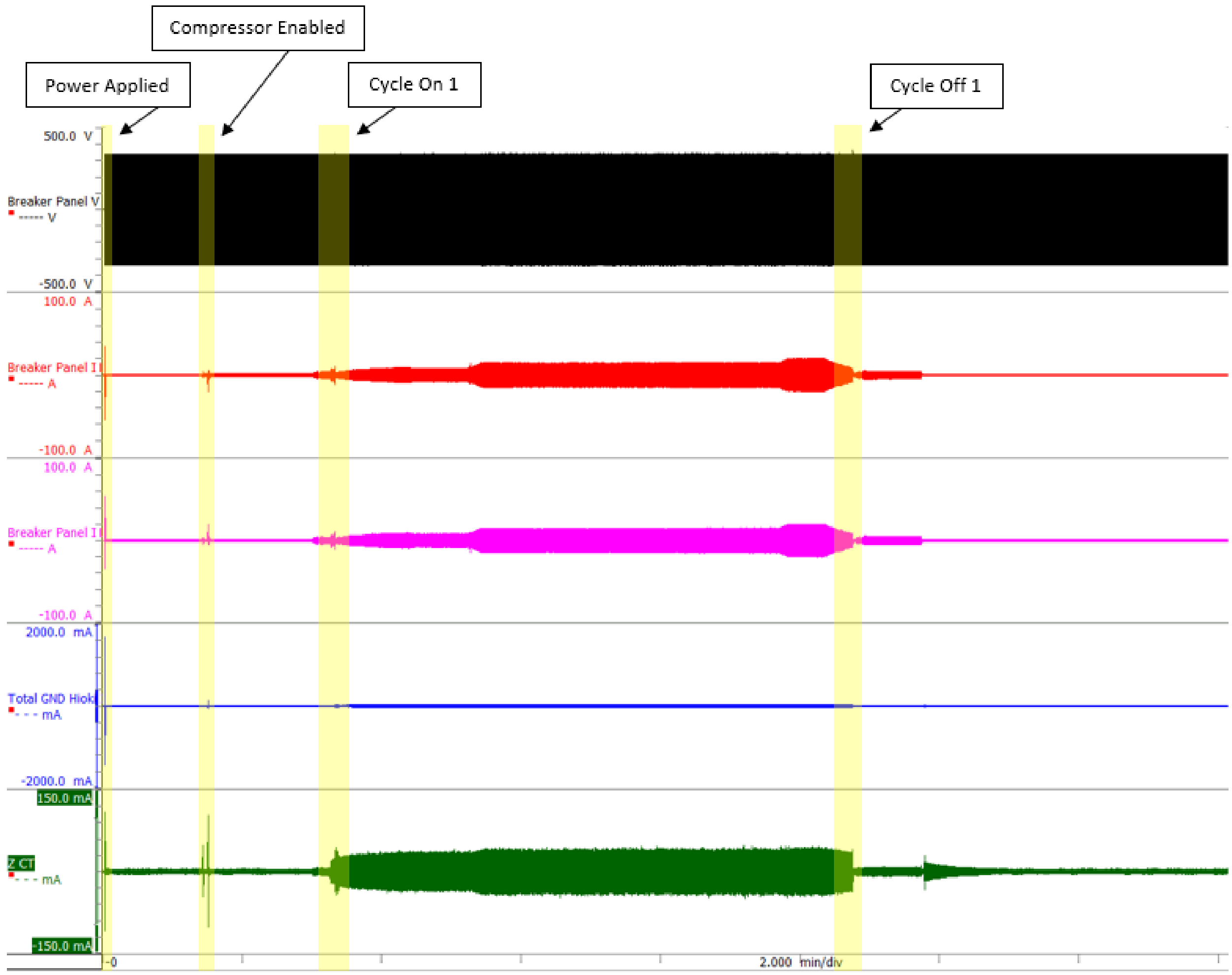


Figure 7-45
Full Nominal Heating, First 20 Minutes, Thermostat Cycling Test

Figure 7-46 shows the maximum RMS leakage current measured by the Z-CT was 40 milliamps for approximately 8 milliseconds.

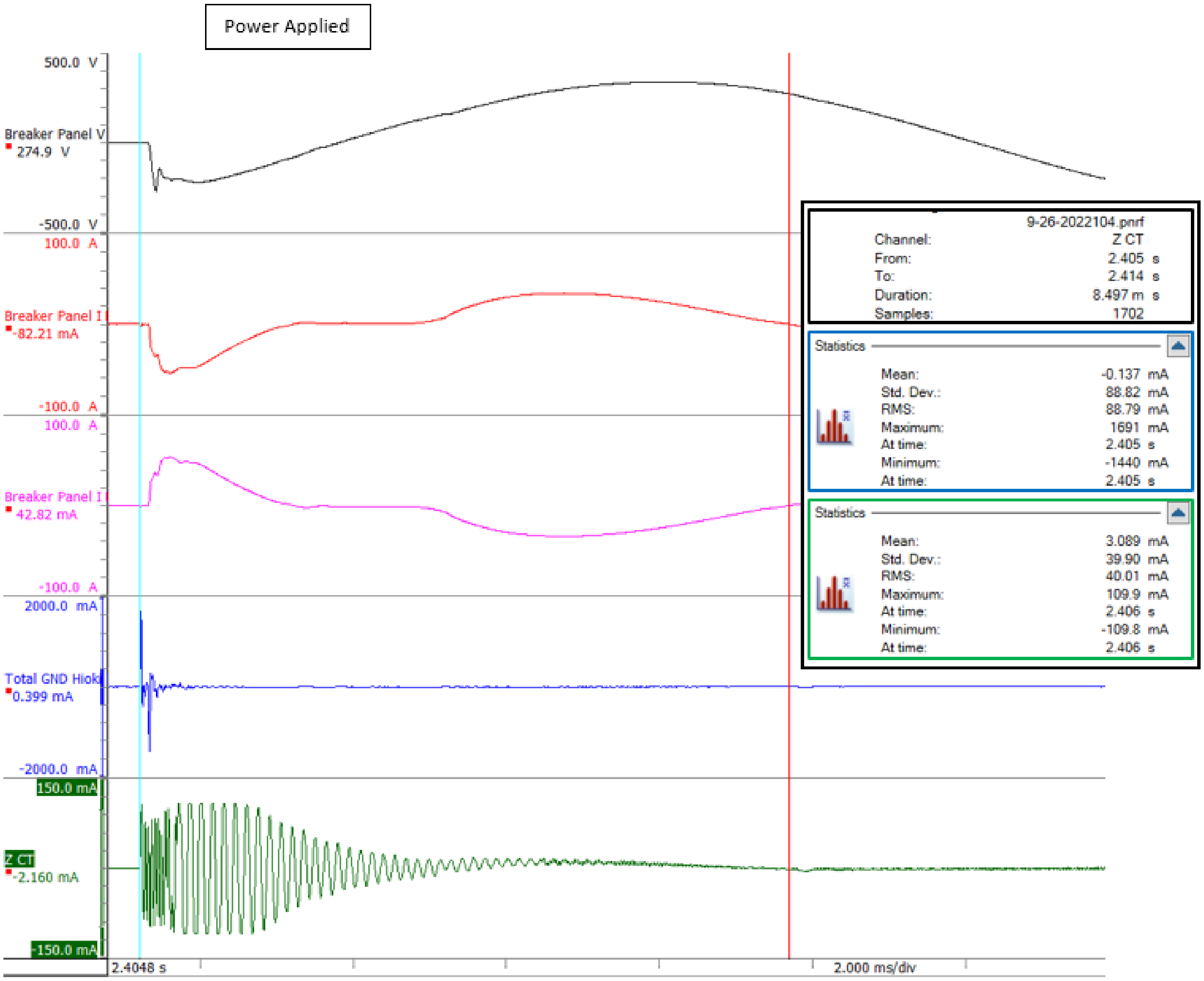


Figure 7-46
Highest Leakage Current, Full Nominal Heating, First 20 Minutes, Thermostat Cycling Test

The second 20-mintute span of the test is shown in Figure 7-47. The waveform shows the greatest RMS leakage current measured by the Z-CT occurred during the second 20 minutes when the compressor turned on after being off for a 5-minute period.

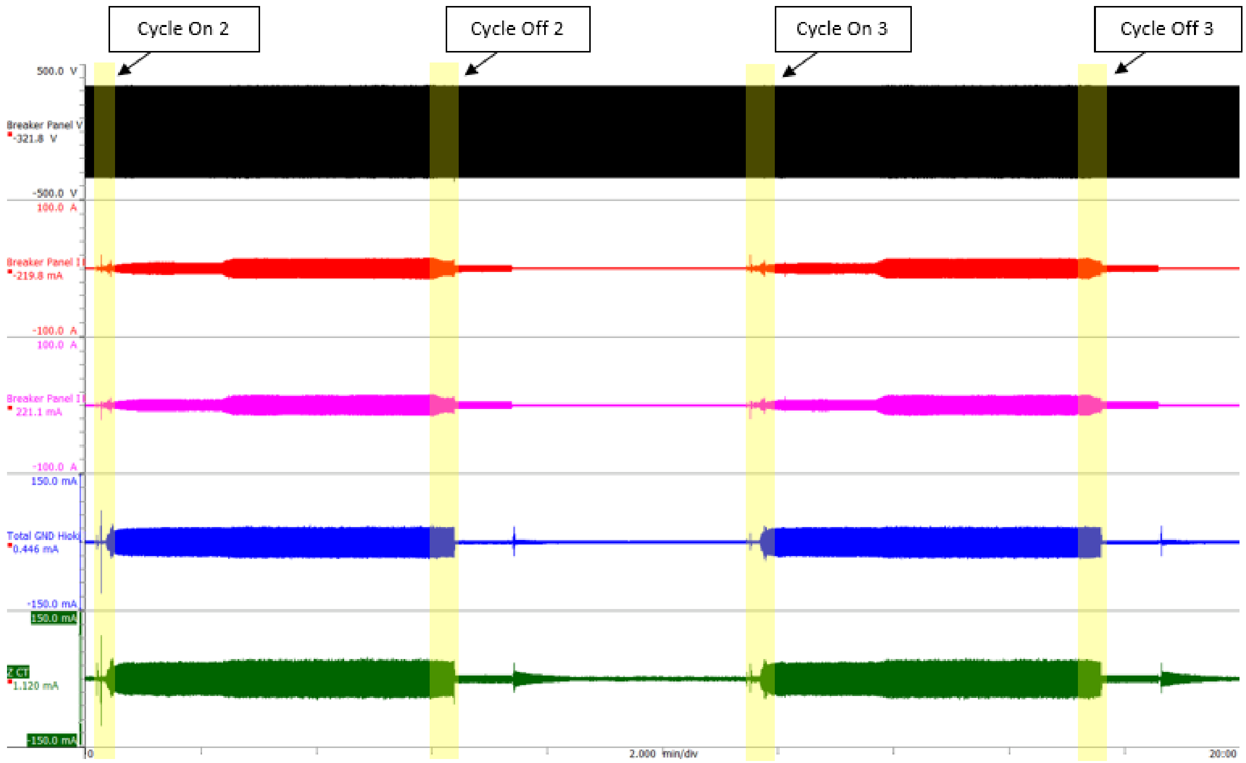


Figure 7-47
Full Nominal Heating, Second 20 Minutes, Thermostat Cycling Test

Figure 7-48 shows the maximum RMS current measured by the Z-CT was 21 milliamps for approximately 4 milliseconds.

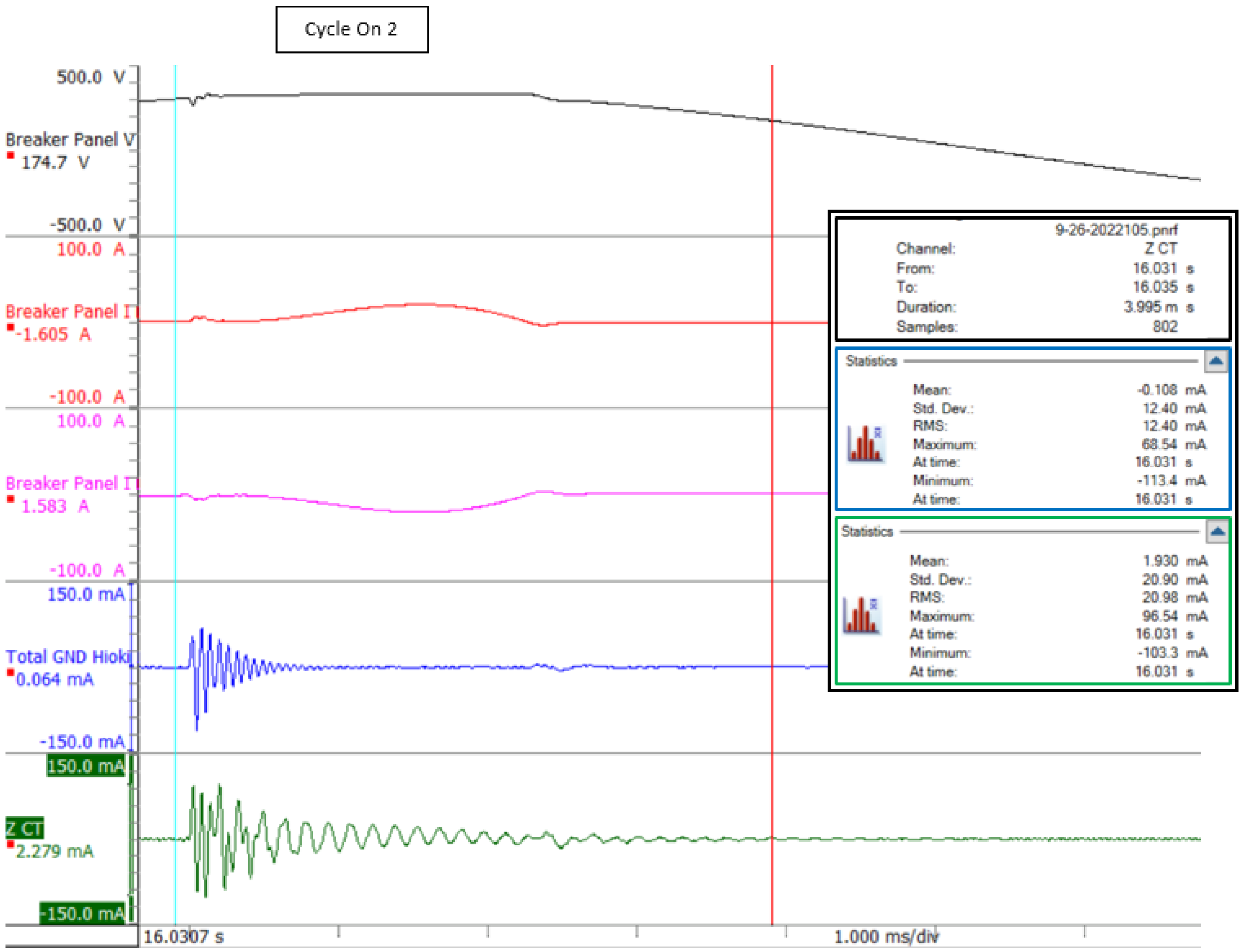


Figure 7-48
Highest Leakage Current, Full Nominal Heating, Second 20 Minutes, Thermostat Cycling Test

Figure 7-49 shows the greatest RMS leakage current measured by the Z-CT during the final 20-minutes occurred when the compressor turned back of after being off for a 5-minute period.

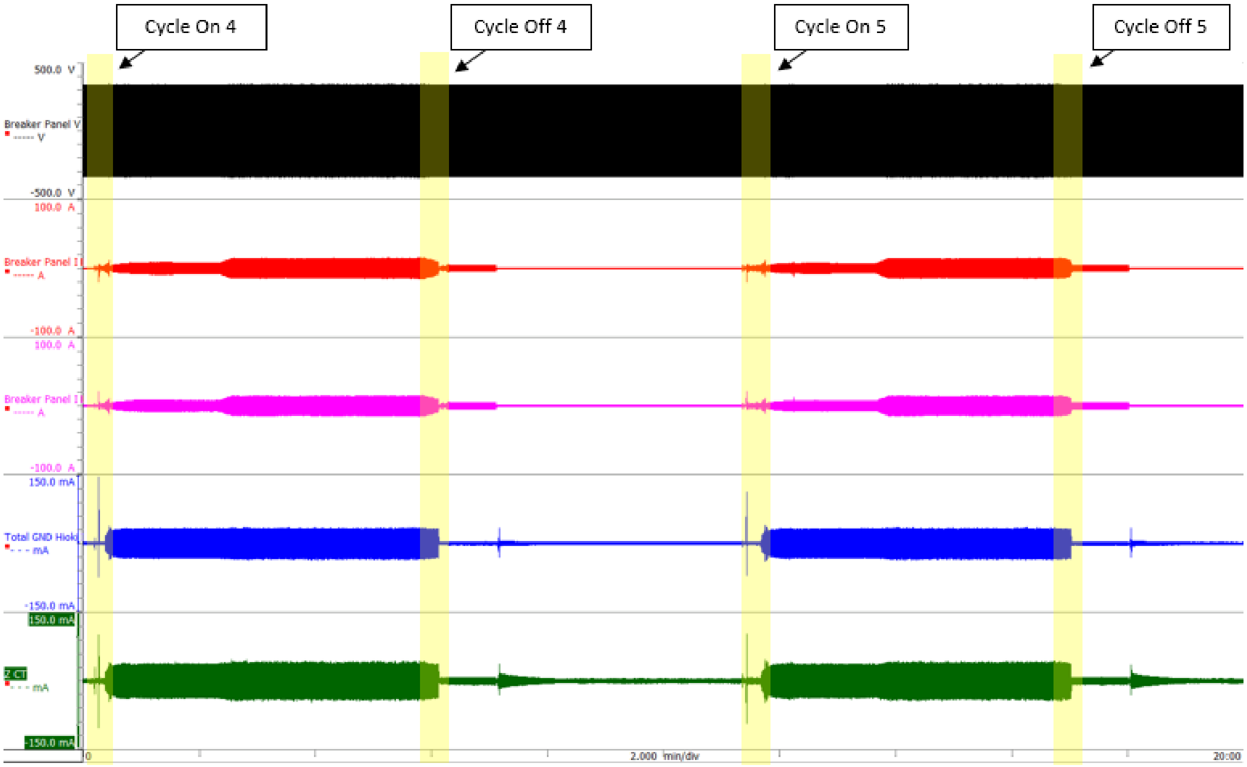


Figure 7-49
Full Nominal Heating, Final 20 Minutes, Thermostat Cycling Test

Figure 7-50 shows the maximum RMS leakage current measured by the Z-CT was 15 milliamps for approximately 7 milliseconds.

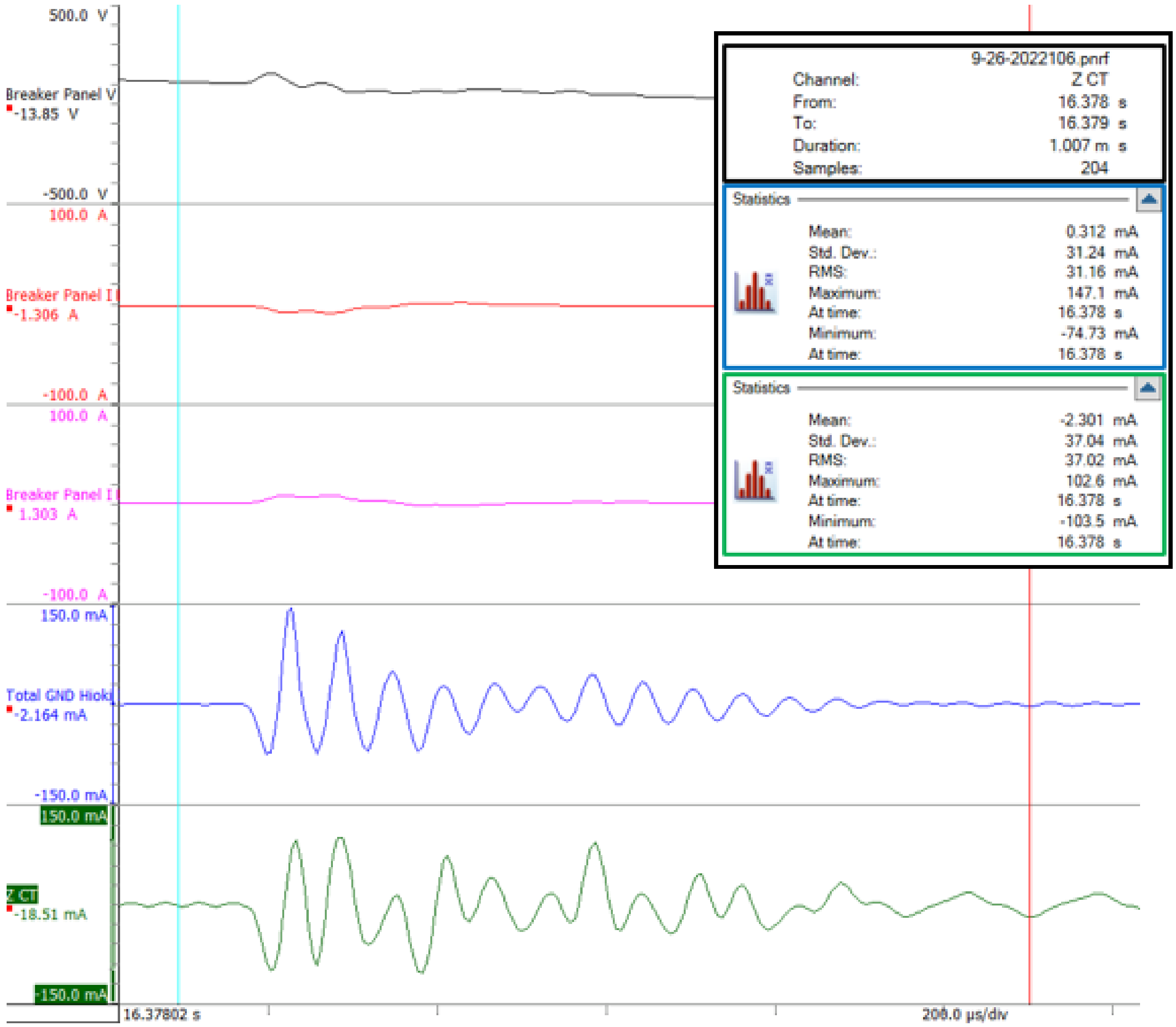


Figure 7-50
Highest Leakage Current, Full Nominal Heating, Final 20 Minutes, Thermostat Cycling Test

Test 3 Conclusion

The purpose of the HVAC Cycling test was to identify critical points in the operating process of the EUT that create the most leakage current. The test was conducted during all three temperature conditions to determine if the temperature or heating and cooling mode affects the magnitude of the leakage current. **Error! Reference source not found.** shows a distinct v ariation in the maximum leakage current that was measured across all the testing. However, as shown in previous tests, the leakage current appears to occur when power is applied, or the compressor is turned on when the voltage is at a maximum.

The data shown in **Error! Reference source not found.** shows maximum leakage current was o bserved when the DC Bus was enabled, or the compressor experienced a step change. Although the leakage current was greater than 6 milliamps during these time periods, the leakage current was an acceptable level as per the time/current curve of UL 943. The EUT was permitted to operate for a period of time before the indoor units were shut off for a 5-minute rest period prior to being enabled for another 5-minutes permitting another cool or heat cycle depending on the thermal condition of the test chambers. During the EUT running time period the Z-CT measured RMS current levels above 6 milliamps, which is above the allowable limits in UL 943. The FFT shown in Figure 7-14 located in the conclusion section of Test 0 shows the majority of the leakage current when the EUT is running lies in the 6 kHz range while the leakage current at 60 Hz is only about 4 mA which is within the limits of UL 943.

Test 4 Defrost Cycle

HVAC manufacturers hypothesize that leakage current may differ when HVAC units are in the defrost mode. An HVAC manufacturer recommended blocking the air inlet with the EUT operating in the maximum heating condition. The HVAC unit was allowed to operate through five defrost cycles. The manufacturer supplied a PC with their proprietary monitoring software. The manufacturer adjusted their defrost time parameter to 5 minutes in order to speed the time to conduct the test. The manufacturer indicated that, if the defrost parameter was not 0, then the system was in some stage of the defrost cycle. Figure 7-51 shows the waveforms from the beginning of the test through the first defrost cycle. The maximum leakage current occurred at the time power was applied to the circuit. This phenomenon was observed several times previously during testing; however, it was not the focus of this test.

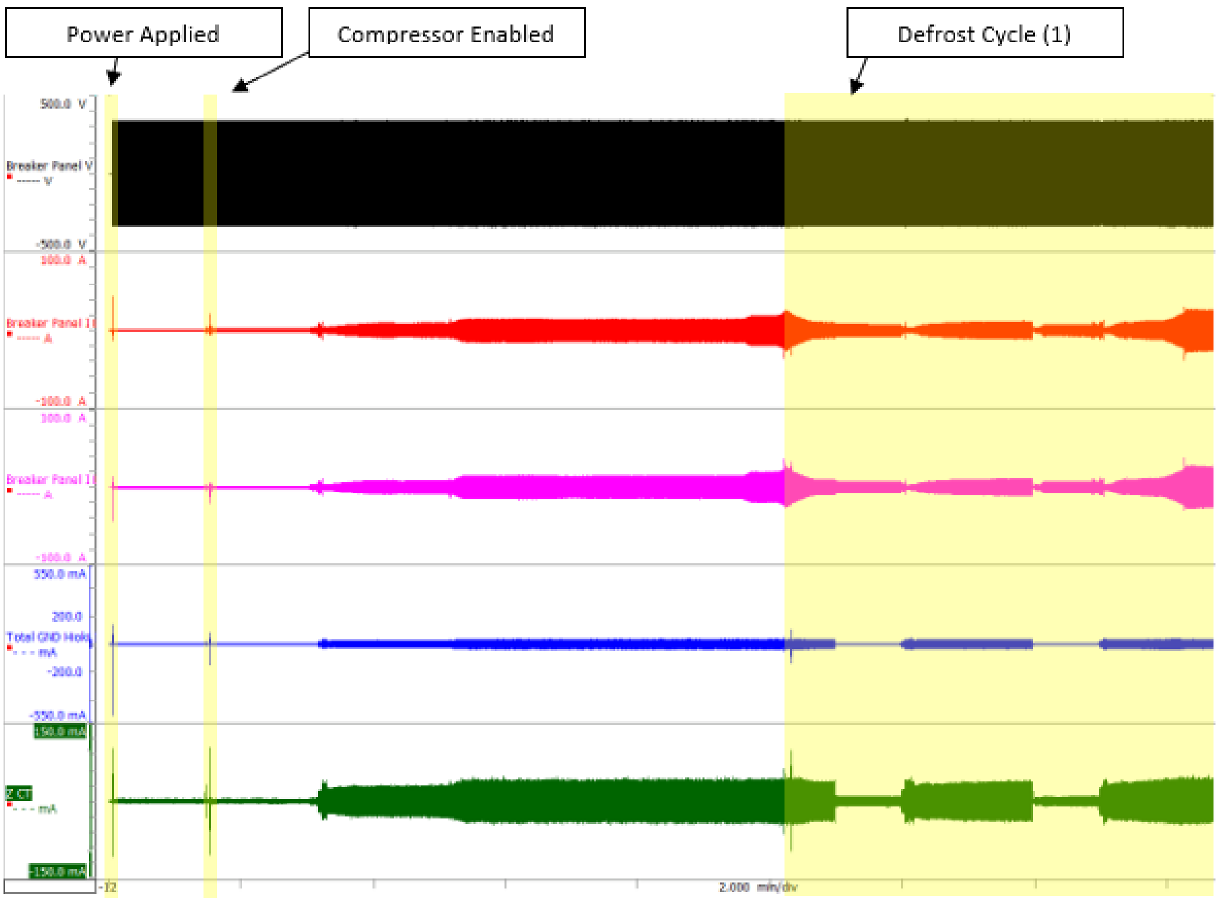


Figure 7-51
Defrost Test: Start – 1st Defrost Cycle

Figure 7-52 shows a zoomed in view of the waveforms when power was applied to the circuit.

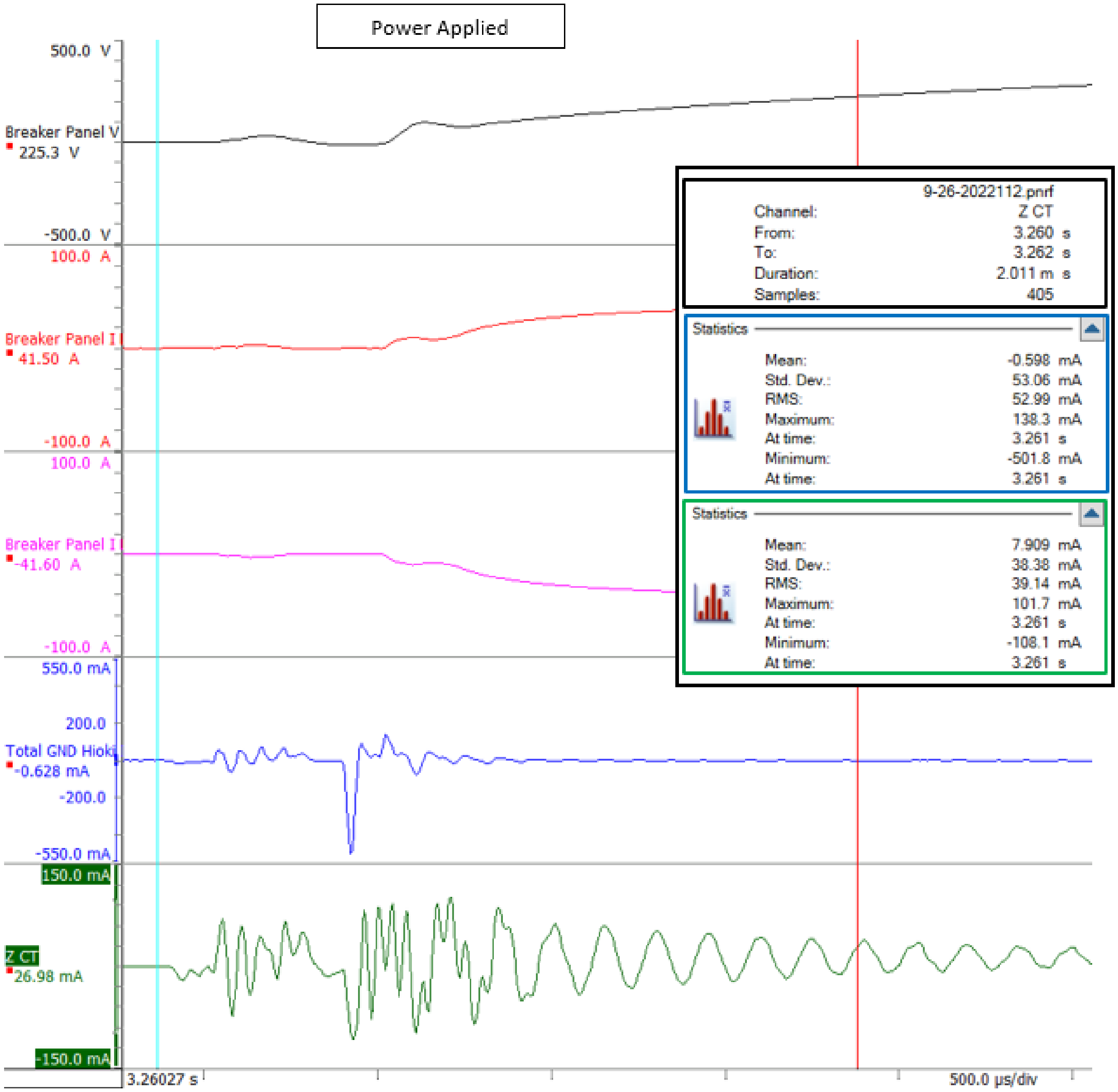


Figure 7-52
Defrost Test: Application of Power

Figure 7-53 shows a zoomed in view of the waveforms when the compressor was enabled. As the current began to rise, the Z-CT current measurement increased before curtailing to nominal current levels.

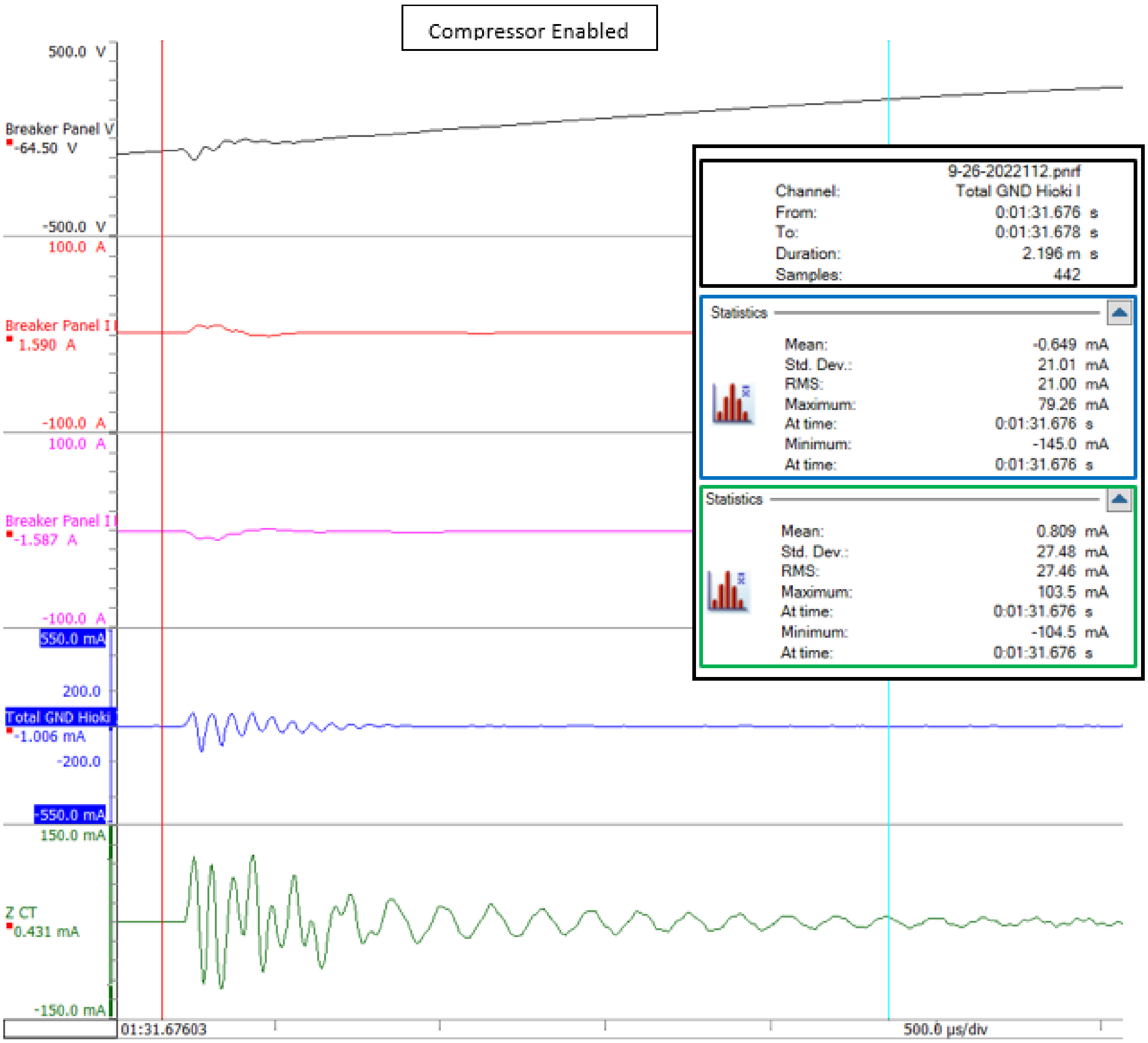


Figure 7-53
Defrost Test: Compressor Enabled

Figure 7-54 shows the first time the EUT entered defrost mode. The waveform shows the total current rise and then decline before a pulse of leakage current appears.

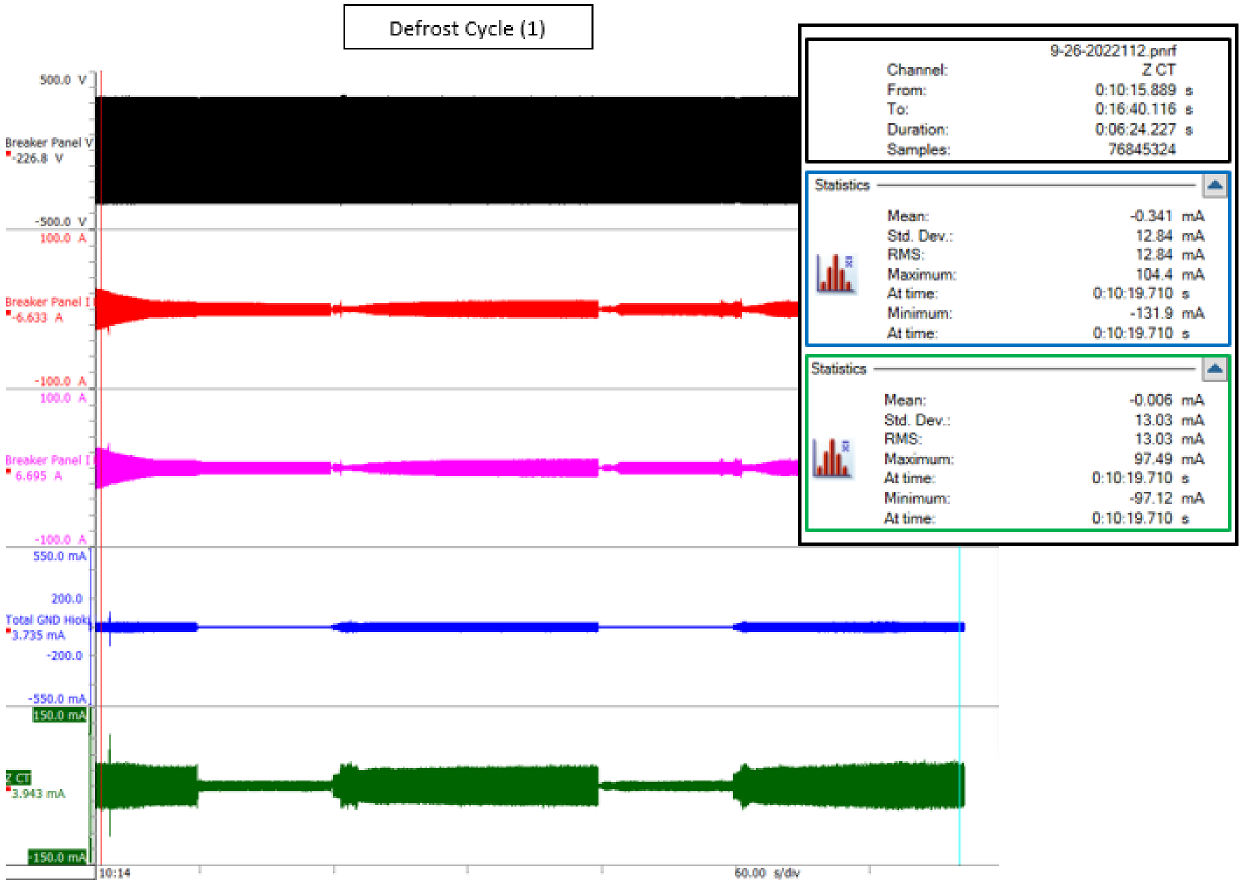
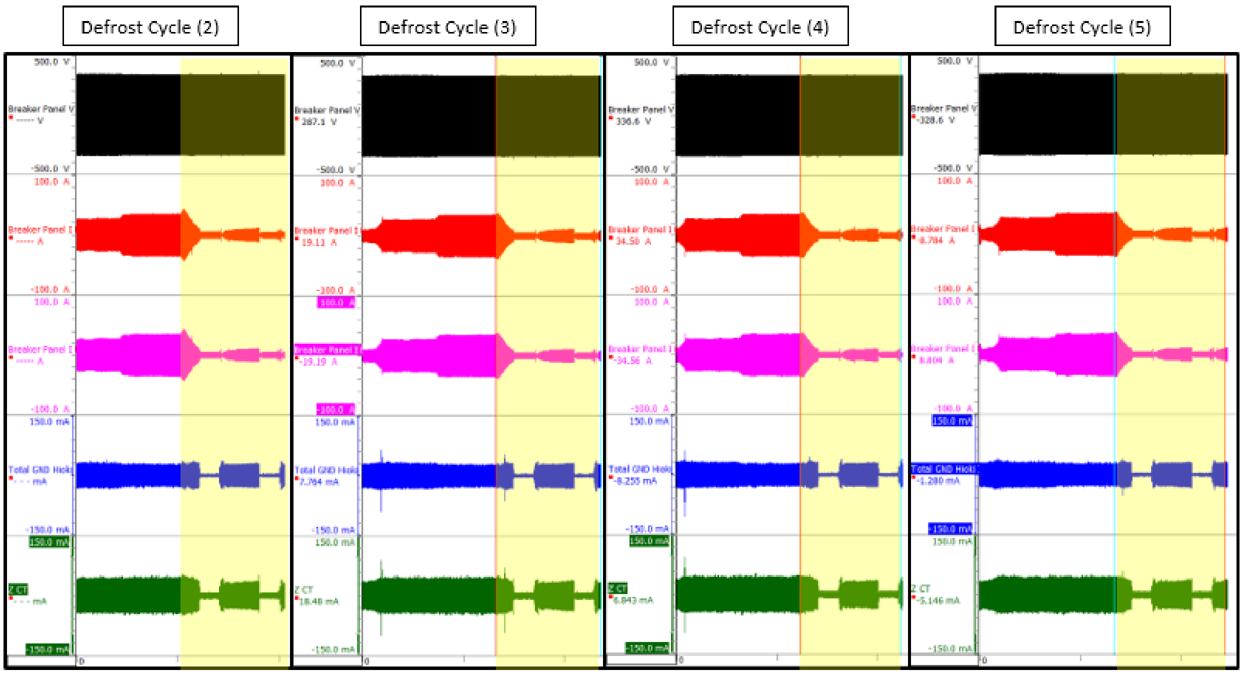


Figure 7-54
Defrost Test: Defrost Cycle (1)

Figure 7-55 shows the waveforms from the period following the defrost cycle 1 through the end of defrost cycle 5. The waveform shows the defrost profile to be very similar to the first time the EUT entered defrost mode. The current initially increased, settled to a lower current level for approximately 1.5 minutes, then the current ramped up slightly for about 1.5 minutes, back down for about a minute before resuming normal operation. The leakage current appeared to be much lower during the time the input current was at minimum indicating the compressor was not running. The leakage current increased as the compressor ran.



5 min/division time base

Figure 7-55
Defrost Test: Defrost Cycle (2) -Defrost Cycle (5)

Error! Reference source not found. shows the leakage currents measured from the beginning o f the Defrost Test through the first defrost cycle.

Table 7-17
Tabular Data from 1st Defrost Mode

Note: All measurements are represented as RMS	Application of Power		Compressor Enabled		Defrost Cycle (1)		
Measurement Time Base	500µ/div		500µ/div		60s/div		
RMS Measurement Time	2.0 ms		2.2 ms		6min 24sec		
UL 943 Limit	1537mA	Within UL 943 Current/Time Limits?	1446mA	Within UL 943 Current/Time Limits?	6mA	Within UL 943 Current/Time Limits?	GFCI Trip?
ZCT Total Leakage Current	39mA	Yes	27mA	Yes	13mA	No	No
Total GND Hioki Leakage Current	53mA	Yes	21mA	Yes	13mA	No	No

Error! Reference source not found. shows the leakage currents measured from defrost cycle 2 t hrough defrost cycle 5.

Table 7-18
Tabular Data from 2nd Defrost Mode – 5thDefrost Mode.

Note: All measurements are represented as RMS	ZCT Total Leakage Current		Total GND Hioki Leakage Current		
Measurement Time Base	5min/division		5min/division		
RMS Measurement Time	4min 58sec – 5min 28 sec		4min 58sec – 5min 28 sec		
UL 943 Limit	6mA	Within UL 943 Current/Time Limits?	6mA	Within UL 943 Current/Time Limits?	GFCI Trip?
Defrost Cycle (2)	11	No	10	No	No
Defrost Cycle (3)	11	No	11	No	No
Defrost Cycle (4)	11	No	11	No	No
Defrost Cycle (5)	11	No	11	No	No

Test 4 Conclusion

The purpose of the HVAC Defrost Cycle test was to identify the power profile and leakage current when the HVAC system transitioned to and during a defrost cycle. The system was permitted to operate through five defrost cycles. A data file was recorded from the time power was applied or the previous defrost cycle was complete, until the monitoring software indicated the defrost cycle was complete. The maximum leakage current during this test was much lower than some of the other tests.

Test 5 Voltage Interruption

HVAC systems are installed in real-world residential and commercial power systems. These systems may experience interruptions in voltage as well as voltage sags that may cause internal components such as relays and contactors to open. Depending on the topology of the system, the compressor may experience a low-impedance interruption—as if the compressor is connected to the secondary of the power transformer feeding the load, or a high-impedance interruption or open circuit condition should a contactor galvanically isolate the compressor from the power system. The hypothesis is that the leakage current may differ when voltage interruptions occur between the two types. High and low impedance interruption tests were conducted when the EUT was operating under Temperature Condition 2 and Temperature Condition 3 as shown in **Error! Reference source not found.**. **Error! Reference source not fo und.** shows the leakage current for each of the tests.

Table 7-19
Tabular Data from Voltage Interruption Test

Type of Interruption	Temperature Chamber Condition	ZCT Measured Leakage Current (mA_{RMS}/time)	Within UL943 Current/Time Limits?	GFCI Trip?	Outdoor Chamber Humidity
Low Impedance	**2**	Power Applied 8mA_{RMS}/5ms Compressor Enabled 28mA_{RMS}/11ms Normal Running 14mA_{RMS}/2min 1sec	Yes Yes No	No	19%
High Impedance	**2**	Power Applied 21mA_{RMS}/6ms Compressor Enabled 15mA_{RMS}/7ms Normal Running 11mA_{RMS}/33sec	Yes Yes No	No	
Low Impedance	**3**	Power Applied 11mA_{RMS}/5ms Compressor Enabled 18mA_{RMS}/5ms Normal Running 11mA_{RMS}/1min 31sec	Yes Yes No	No	57-71% (possible probe error)
High Impedance	**3**	Power Applied 21mA_{RMS}/6ms Compressor Enabled 10mA_{RMS}/9ms Normal Running 11mA_{RMS}/2min 9sec	Yes Yes No	No	

Temperature Condition 2 Tests

Low Impedance Interruption Test

Figure 7-56 shows the waveforms for the low-impedance interruption test while the thermal chambers were configured for temperature condition 2. The figure shows where the voltage interruption was executed, where the compressor was enabled, and when the compressor was running. The leakage current during these time periods was analyzed and is discussed in detail below.

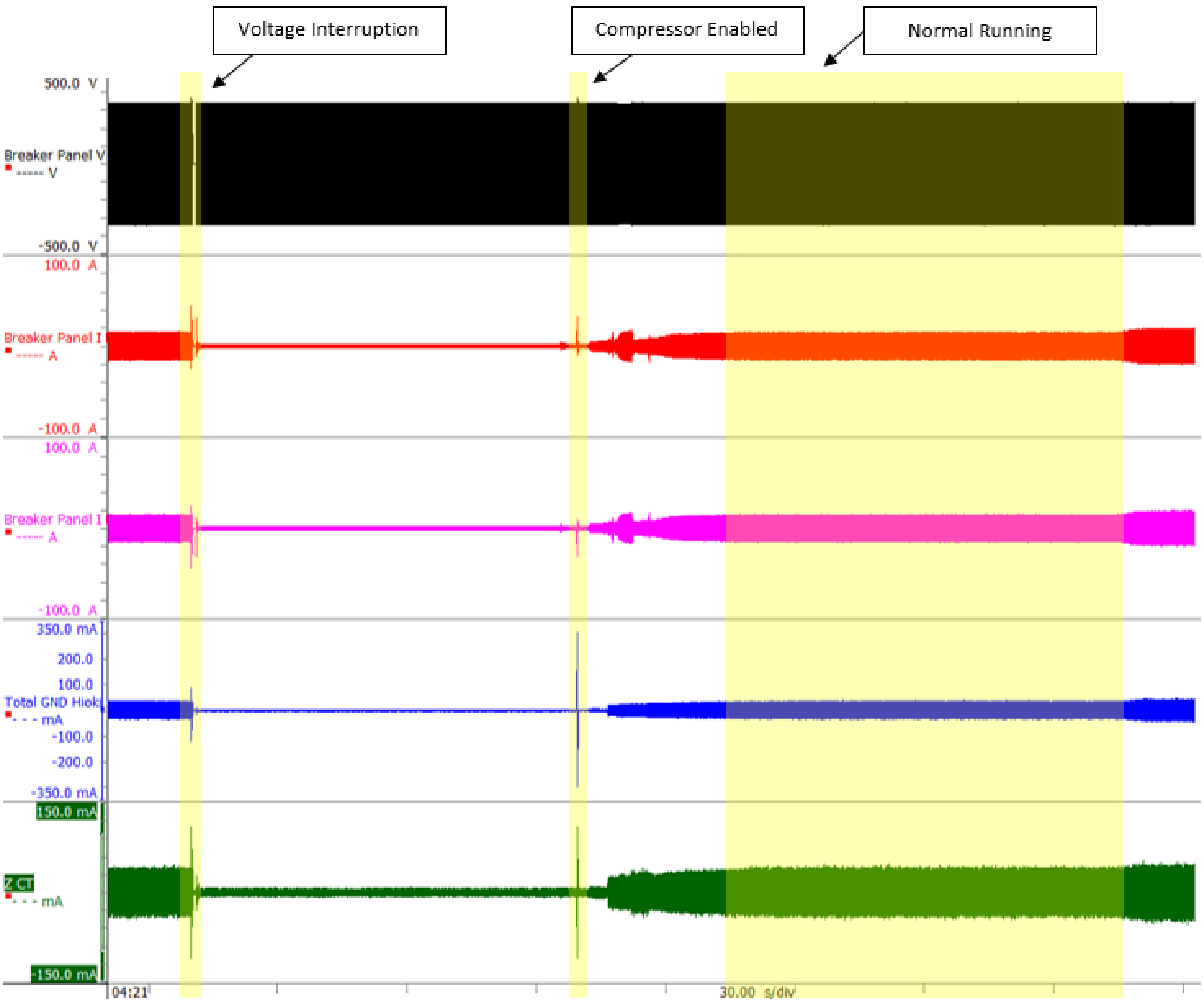


Figure 7-56
Temperature Condition 2, Low Impedance Interruption Test

Figure 7-57 shows a zoomed in view of the voltage interruption event. The figure shows the leakage current measured when the voltage is reapplied at the end of the event. The waveforms in the red outline show the 1-ms time period when voltage was applied after the 1-second interruption. The statistical data shown under the waveforms is associated with the waveforms and time period within the red box. The 200-ms/division waveform is shown to draw attention to the voltage waveform in order to show that a low impedance voltage interruption creates a crisp transition from full nominal voltage to 0 volts. If the voltage interruption is created via a transformer (low impedance interruption) the voltage transition will have this crisp edge. The high impedance interruption creates a different transition that will be shown in the next section.

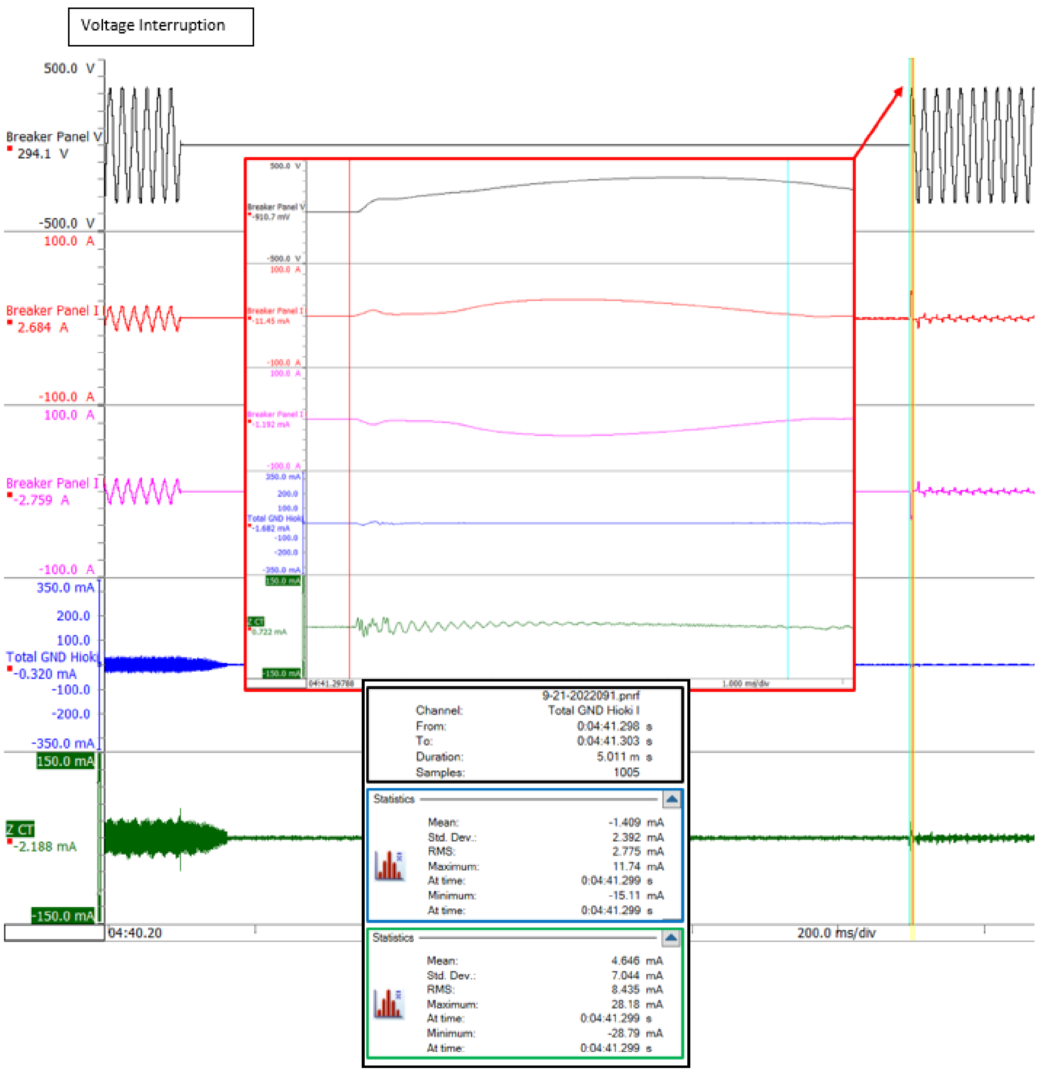


Figure 7-57
Temperature Condition 2; Leakage Current Following Low Impedance Interruption

Figure 7-58 shows the waveforms when the compressor was enabled. Maximum leakage current measured by the Z-CT was 28 mA RMS. The waveforms show the Compressor was enabled at the peak of the voltage, approximately 90 degrees POW. This may be the reason the maximum leakage current was higher for this test than the other interruption tests.

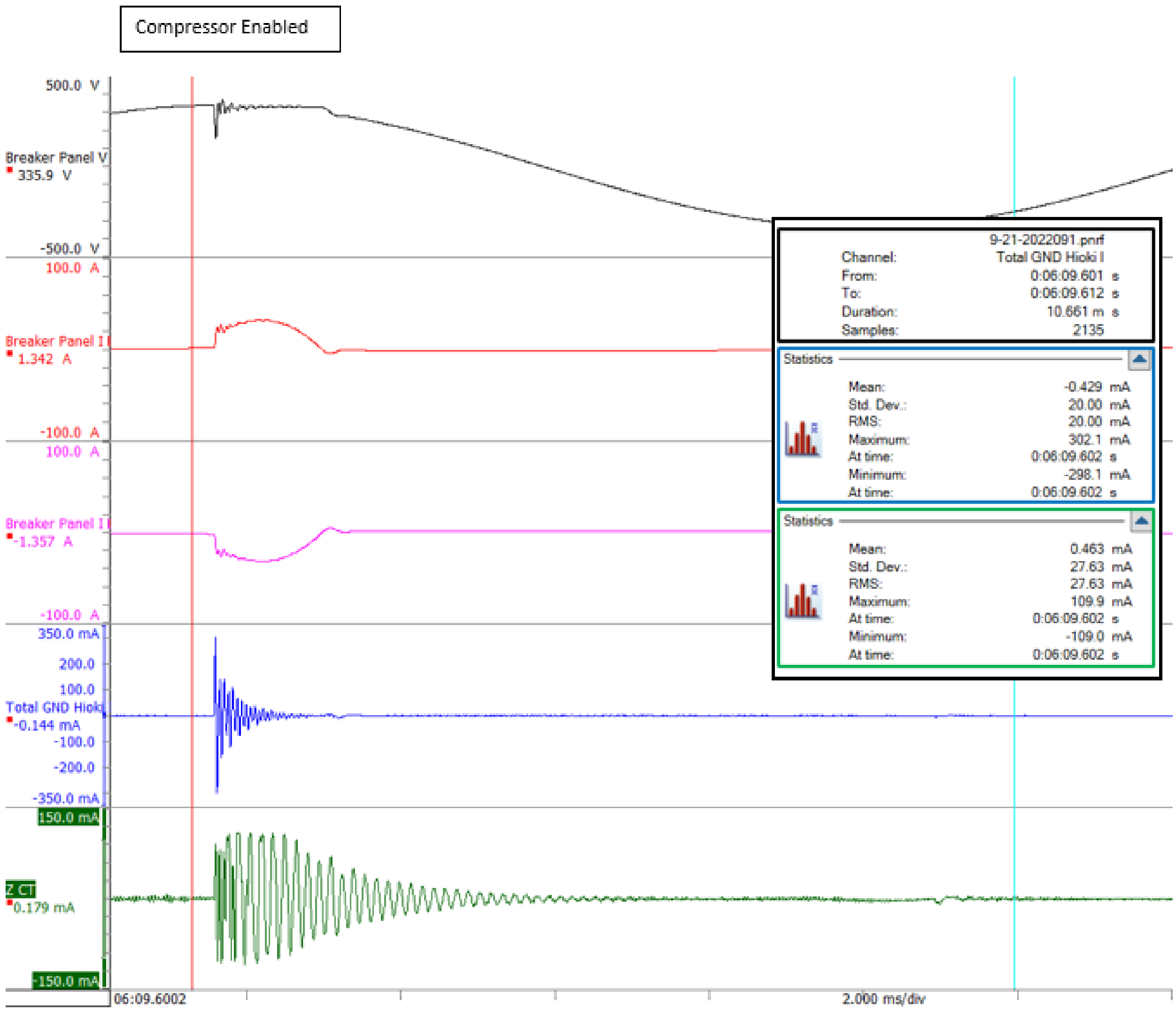


Figure 7-58
Temperature Condition 2, Compressor Enabled Following Low Impedance Interruption

Figure 7-59 shows the waveforms when the compressor was running nominally. During this time, the leakage current was significantly lower than when the compressor was enabled.

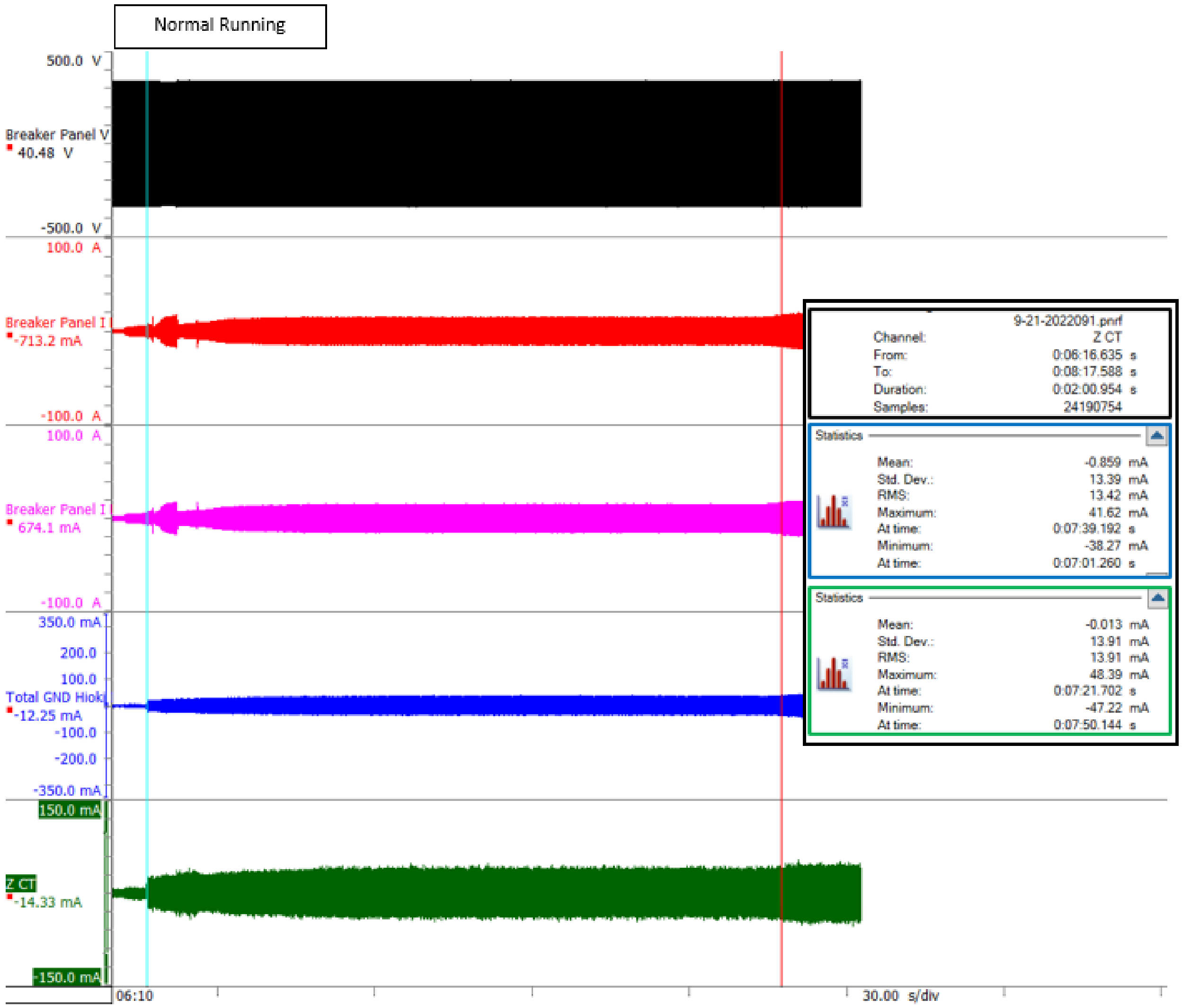


Figure 7-59
Temperature Condition 2, Compressor Running Following Low Impedance Interruption

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the low impedance test while set to Temperature Condition 2. The measurements of when the voltage returned after the interruption, when the compressor was enabled, and when the compressor was running nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time period was within the time/current limits of UL 943; however, the RMS current measured by the Z-CT during the nominal running time period was 8 mA above the RMS current limitations of UL 943.

Table 7-20
Tabular Data from the Low Impedance Interruption Test at Temperature Condition 2

Note: All measurements are represented as RMS	**Application of Power Following Interruption**		**Compressor Enabled**		**Normal Running**		
Measurement Time Base	1ms/div		2ms/div		30s/div		
RMS Measurement Time	5ms		11ms		2min 1sec		
UL 943 Limit	**813mA**	**Within UL 943 Current/Time Limits?**	**469mA**	**Within UL 943 Current/Time Limits?**	**6mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	8mA	Yes	28mA	Yes	14mA	No	No
Total GND Hioki Leakage Current	3mA	Yes	20mA	Yes	13mA	No	No

High Impedance Interruption Test

Figure 6-60 shows the waveforms for the high-impedance interruption test while thermal chambers were configured for Temperature Condition 2 as shown in **Error! Reference source n ot found.**. The figure shows where the voltage interruption was executed, where the compressor was enabled, and when the compressor was running. The leakage current during these time periods was analyzed and is discussed in detail below.

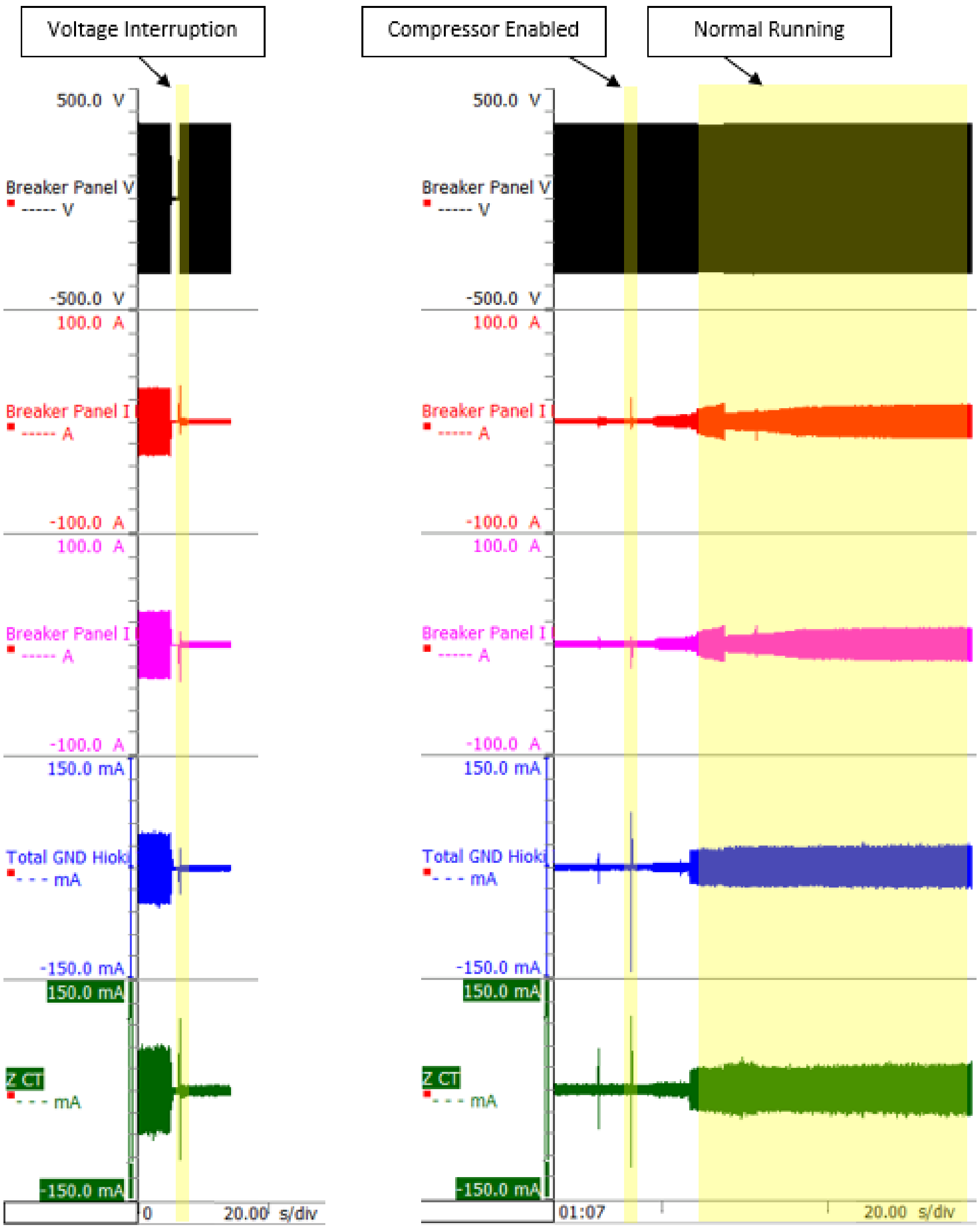


Figure 7-60
Temperature Condition 2, High Impedance Interruption Test

Figure 7-61 shows the entire 1-second voltage interruption event, with a zoomed in view of when voltage was reapplied after the interruption outlined in red. The statistical data of the leakage current shown to the right of the waveforms is associated with the zoomed in view outlined in red. The 200-ms/division waveform shows that a high impedance voltage interruption creates a ringing effect due to the back electromotive force (EMF) when transitioning from full nominal voltage to 0 volts. This ringdown is a typical indicator that the voltage was switched into an open circuit (high-impedance interruption).

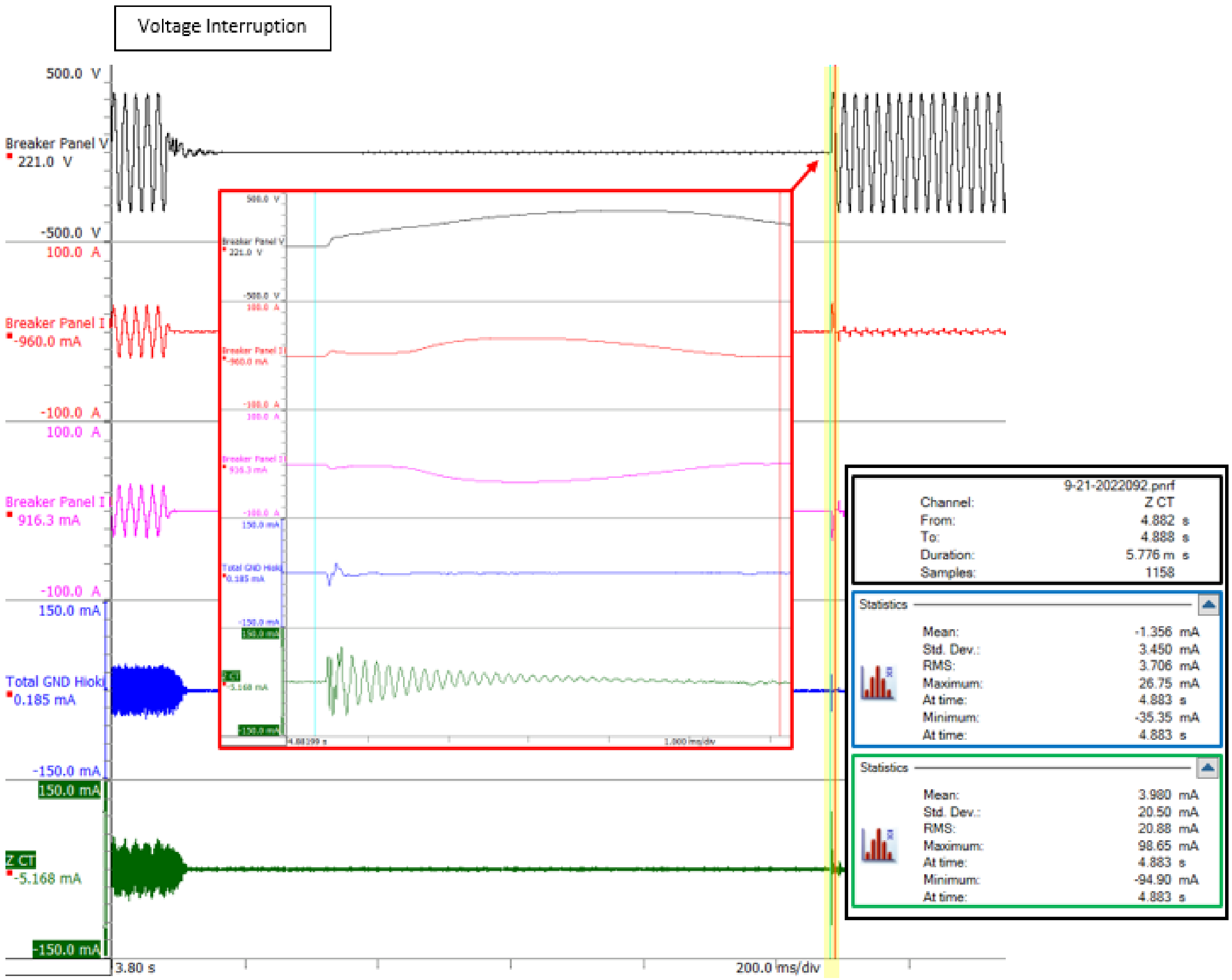


Figure 7-61
Temperature Condition 2; Leakage Current Following High Impedance Interruption

Figure 7-62 shows the waveforms when the compressor is enabled following the voltage interruption. The maximum leakage current measured by the Z CT was 15 mA RMS. The waveforms show the compressor was enabled at about 315 degrees POW, approximately half of the peak voltage. This may be why the leakage current was almost half of the previous test when the compressor was enabled at the peak of the voltage.

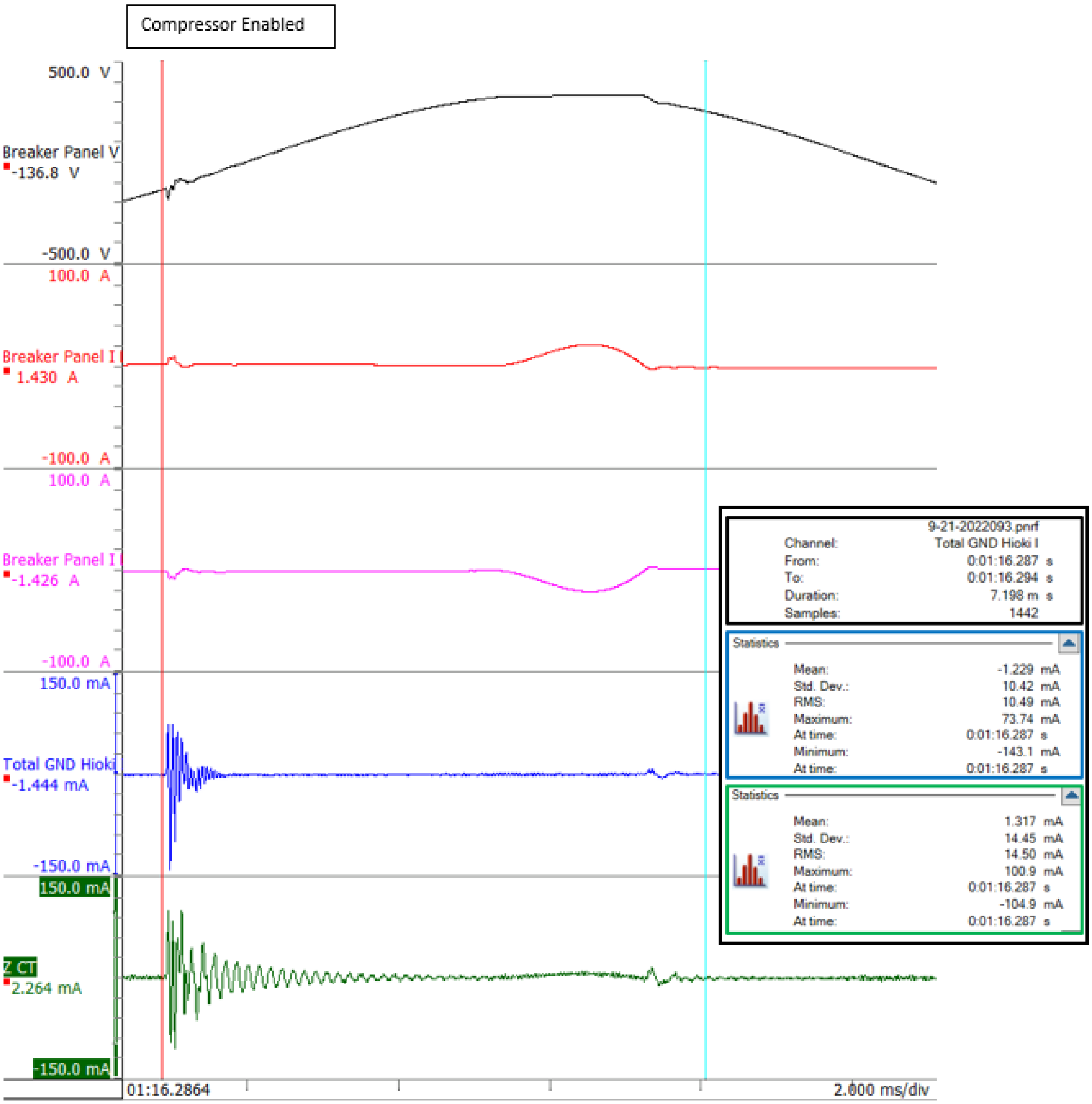


Figure 7-62
Temperature Condition 2, Compressor Enabled Following High Impedance Interruption

Figure 7-63 shows the waveforms when the compressor was running nominally. During this time, the leakage current was significantly lower than when the compressor was enabled; however, the leakage current measured by the Z-CT is above the limits in UL 943.

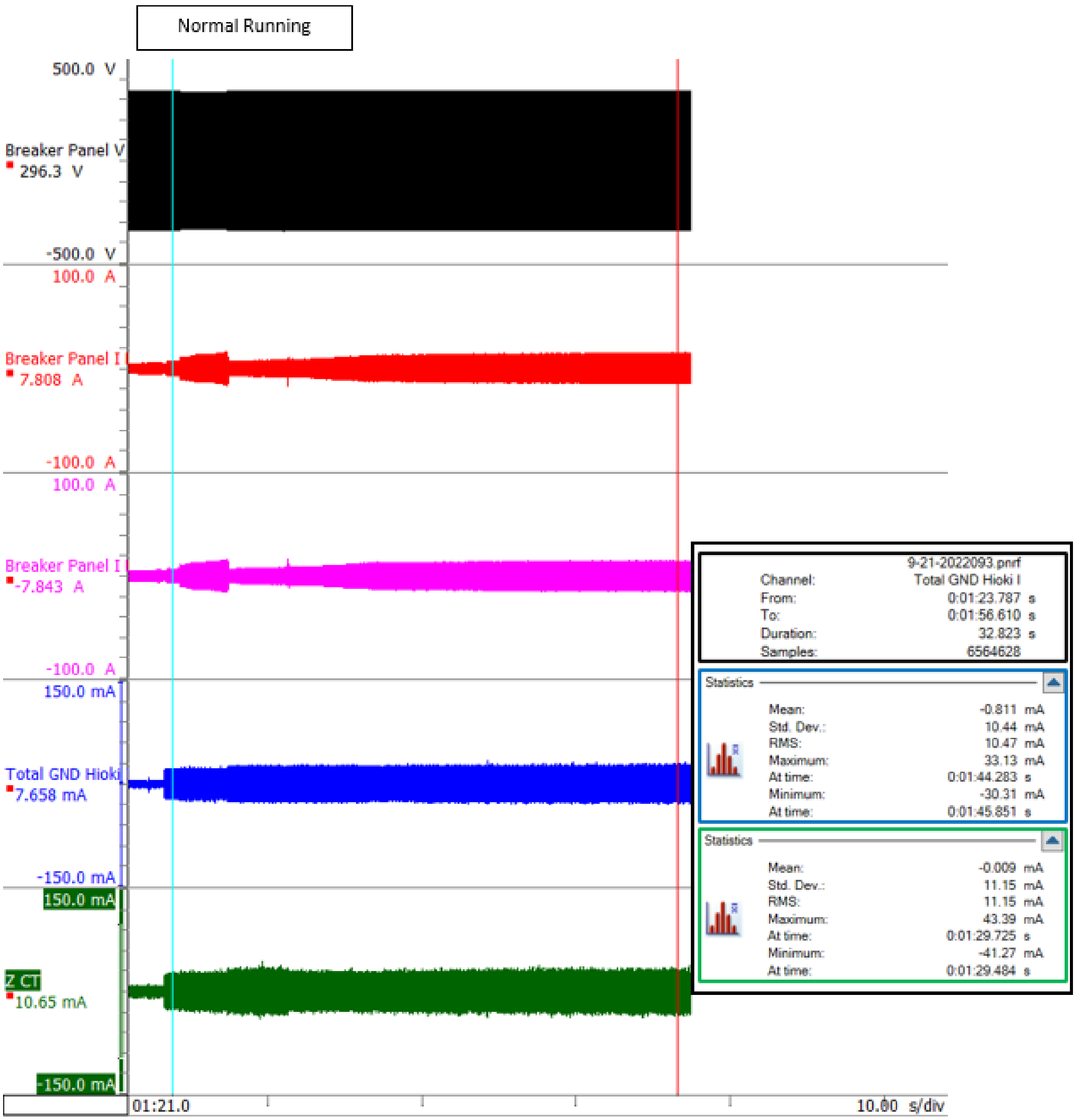


Figure 7-63
Temperature Condition 2, Compressor Running Following High Impedance Interruption

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the high impedance test while set to Temperature Condition 2. The measurements of when the voltage returned after the interruption, when the compressor was enabled, and when the compressor was running nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor-start time periods was within the time/current limits of UL 943; however, the RMS current measured by the Z-CT during the nominal running time period was 5 mA above the RMS current limitations of UL 943.

Table 7-21
Tabular Data from the High Impedance Interruption Test at Temperature Condition 2

Note: All measurements are represented as RMS	**Application of Power Following Interruption**		**Compressor Enabled**		**Normal Running**		
Measurement Time Base	1ms/div		2ms/div		10s/div		
RMS Measurement Time	6ms		7ms		33sec		
UL 943 Limit	**716mA**	**Within UL 943 Current/Time Limits?**	**643mA**	**Within UL 943 Current/Time Limits?**	**6mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	21mA	Yes	15mA	Yes	11mA	No	No
Total GND Hioki Leakage Current	4mA	Yes	10mA	Yes	10mA	No	No

Temperature Condition 3 Tests

Low-Impedance Interruption Test

Figure 7-64 shows the waveforms for the low-impedance interruption test while the thermal chambers were configured for Temperature Condition 3. The figure shows where the voltage interruption was executed, where the compressor was enabled, and when the compressor was running. The leakage current during these time periods was analyzed and is discussed in detail below.

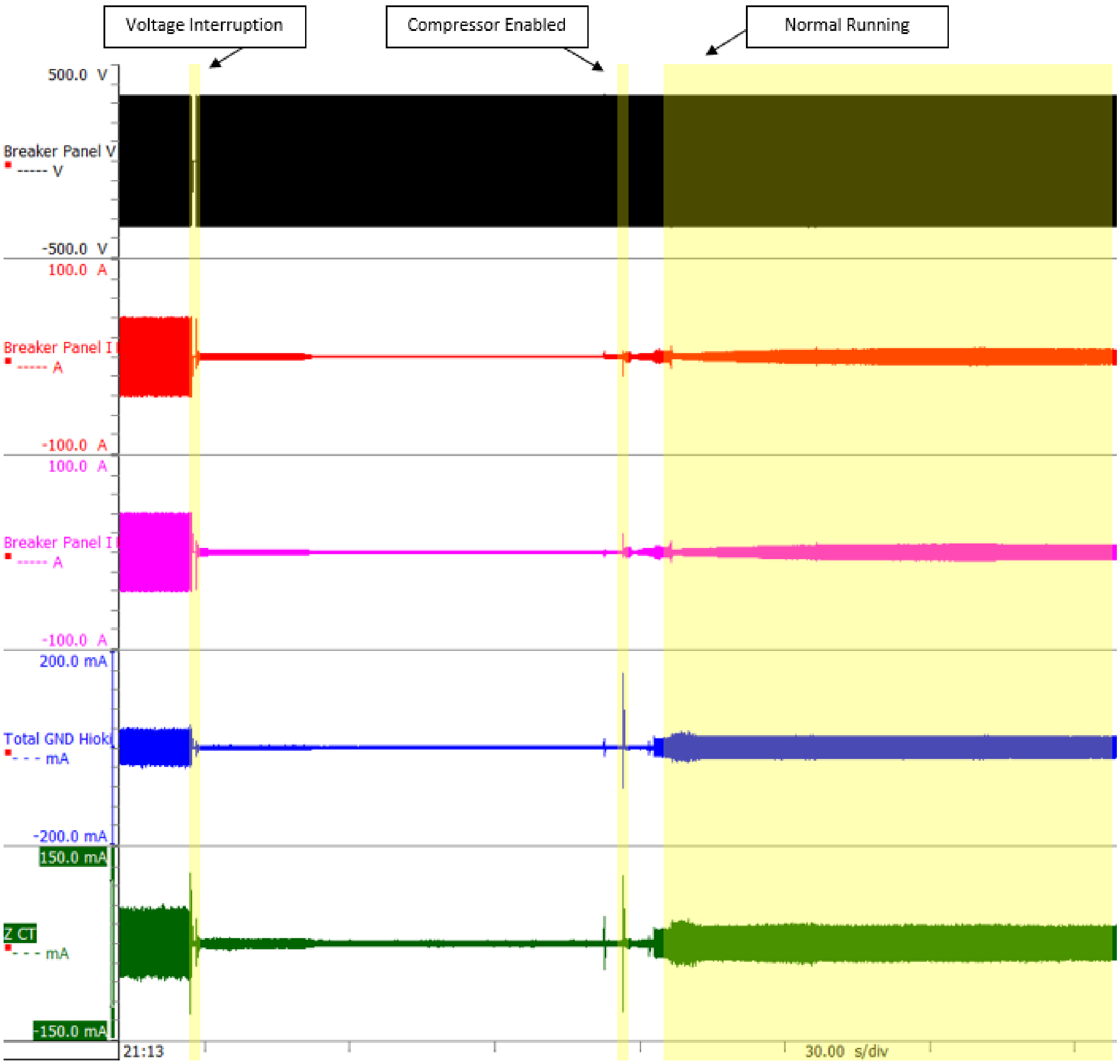


Figure 7-64
Temperature Condition 3, Low Impedance Interruption Test

Figure 7-65 shows the entire 1-second voltage interruption event and a zoomed-in view of the leakage current that resulted when the voltage returned after the interruption outlined in red. The statistical data to the right of the waveforms is associated with the 5-ms time period outlined in red. The 200-ms/division waveform is shown to draw attention to the voltage waveform in order to show that a low-impedance voltage interruption creates a crisp transition from full nominal voltage to 0 volts. If the voltage interruption is created via a transformer (low-impedance interruption) the voltage transition will have this crisp edge. The high-impedance interruption creates a different transition that will be shown in the next section.

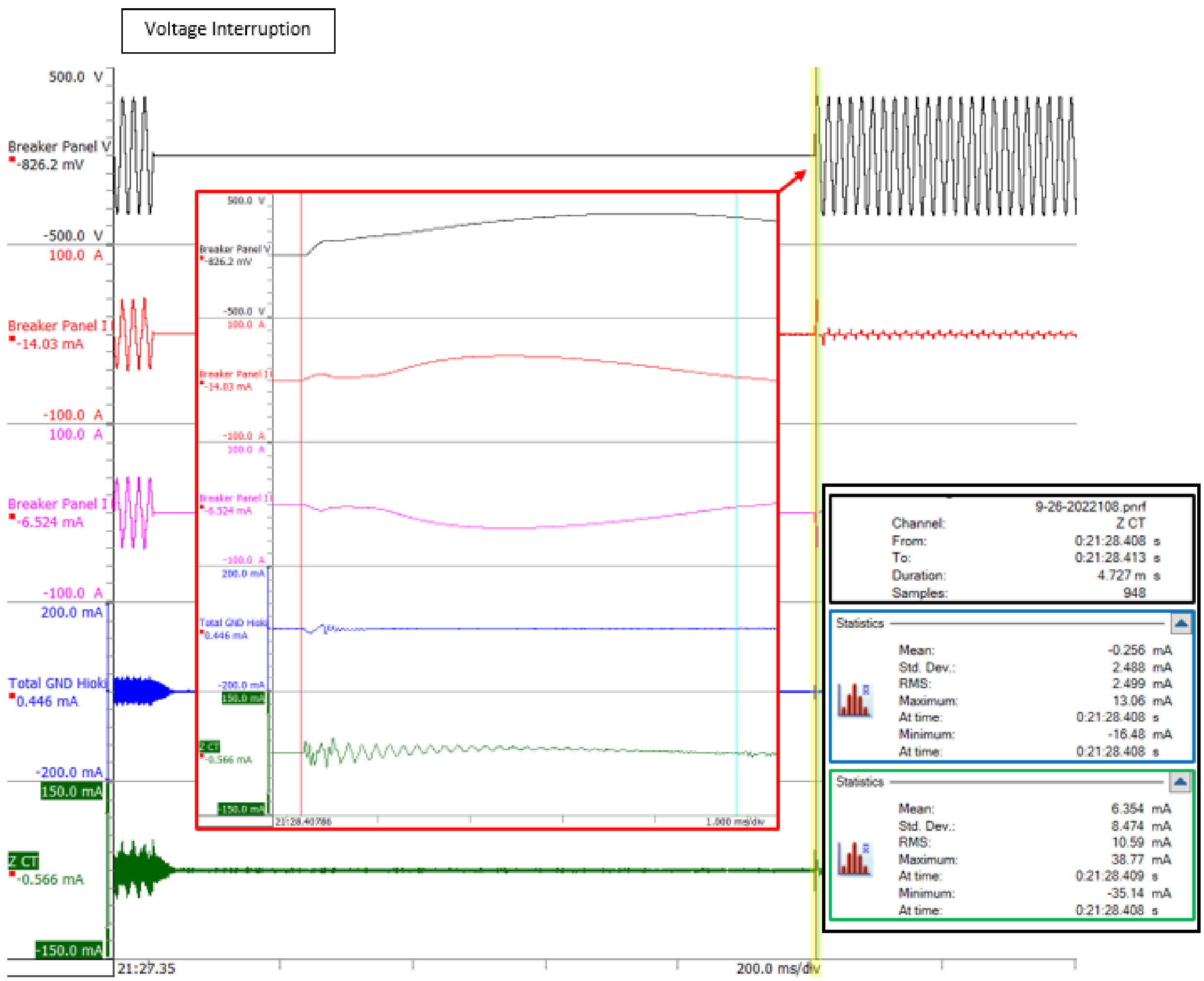


Figure 7-65
Temperature Condition 3; Leakage Current Following Low Impedance Interruption

Figure 7-66 shows the waveforms when the compressor was enabled. The maximum leakage current measured by the Z-CT was 18 mA RMS. The waveforms show the compressor was enabled at about 225 degrees POW, approximately half of the negative peak voltage. This may be why the leakage current was almost half of the leakage current observed during the low-impedance interruption test conducted in Temperature Configuration 2.

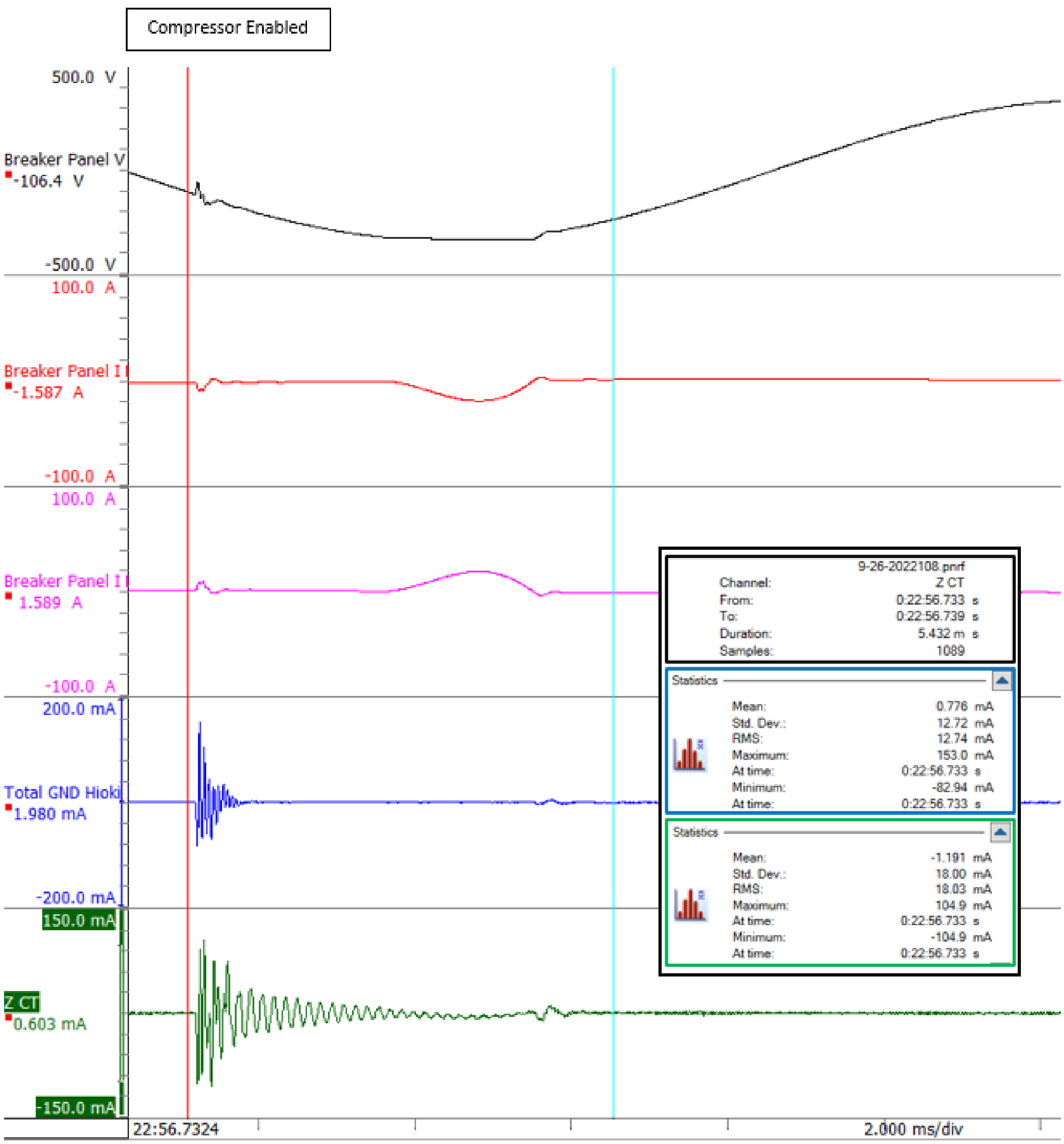


Figure 7-66
Temperature Condition 3, Compressor Enabled Following Low Impedance Interruption

Figure 7-67 shows the waveforms when the compressor was running nominally. During this time, the leakage current was lower than when the compressor enabled; however, the Z-CT measured leakage current values greater than the acceptable limits of UL 943.

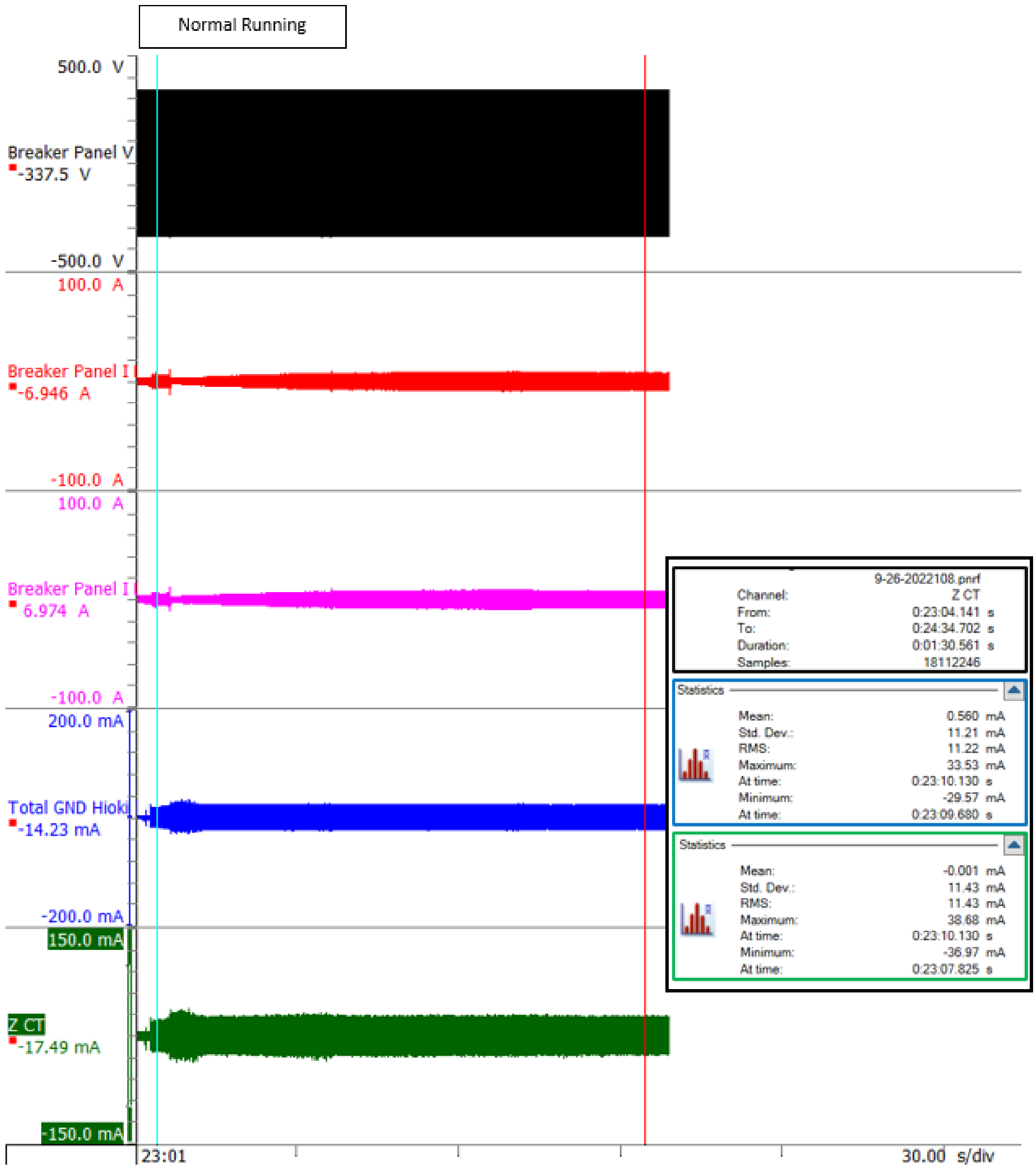


Figure 7-67
Temperature Condition 3, Compressor Running Following Low Impedance Interruption

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the low-impedance test while set to Temperature Condition 3. The measurements of when the voltage returned after the interruption, when the compressor was enabled, and when the compressor was running nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time periods was within the time/current limits of UL 943; however, the RMS current measured by the Z-CT during the nominal running time period was 5 mA above the RMS current limitations of UL 943.

Table 7-22
Tabular Data from the Low Impedance Interruption Test at Temperature Condition 3

Note: All measurements are represented as RMS	**Application of Power Following Interruption**		**Compressor Enabled**		**Normal Running**		
Measurement Time Base	1ms/div		2ms/div		30s/div		
RMS Measurement Time	5ms		5ms		1min 31sec		
UL 943 Limit	**813mA**	**Within UL 943 Current/Time Limits?**	**813mA**	**Within UL 943 Current/Time Limits?**	**6mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	11mA	Yes	18mA	Yes	11mA	No	No
Total GND Hioki Leakage Current	2mA	Yes	13mA	Yes	11mA	No	No

High-Impedance Interruption Test

Figure 7-68 shows the waveforms for the high-impedance interruption test while thermal chambers were configured for Temperature Condition 3 as shown in **Error! Reference source not found.**. The figure shows where the voltage interruption was executed, where the compressor was enabled, and when the compressor was running. The leakage current during these time periods was analyzed and is discussed in detail below.

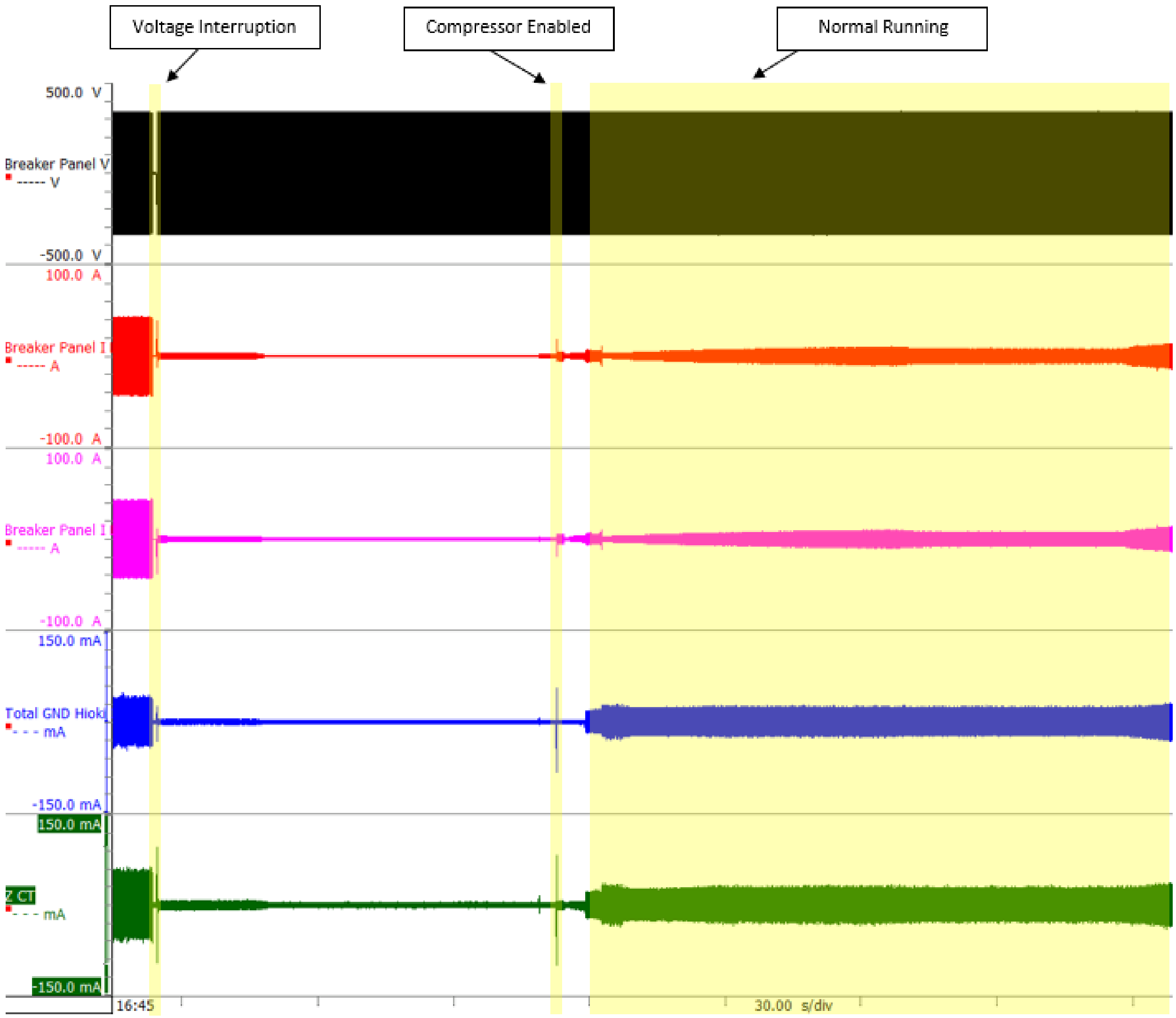


Figure 7-68
Temperature Condition 3, High Impedance Interruption Test

Figure 7-69 shows the entire 1-second voltage interruption event, with a zoomed-in view of when voltage was reapplied after the interruption outlined in red. The statistical data of the leakage current shown to the right of the waveforms is associated with the 6-ms view outlined in red. The 200-ms/division waveform shows that a high impedance voltage interruption creates a ringing effect due to the back electromotive force (EMF) when transitioning from full nominal voltage to 0 volts. This ringdown is a typical indicator that the voltage was switched into an open circuit (high-impedance interruption).

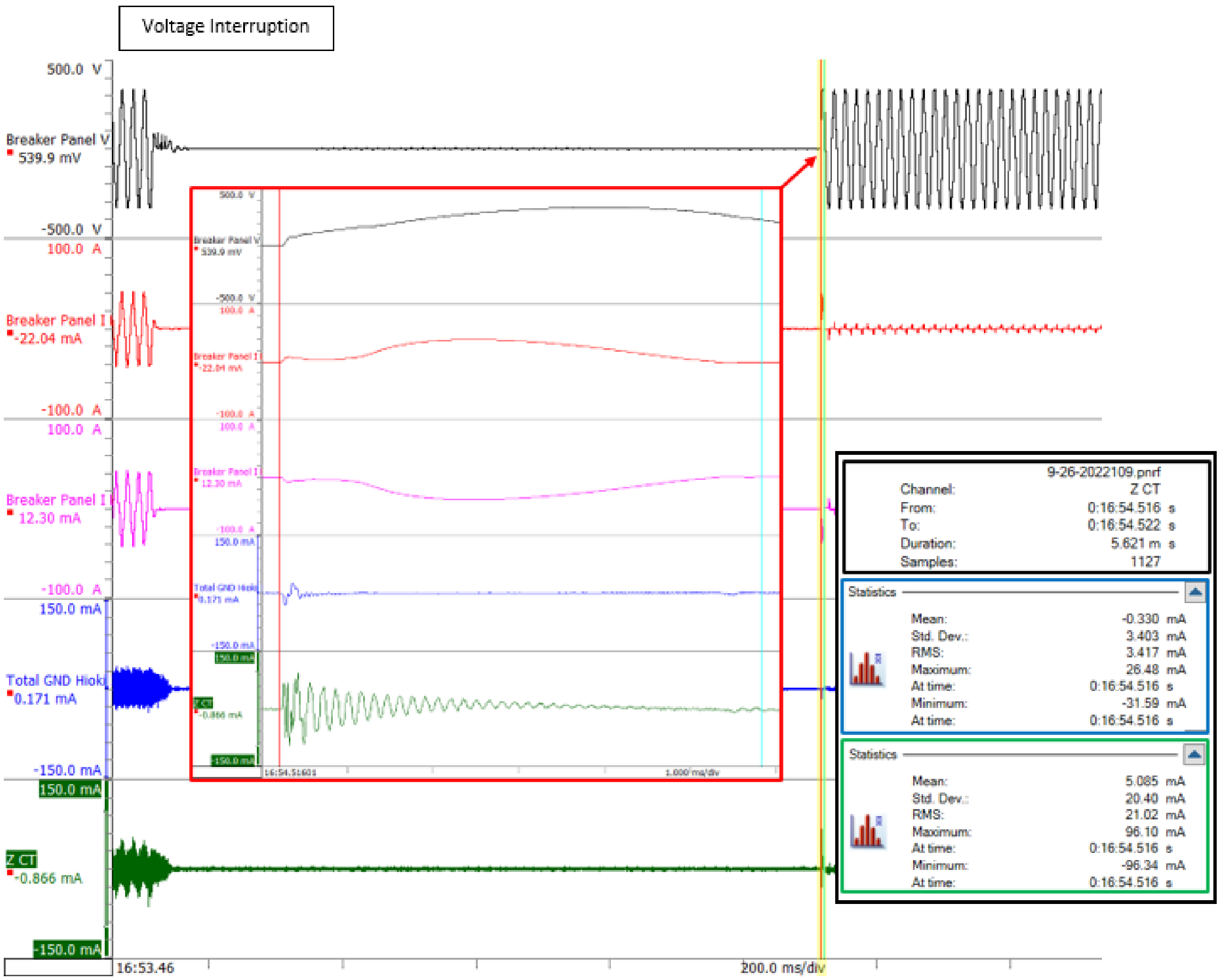


Figure 7-69
Temperature Condition 3; Leakage Current Following High Impedance Interruption

Figure 7-70 shows the waveforms when the compressor is enabled following the voltage interruption. The maximum leakage current measured by the Z-CT was 10 mA RMS. The waveforms show the compressor was enabled at about 304 degrees POW, closer to the negative peak voltage than the zero crossing, although this is the second lowest maximum leakage current measured during any of the four tests.

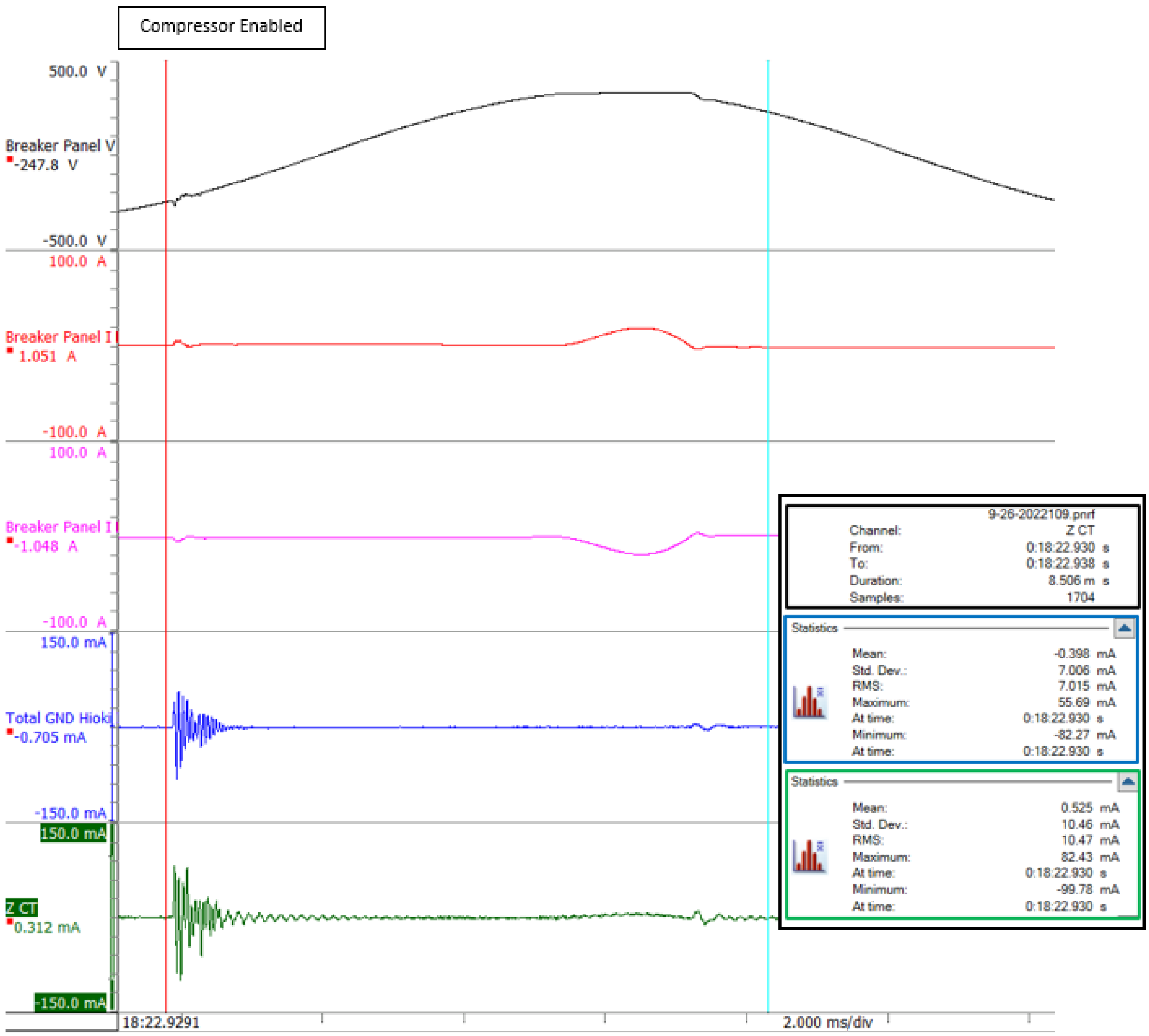


Figure 7-70
Temperature Condition 3, Compressor Enabled Following High Impedance Interruption

Figure 7-71 shows the waveforms when the compressor was running nominally. During this time, although the leakage current was lower than some of the other tests, the current measured by the Z-CT was above the limits in UL 943.

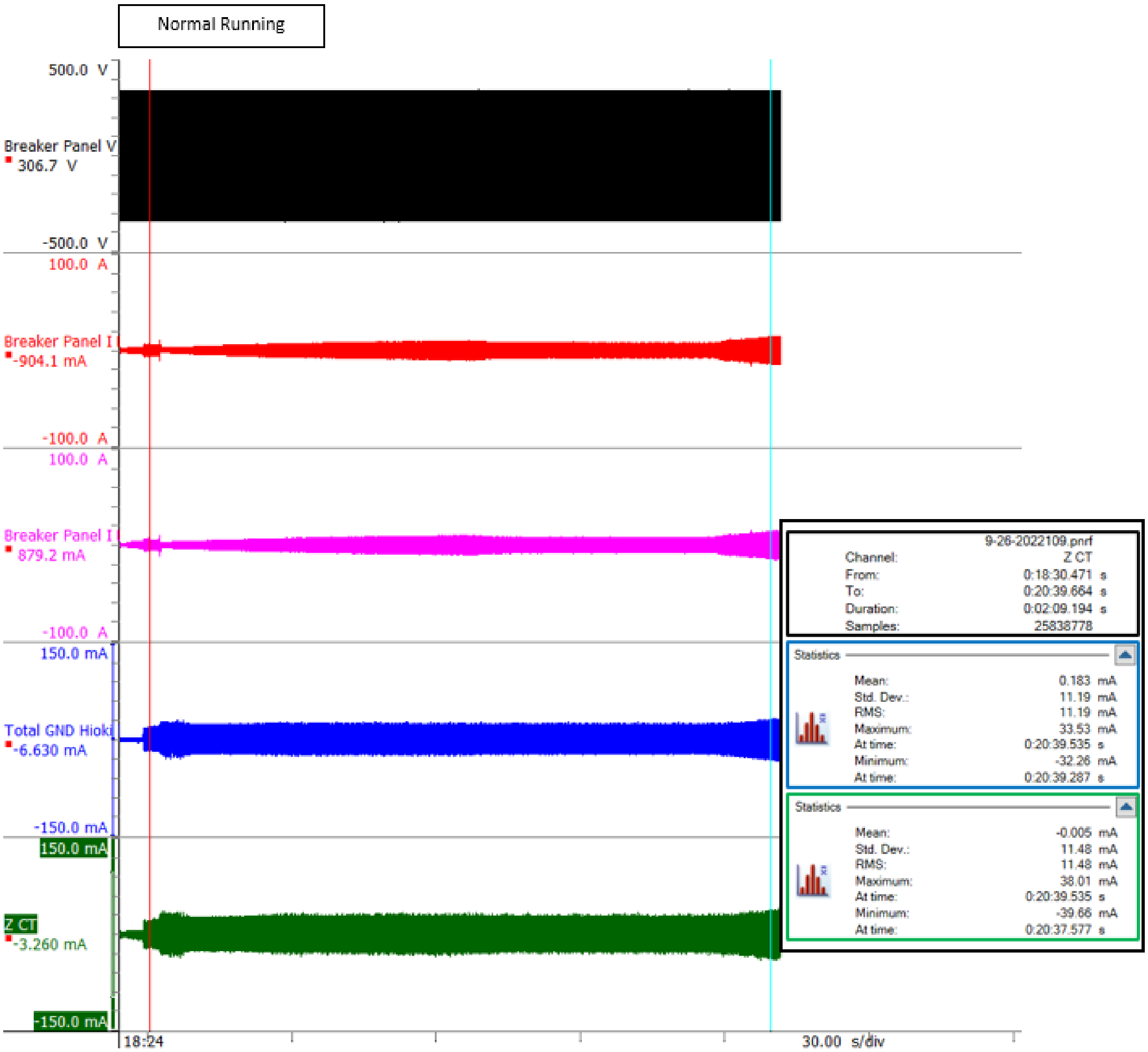


Figure 7-71
Temperature Condition 3, Compressor Running Following High Impedance Interruption

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the high-impedance test while set to Temperature Condition 3. The measurements of when the voltage returned after the interruption, when the compressor was enabled, and when the compressor was running nominally were monitored and recorded. The RMS leakage current measured by the Z-CT during application of power and the compressor start time periods was within the time/current limits of UL 943; however, the RMS current measured by the Z-CT during the nominal running time period was 5 mA above the RMS current limitations of UL 943. The reason for this phenomenon is the RMS current may be a combination of fundamental and higher order frequency components. The GFCI may only respond to the fundamental current, an example of this may be seen in Figure 7-14 within the conclusion section of Test 0.

Table 7-23
Tabular Data from the High Impedance Interruption Test at Temperature Condition 3

Note: All measurements are represented as RMS	**Application of Power Following Interruption**		**Compressor Enabled**		**Normal Running**		
Measurement Time Base	1ms/div		2ms/div		30s/div		
RMS Measurement Time	6ms		9ms		2min 9sec		
UL 943 Limit	**716mA**	**Within UL 943 Current/Time Limits?**	**1543mA**	**Within UL 943 Current/Time Limits?**	**6mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	21mA	Yes	10mA	Yes	11mA	No	No
Total GND Hioki Leakage Current	3mA	Yes	7mA	Yes	11mA	No	No

Test 5 Conclusion

High- and low-impedance voltage interruptions were applied to the HVAC system while operating in Temperature Conditions 2 and 3 shown in **Error! Reference source not found.**. The m aximum leakage current for each test was measured when power was applied following the voltage interruption or when the compressor was enabled following the voltage interruption. The leakage current was a maximum when the compressor was enabled at the peak of the voltage waveform. The leakage current appeared to be lower when the compressor was enabled with voltage closer to 0 degrees POW in most cases. The only time leakage current exceeded the limits of UL 943 was during the normal running phase of the test. Leakage current was not significantly high when the voltage returned immediately after the interruption; therefore, consider removing this test when looking for events that may cause GFCIs to trip.

Test 6 High/Low Voltage Range

HVAC systems are installed in real-world residential and commercial power systems. As loading changes on the power grid, so may the nominal voltage. The purpose of this test is to investigate the response of the EUT when operating at the minimum and maximum "acceptable" voltage levels provided in the ANSI C84.1 standard. The test was conducted using a power amplifier to increase and decrease the nominal voltage to 86%, 90%, 95%, and 106%, while the thermal chambers were set to operate at Temperature Condition 2. **Error! Reference source not found.** shows the RMS leakage current measured by the Z-CT for each voltage level.

Table 7-24
High/Low Voltage Range Test Maximum Leakage Current

High/Low Voltage Test	Temperature Condition	Measured ZCT Leakage Current (mA_{RMS}/time)	Within UL943 Current/Time Limits?	GFCI Trip?	Outdoor Chamber Humidity
106%	2	21mA_{RMS}/5min 24sec	No	No	10%-20%
95%	2	23mA_{RMS}/5min 1sec	No	No	10%-20%
90%	2	25mA_{RMS}/5min 2sec	No	No	10%-20%
86%	2	11mA_{RMS}/5min 6sec	No	No	10%-20%

Figure 7-72 shows all the test levels conducted in one waveform. The four voltage levels were injected into the outdoor unit for approximately 5 minutes at each level with a transition back to 100% voltage for a period of 2 minutes before executing the next voltage test level. The highlighted areas are shown individually in the body of this section of the report. The leakage currents during these time periods were analyzed and are discussed in this section of the report. The data shows very little deviation of the leakage current measured by the Z-CT during the 5-minute test intervals at each voltage level. Post analysis of the data indicates that after the 90 percent of nominal test, the HVAC unit seems to have tripped on overcurrent when the nominal voltage was suddenly restored. Therefore, 86 percent of nominal test results are invalid since the unit had not fully recovered properly to start the test.

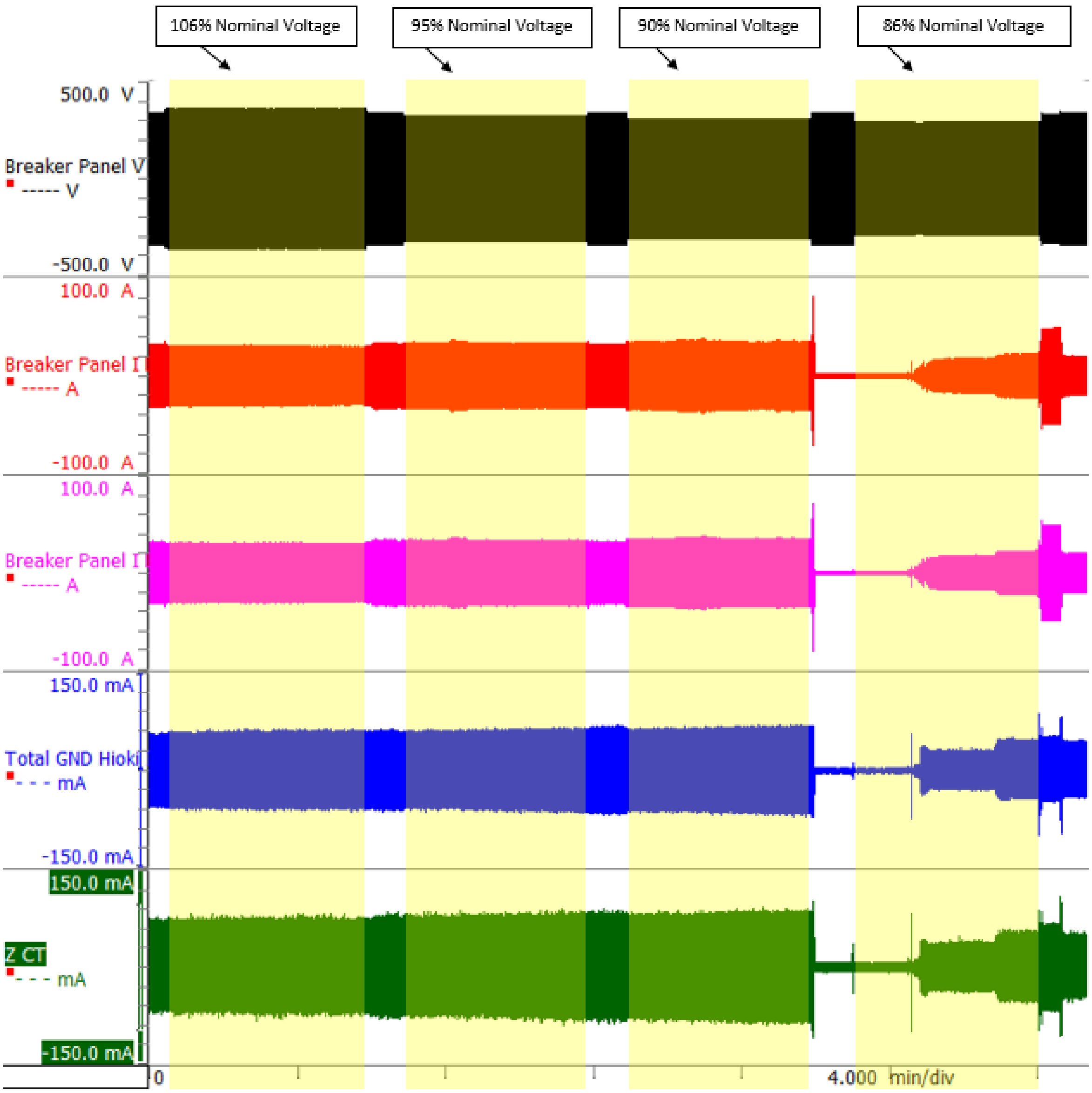


Figure 7-72
High/Low Voltage Range Test

Figure 7-73 shows the waveforms when the nominal voltage was increased to 106%. The waveforms show there is no significant change in the leakage current between 100% voltage and 106% voltage. The leakage current measured by the Z-CT was above the allowable limits of UL 943; however, the GFCI did not trip.

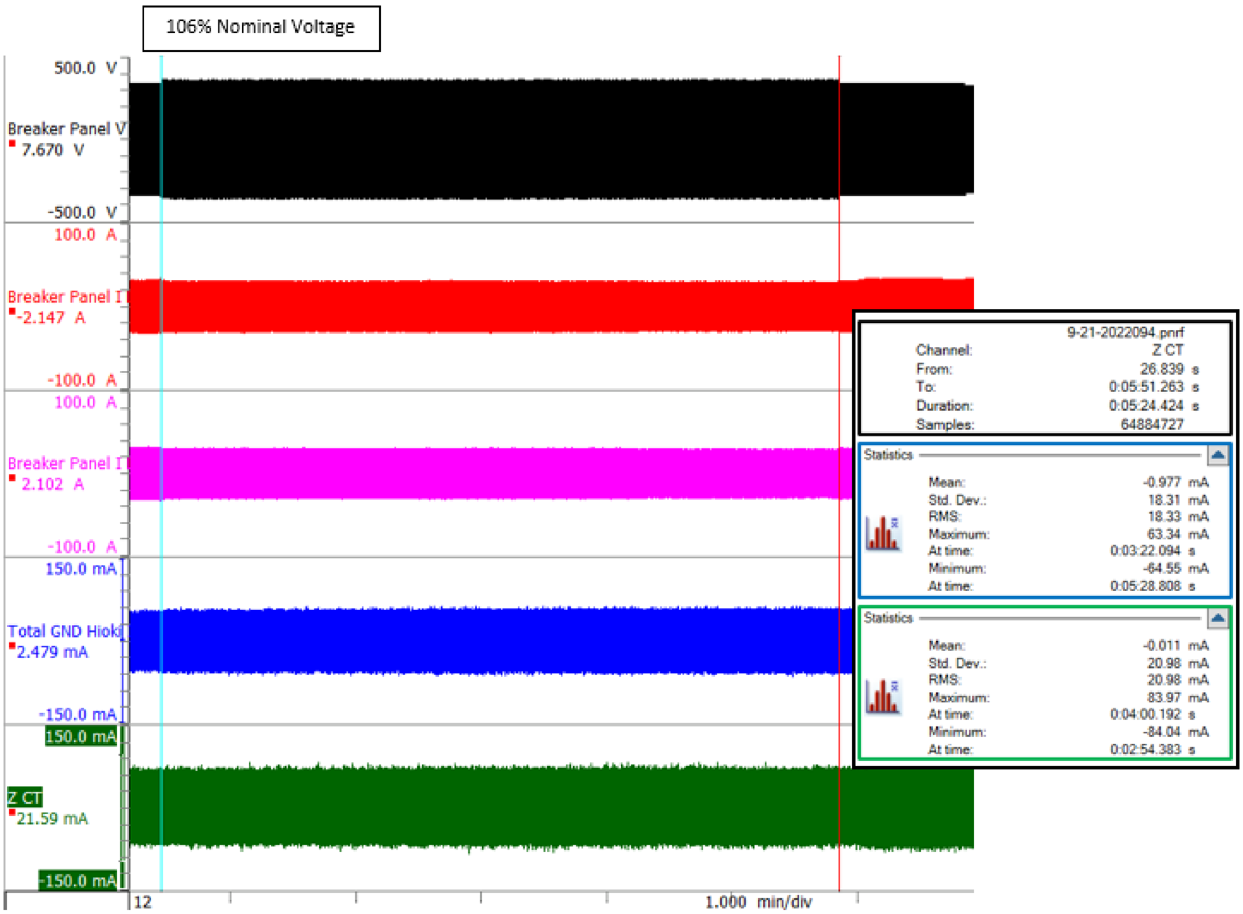


Figure 7-73
106% Voltage Step

Figure 6-74 shows the waveforms when the nominal voltage was decreased to 95%. The waveforms show there is no significant change in the leakage current between 100% voltage and 95% voltage. The leakage current measured by the Z-CT was above the allowable limits of UL 943; however, the GFCI did not trip.

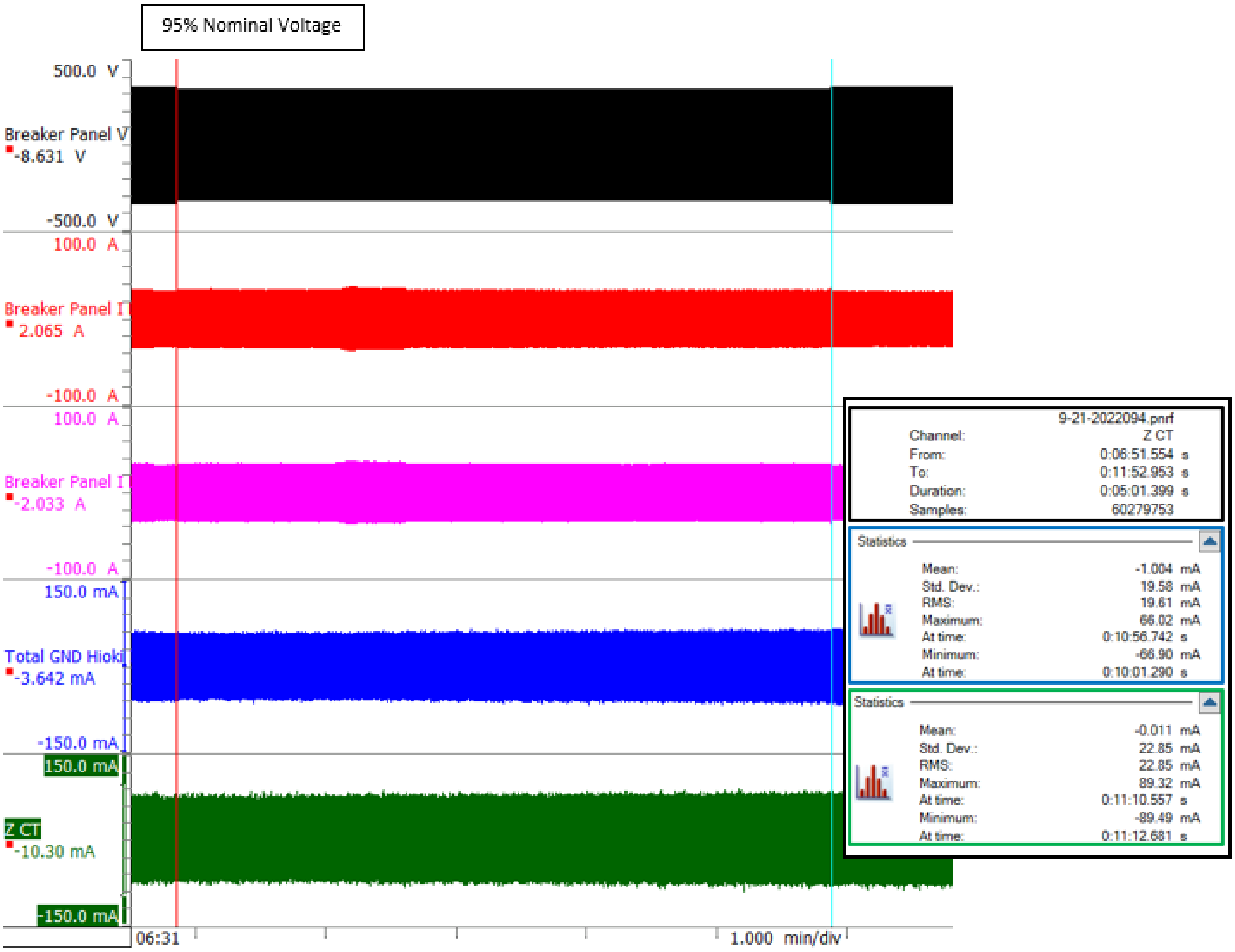


Figure 7-74
95% Voltage Step

Figure 6-75 shows the waveforms when the nominal voltage was decreased to 90%. The waveforms show there is no significant change in the leakage current between 100% voltage and 90% voltage. The leakage current measured by the Z-CT was above the allowable limits of UL 943; however, the GFCI did not trip. Approximately 1.3 seconds after the transition from 90% voltage to 100% voltage, the filter circuit began to stop filtering the current harmonics. The compressor then turned off the output, approximately 1.3 seconds after the transition from 90% voltage to 100% voltage as seen in Figure 6-75.

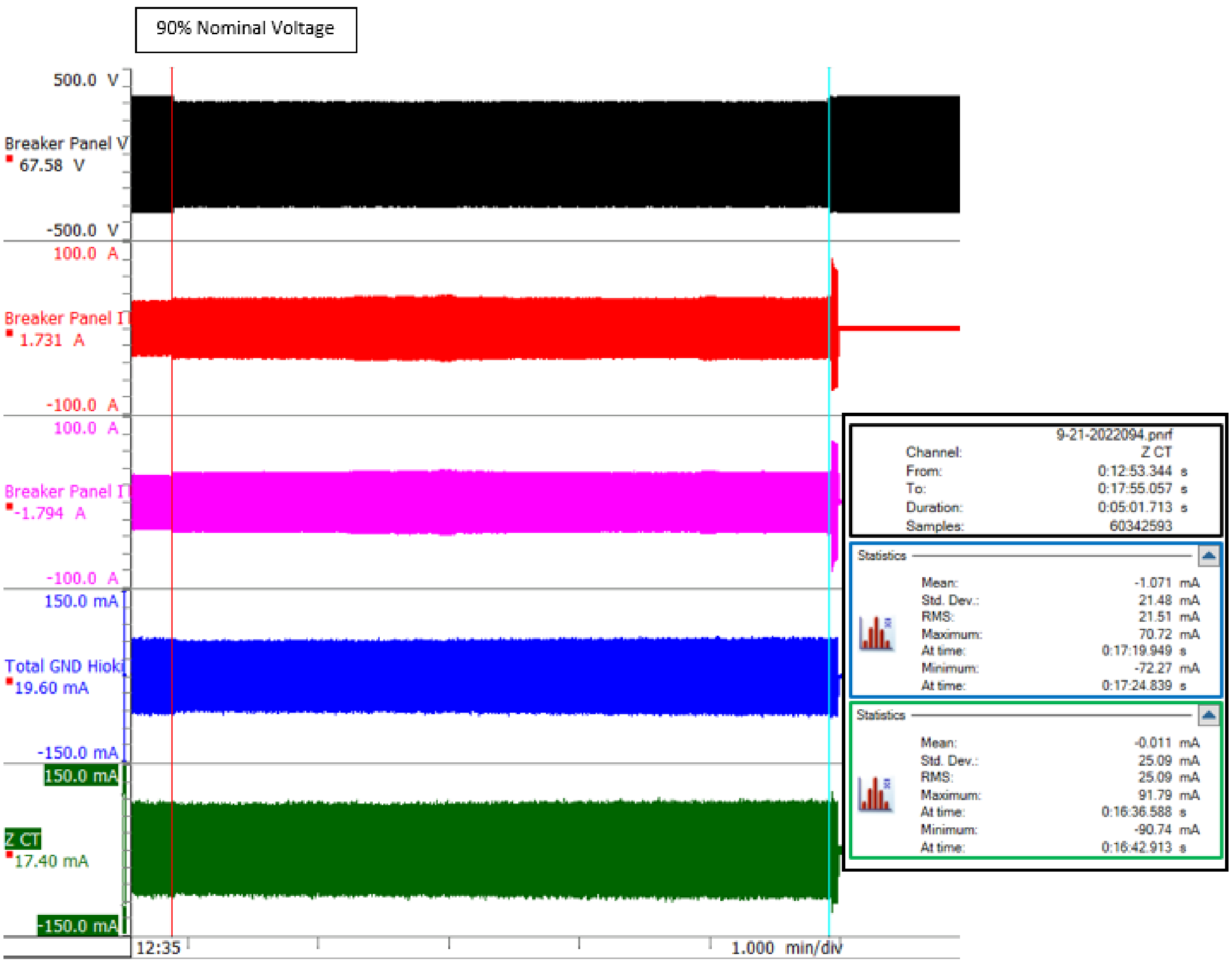


Figure 7-75
90% Voltage Step

Figure 6-76 shows the current waveform is no longer sinusoidal and has high 3rd and 5th harmonic content, indicating the power factor correction turned off. The unfiltered condition remained for 2.5 seconds before the compressor turned off the output. The output remained off for approximately 1.5 minutes before automatically restarting.

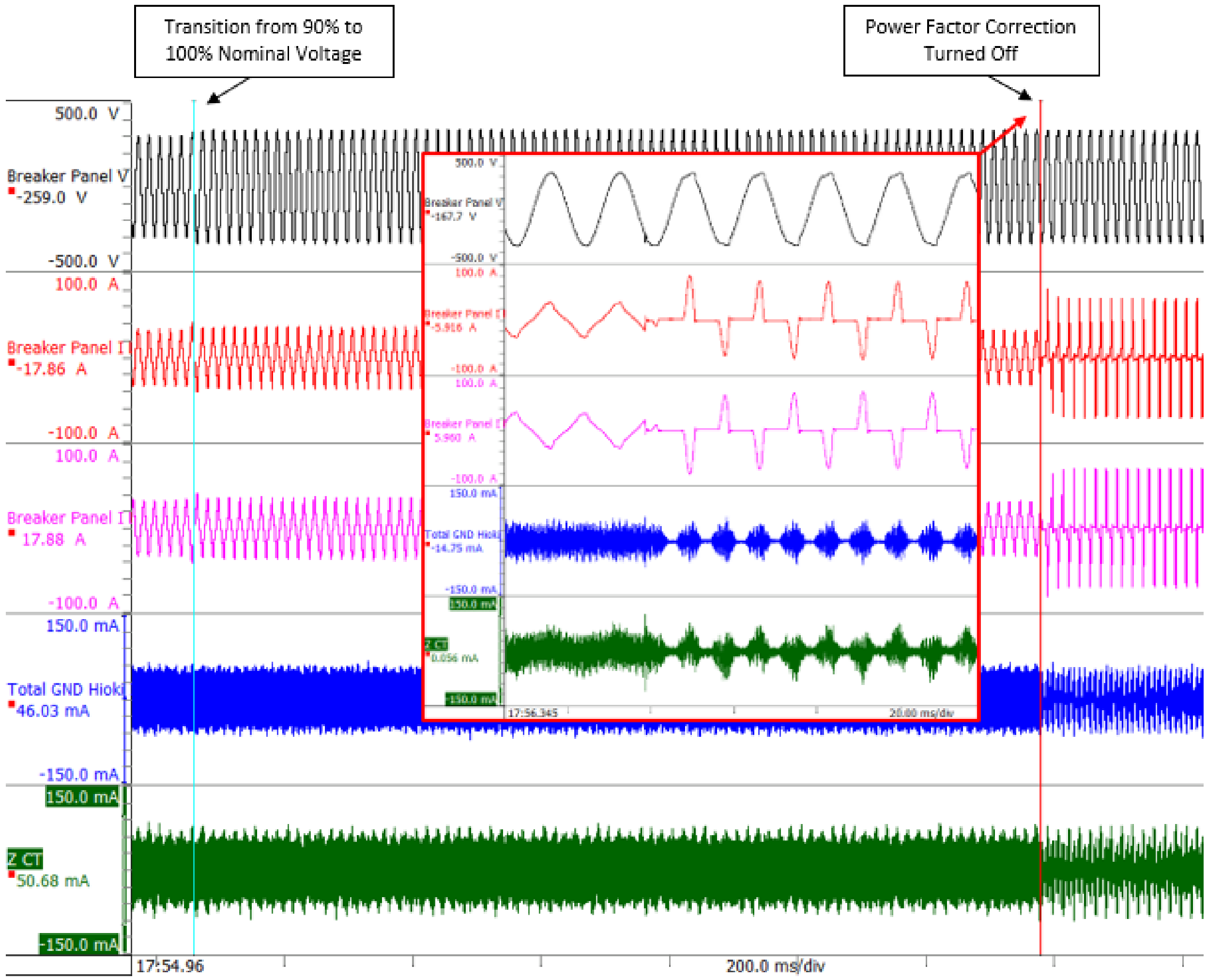


Figure 7-76
90% Voltage to 100% Voltage Step

Figure 7-77 shows the waveforms when the nominal voltage was decreased to 86%. The compressor had shut off after the transition from 90% voltage to 100% voltage during the previous test point; therefore, the compressor was off for approximately 1 minute and 40 seconds at the beginning of the 86% voltage test. The highlighted portions of the figure show when the compressor was off, when the compressor was enabled, and when the compressor was running normally at 86% nominal voltage. The statistical data to the right of the waveforms is associated with the entire 5-minute span of the 86% voltage test (the time in between the light blue and red cursors). The leakage current measured by the Z-CT was above the allowable limits of UL 943; however, the GFCI did not trip.

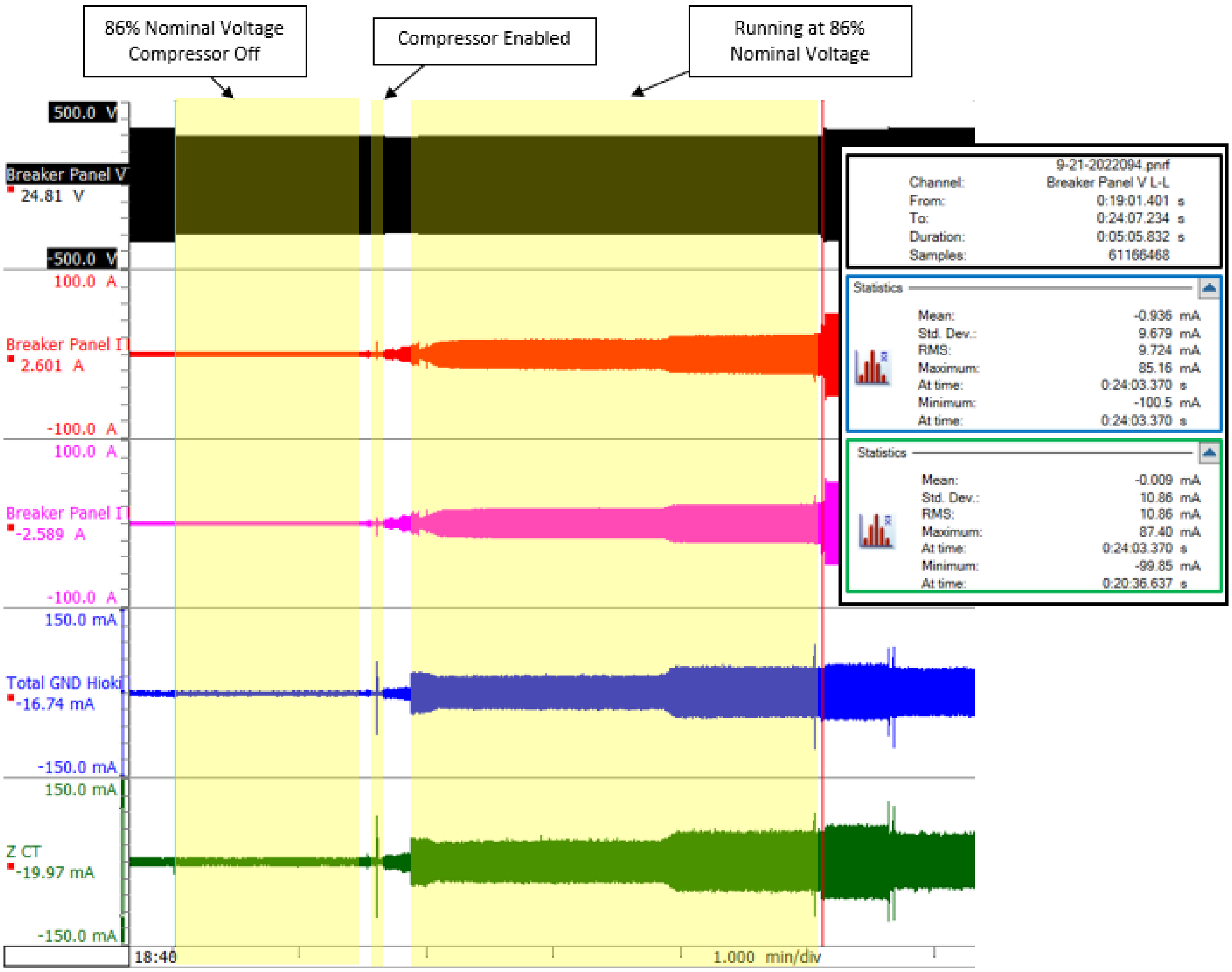


Figure 7-77
85% Voltage Step

Tabular data for each individual highlight section can be found in **Error! Reference source not found.**. Similar to the 90% voltage test, when the voltage transitioned from 86% voltage to 100% voltage the power factor correction circuit turned off. It remained off for approximately 30 seconds.

Table 7-25
Tabular Data for the 86% Voltage Test

Note: All measurements are represented as RMS	**86% Voltage Compressor Off**		**86% Voltage Compressor Enabled**		**86% Voltage Compressor Running**		
Measurement Time Base	30sec/div		2ms/div		1min/div		
RMS Measurement Time	1min 35sec		3ms		3min 24sec		
UL 943 Limit	**8mA**	**Within UL 943 Current/Time Limits?**	**1162mA**	**Within UL 943 Current/Time Limits?**	**6mA**	**Within UL 943 Current/Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	1mA	Yes	18mA	Yes	13mA	No	No
Total GND Hioki Leakage Current	1mA	Yes	11mA	Yes	12mA	No	No

Error! Reference source not found. shows all the tabular measurement data for the RMS l eakage current measured during the High/Low Voltage Range Test under full cooling temperature conditions. Four voltage levels were injected into the outdoor unit for approximately 5 minutes at each level with a transition back to 100% voltage for a period of 2 minutes before executing the next voltage test. The tabular data shows the leakage current measured by the Z-CT was always above the UL 943 allowable limits for a 5-minute time period.

Table 7-26
Tabular Data for the High/Low Voltage Range Test

Note: All measurements are represented as RMS	**106%**		**95%**		**90%**		**86%**		
Measurement Time Base	1min/div		1min/div		1min/div		1min/div		
RMS Measurement Time	5min 24sec		5min 1sec		5min 2sec		5min 6sec		
UL 943 Limit	**6mA**	**Within UL 943 Current/ Time Limits?**	**6mA**	**Within UL 943 Current/ Time Limits?**	**6mA**	**Within UL 943 Current/ Time Limits?**	**6mA**	**Within UL 943 Current/ Time Limits?**	**GFCI Trip?**
ZCT Total Leakage Current	21mA	No	23mA	No	25mA	No	11mA	No	No
Total GND Hioki Leakage Current	18mA	No	20mA	No	22mA	No	10mA	No	No

Test 6 Conclusion

High- and low-voltage tests were conducted between 86% and 106% of the nominal voltage. Leakage current values were reported from the Z-CT. The RMS leakage current values measured during the test appear larger than the acceptable limit of 6 milliamps called out in UL 943, yet the GFCI used to power the outdoor unit did not trip. It was noted that distortion power factor increased significantly when transitioning from 90% voltage to 100% voltage and from 86% voltage to 100% voltage. The compressor tripped and automatically returned to normal operation.

Test X Ad Hoc Voltage Sag

HVAC systems are installed in real-world residential and commercial power systems. These systems may experience voltage sags that are known to cause industrial, commercial, and residential equipment to trip or mis-operate. Voltage sag testing was part of the original test regimen; however, time limitations led to it being removed from the protocol. EPRI has conducted voltage sag testing on many industrial and commercial systems and found components and systems to react differently to voltage sags than voltage interruptions. Some cursory voltage sags were conducted to see how the HVAC system would react to voltage sags. Figure 7-78 shows the reaction of the HVAC system to a 30-cycle, 80% voltage sag. The figure shows that the voltage sag occurred at the beginning of the waveform, shortly after the voltage sag, the distortion power factor increased the power factor correction significantly for 30 seconds, attempted to enable for 4 seconds, and turned off again. This continued for several minutes until power was manually cycled.

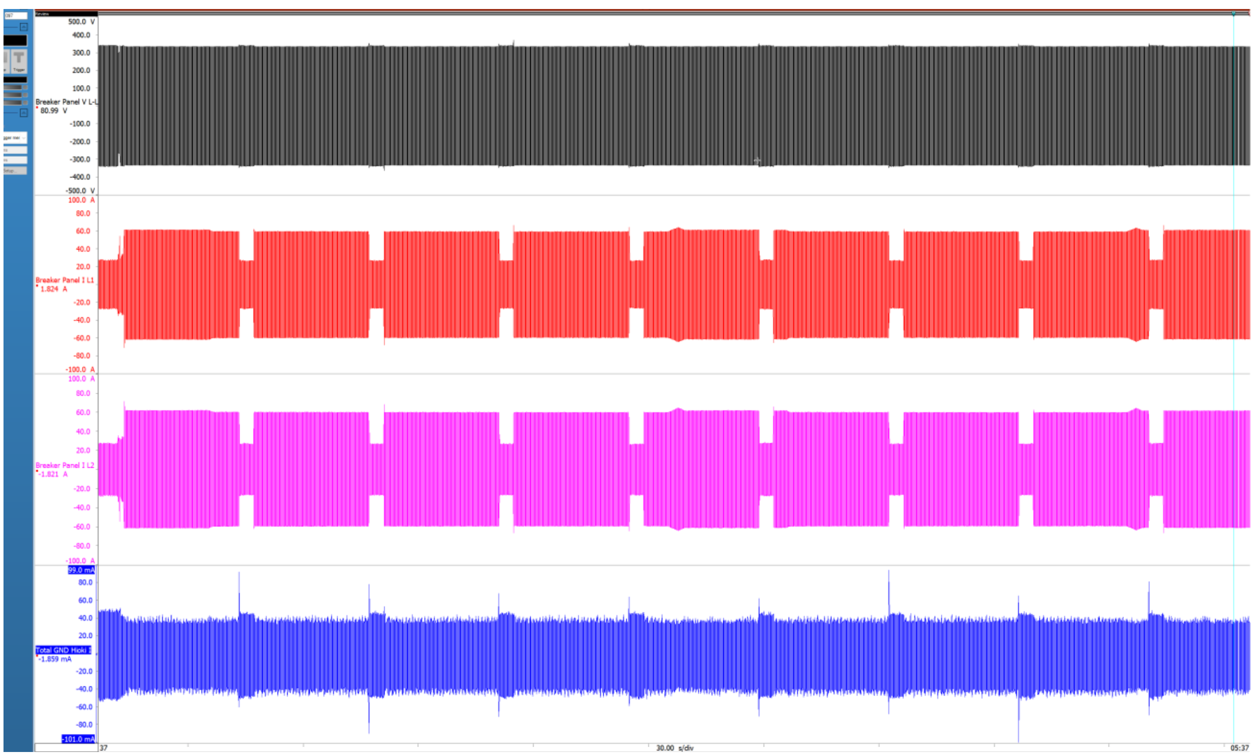


Figure 7-78
Reaction of HVAC after 30-cycle, 80% Voltage Sag

Figure 7-79 shows the 30-cycle, 80% voltage sag and the point where the distortion power factor increased again. Figure 7-79 and Figure 7-80 show the normal current signature prior to the voltage sag, immediately after the voltage sag, and 2 seconds after the voltage sag. The leakage current averaged 45 milliamps peak at 16.6 kHz when distortion was not present. The leakage current may be seen to increase as high as 100 milliamps peak at far right for a couple of cycles as shown in **Error! Reference source not found.**.

Figure 7-79
30-cycle, 80% Voltage Sag

The current signature highlighted in red within Figure 7-80 shows a high content of 3rd and 5th harmonic contribution.

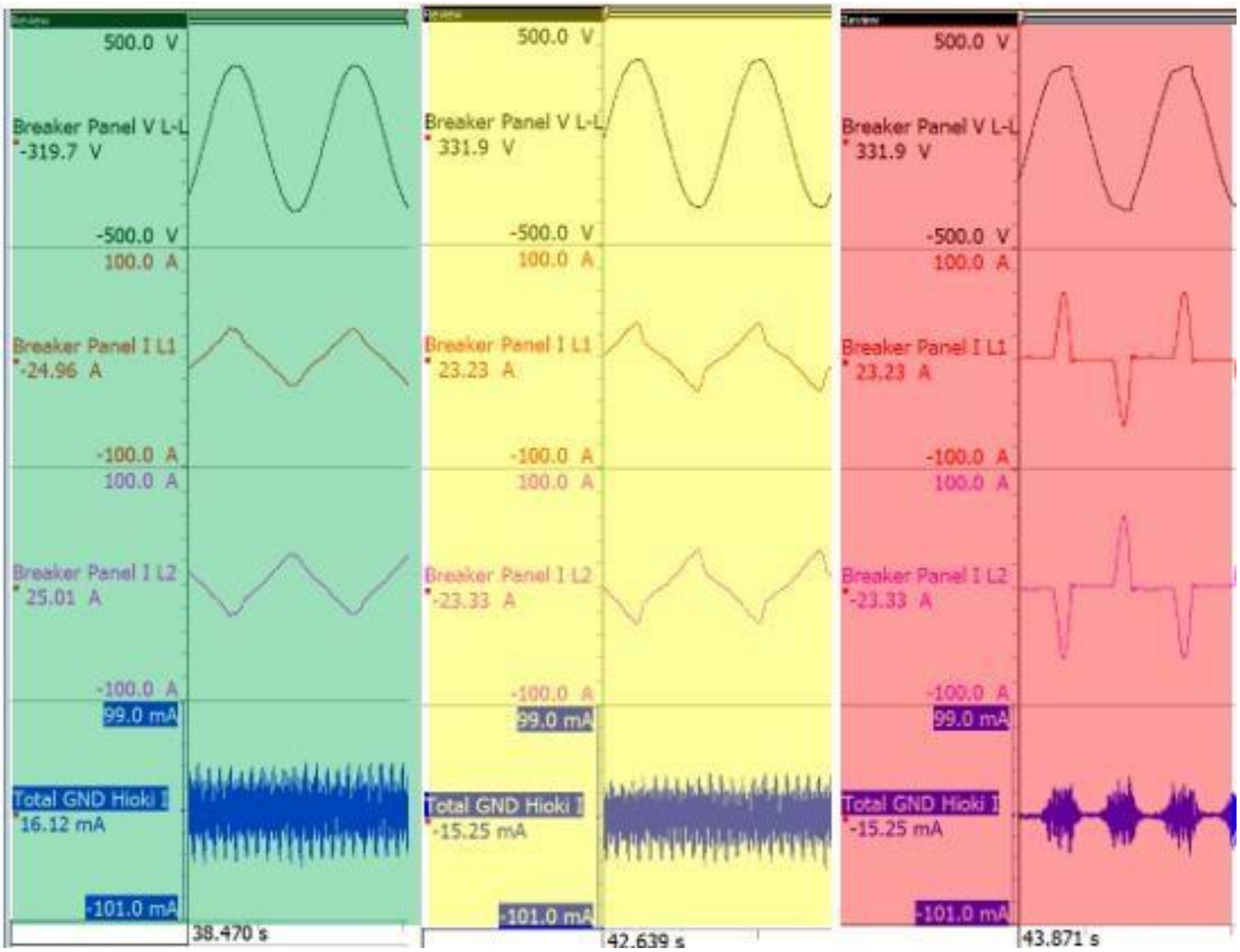


Figure 7-80
Comparison of Current Signature Prior, Immediately After, and 2 Seconds Post Voltage Sag

Test X Conclusion

A few cursory voltage sag tests were conducted on the HVAC system while conducting the updated test regimen. Many of the voltage sag tests resulted in increased distortion, correction turning off, the compressor tripping, and automatically restarting. A voltage sag was conducted early in the testing while the system was powered through a GFCI circuit breaker known to be sensitive to tripping. The breaker tripped one time during a voltage sag and then was not repeatable as time did not permit continuation of these types of tests.

A TESTING PROTOCOL FOR AHRI PROJECT 8029 GFCI HVAC SYSTEM COMPATIBILITY

Background

When electrical equipment operates in harmony with the power system, the system is said to be in a state of compatibility. In addition to being compatible with the grid from an operational standpoint, connected equipment should be safe and reliable for those who operate and perform maintenance on it. Therefore, in developing specifications for compatibility, various industry operational and safety standards are considered.

Recently, the 2020 National Electric Code (NEC) was revised with additional requirements for Ground Fault Circuit-Interrupters (GFCIs). Section 210.8(F) specifically addresses GFCI protection related to dwelling unit outdoor outlets. Per NEC Article 100, an “Outlet” is not a plug or receptacle as one might traditionally think, but a point in the wiring system where the current is taken from supply equipment to branch off to outdoor equipment such as with an air conditioning or heat pump compressor unit.

As states began to adopt the new 2020 NEC, contractors began to install GFCI breakers per Section 210.8(F). As HVAC equipment manufacturers did not design their systems to account for GFCI requirement, problems began to occur immediately. Many homeowners began to report GFCIs tripping in air-conditioning and heating systems–sometimes multiple times each day. Equipment affected by the tripping includes single-, two- and variable-speed air-conditioners, heat pumps, and heat pump pool heaters.

This test protocol addresses evaluating HVAC systems with different GFCI’s installed upstream. This protocol will achieve this by connecting a GFCI and HVAC unit as a system and conducting a series of tests. Once the testing regimen is complete the GFCI will be replaced with another GFCI, and the test regimen will be repeated until all samples of GFCIs have been installed. At the time of the crafting of this protocol some GFCI manufacturers react to currents detected at the fundamental frequency, while others react to the sum the fundamental frequency as well as all harmonic frequencies. Some GFCI manufacturers design their GFCIs to react to currents along Dalziel’s curve (for frequency-vs.-current let go threshold) shown in Figure A-1. Dalziel’s test results in Table A-1 show the human body may be able to tolerate higher current levels as the frequency increases.

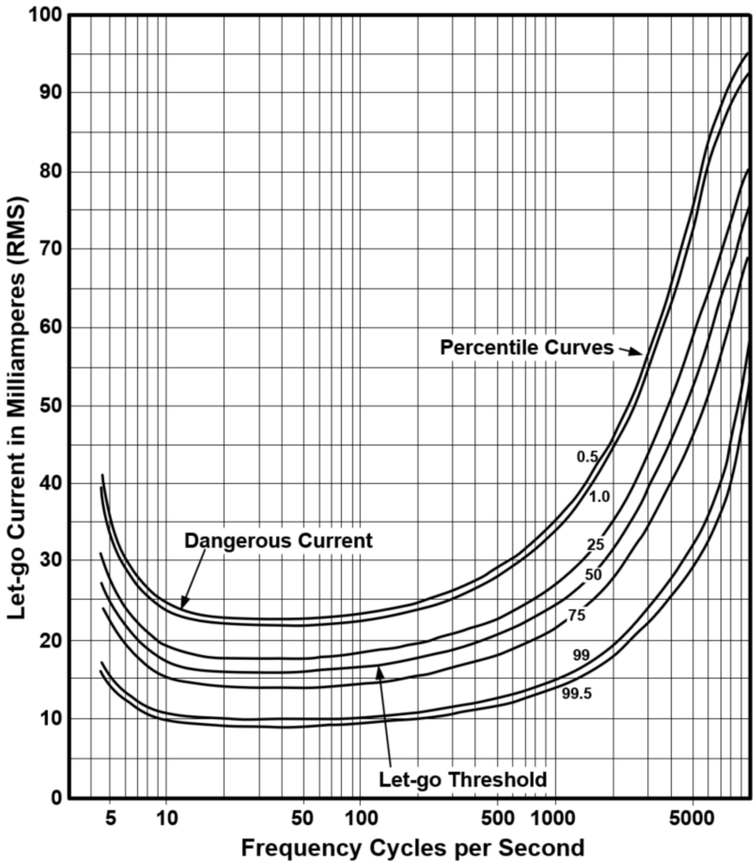


Figure A-1
Dalziel's Frequency vs AC Current Let go Threshold.

Table A-1
Dalziel's Test Table

Milliamperes (thousandths of an ampere)						
			Alternating Current			
			RMS Values			
	Direct Current		60 Cycle		10,000 Cycles	
Effect	Men	Women	Men	Women	Men	Women
No Sensation on hand	1	0.6	0.4	0.3	7	5
Slight Tingling, Perception threshold	5.2	3.5	1.1	0.7	12	8
Shock—not painful and muscular control not lost	9	6	1.8	1.2	17	11
Painful shock—painful but muscular control not lost	62	41	9	6	55	37
Painful shock—let-go threshold	76	51	16	10.5	75	50
Painful and severe shock—muscular contractions, breathing difficult	90	60	23	15	94	63
Possible ventricular fibrillation from short shocks						
Shock duration 0.03 sec.	1300	1300	1000	1000	1100	1100
Shock duration 3.0 sec.	500	500	100	100	500	500
Ventricular fibrillation—certain death	Multiply values immediately above by 2.75. To be lethal, short shocks must occur during susceptible phase of heart cycle					

Two GFCIs were chosen to evaluate their performance when installed upstream of a single-stage, HVAC system and again for a VFD-controlled, HVAC system. Figure A-2 shows both GFCIs.

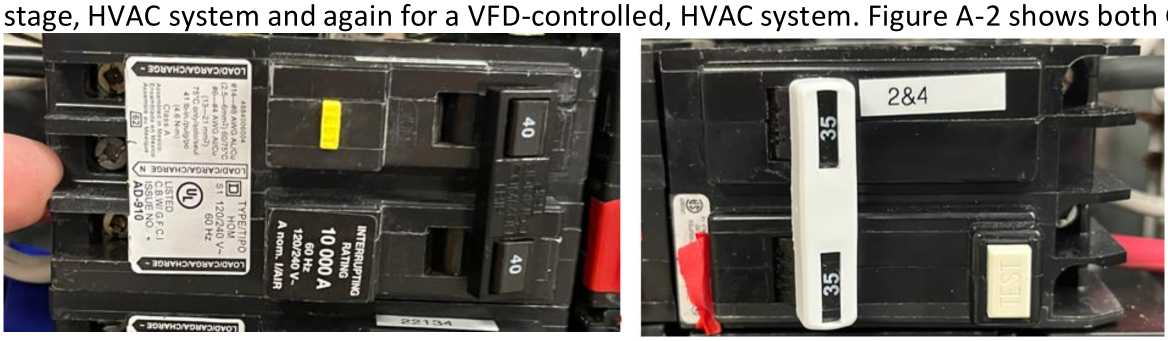


Figure A-2
GFCI Samples Used

One HVAC manufacturer informed the team of a breaker whose firmware has been updated, therefore; two of the breakers tested are the same model—ergo, the reason for only four breakers in the photo shown in Figure A-2.

Finally, the chosen GFCI and HVAC unit may be tested as a system. The purpose of this initial protocol is to test the two different topologies of AC systems shown in Table A-2. Prior to testing, the drawings of the HVAC test units will be inspected to understand the potential leakage current paths to ground. The results from this testing will assist in determining a final test protocol for the testing of future combinations of GFCI/HVAC units.

Table A-2
HVAC Test Units

Test Unit #	Size	Type
1	4 Ton	Single Stage
6	4 Ton	VFD

This test protocol is designed to test the GFCI and HVAC combination, referred to hereafter as equipment under test (EUT), under normal operating conditions as well as when power quality incidents occur on the grid. This test protocol includes ten tests that address testing that simulates operation of single-phase HVAC systems when the power system is operating normally as well as testing when abnormal power quality phenomena occur on the power system. There are five tests described generally in Table A-3 for operation when the power system is operating nominally. These tests will be conducted under four different temperature conditions as shown in Table A-8. The test protocol is also intended to aid in testing the EUT while experiencing five different power quality events from the grid shown in Table A-4.

Table A-4
Normal Operation Test Matrix

Test No.	Test	Procedure	Purpose
0	Power Applied: Extended Off Time	Power down HVAC system overnight, start in the morning to mimic extended off time. Use Test 1 Procedure.	Refrigerants and oils may settle in the compressor. This may contribute to additional leakage current – causing GFCI to trip during start-up sequence.
1	Po wer App lied	Apply power to the compressor at 0- degrees, 45-degrees, and 90-degrees point-on- wave.	VFD-controlled compressors have a DC bus. Current inrush is created when charging the filter capacitors. The magnitude of the inrush current may vary depending on the instantaneous voltage when the AC power is applied.
2	HVA C Run ning	Monitor the output voltages and current and any suspected leakage current paths while the HVAC is bringing the indoor chamber to the set temperature from a starting temperature to a setpoint.	The purpose of this test is to observe if the HVAC unit can bring the conditioned area from a high initial starting temperature (example 85 degrees F) to 67 degrees F (ASHRE 55-2017) and less than 65% humidity (ASHRE 62.1-2016) without tripping the GFCI.
3	Thermo stat Cycli ng	Monitor the output voltages and current and any suspected leakage current paths while the HVAC unit is cycled in a 5-minute ON/ 5- minute OFF test pattern for one hour[4].	Determine if the GFCI trips while the HVAC unit cycles. Chambers to be in condition to cause maximum speed and loading.
4	Defrost Cycling Test	Monitor the output voltages and current and any suspected leakage current paths while the HVAC operating in thermal condition 3 shown in Table 1-7.	The purpose of this test is to monitor the leakage current paths while the HVAC unit is operating in defrost cycling mode. Complete one defrost cycle for test as a minimum.
5	Ungrounded / High Resistanc e Ground ***(defer to Phase 2)***	With the unit configured as a system, remove the ground connection from the outdoor compressor unit, and then insert a low resistance in series with the compressor ground connection.	Observe the performance of the system if the ground path for the outdoor compressor unit is partially or completely redirected through the ground path of the indoor unit.

[4] In phase 1, do for one hour only. Potentially conduct test for longer period in Phase 2.

6	Loose Neutral ***(defer to Phase 2)***	Disconnect the electrical bond between the neutral and ground buss bars	Observe the behavior of the EUT when there is a loose neutral condition.

Table A-5
PQ Conditions Test Matrix

Test No.	Test	Procedure	Purpose
7	Voltage Sag ***<u>(defer to Phase 2)</u>***	Inject Type I voltage sags into the input of the GFCI/HVAC Test Setup while the HVAC System is in a Normal Operating Condition utilizing IEEE 1668 Box-in-Method as a guide.	Determine if the response of the HVAC system to voltage sags that may cause the GFCI to trip using IEEE 1668 as a guide.
8	Voltage Swell ***<u>(defer to Phase 2)</u>***	Using the voltage sag/swell generator inject Type I voltage swells from 100% to 120% in 5% increments utilizing a modified version of IEEE 1668 Box-in-Method as a guide.	Determine if the response of the HVAC system to voltage swell may cause the GFCI to trip.
9	Voltage Interruption	Inject voltage interruptions into the EUT. Observe and document the performance of the EUT. Perform the test with all tap jumpers of the voltage sag generator on the 0% tap and again with the voltage tap jumpers removed.	Determine if the response of the HVAC system may cause the GFCI to trip for high impedance voltage interruptions (open circuit) and low impedance voltage interruptions (tap transformer set to 0%).
10	Steady-State Voltage Distortion ***<u>(defer to Phase 2 or potentially eliminate)</u>***	Using a power amplifier inject voltage distortion levels in IEEE-519	Investigate the response of the EUT when voltage distortion within the bounds of IEEE-519 are observed.
11	High/Low Voltage Range Test (C84.1)	Using a power amplifier increase the nominal voltage to the maximum and minimum in three-volt increments until the EUT trips or the C84.1 Range B limits are reached. If the minimum/maximum voltage level is achieved allow the unit to operate for two 5-minute on/off cycles as described in the thermostat cycling test.	Investigate the response of the EUT when operating at the minimum and maximum “acceptable” voltage levels provided in the ANSI C84.1 standard.

Addendum: Common US Commercial or Multi-Family Dwellings 208/120V 120 Degree Testing

Per Figure 4-14, the common configuration in US Residential households is a Single-Phase 240/120V Split-Phase arrangement. In this arrangement, the L1 and L2 voltage vectors are 180 degrees a part. The tests in this protocol are to be executed using this arrangement first. There is exist a 208V three-phase source arrangement that can be found in Common US Commercial or Multi-Family Dwellings. In this case, the HVAC equipment would be connected phase to phase across two of the Phases (L1-L2), (L2-L3), or (L1-L3) with the voltage vectors 120 degrees apart from one another.

Table A-6
Addendum Test 208Vac Common US Commercial or Multi-family Dwellings Test Arrangement

Test No.	Test	Procedure	Purpose
12	TBD	Repeat chamber conditions and specific test that resulted in the LOWEST measured leakage current in the Common US Household 240/120V Split phase arrangement.	Baseline effect of source voltage arrangement and vector phase angles on the LOWEST measured leakage current test values.
13	TBD	Repeat chamber conditions and specific test that resulted in the HIGHEST measured leakage current in the Common US Household 240/120V Split phase arrangement.	Baseline effect of source voltage arrangement and vector phase angles on the HIGHEST measured leakage current test values.

GFCI/HVAC Test Setup

The test setup for all twelve tests listed in Table A-3 and Table A-4 is shown in Figure A-3 below. Each type of HVAC system may be powered differently. The configuration of a typical single or two stage heat pump is shown in Figure A-3. Power for the indoor unit of variable refrigerant flow systems may be powered from the outdoor unit thus not requiring a second breaker from the circuit panel.

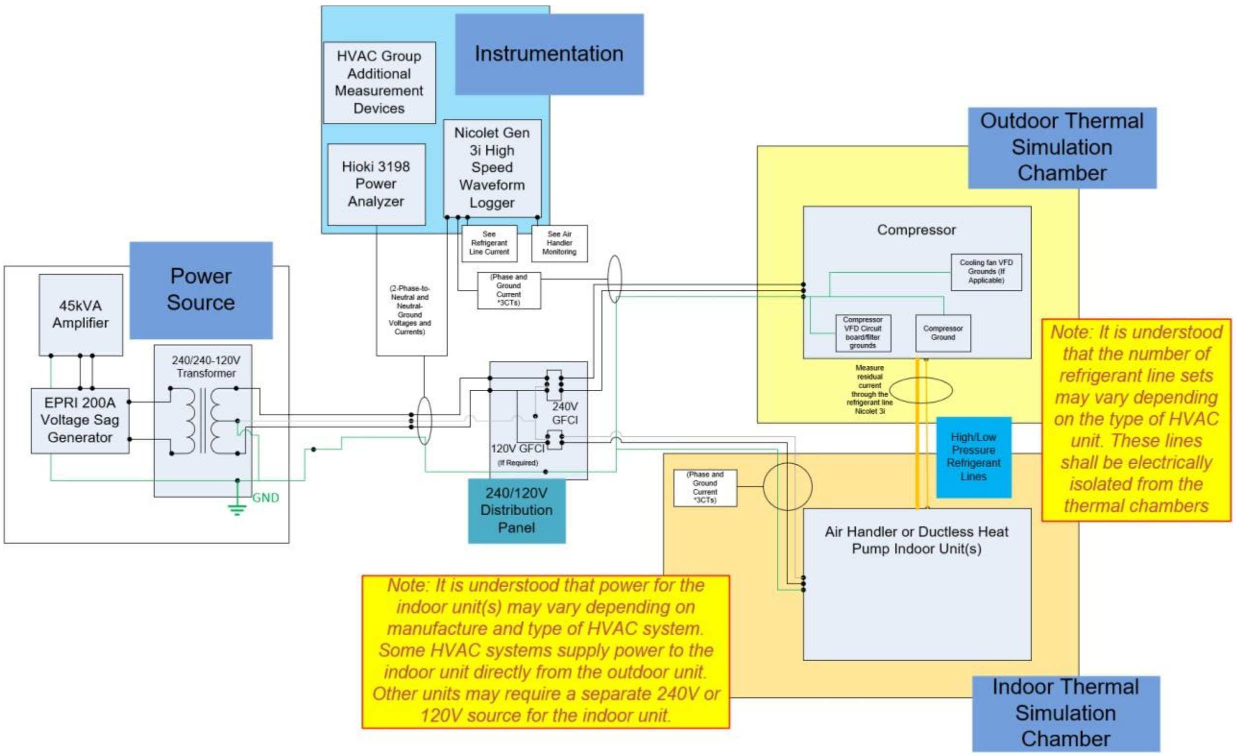


Figure A-3
Test Setup

The test setup procedure is shown below.

Test Setup Procedures

1) Initial Test Setup Procedure

   a. Lockout and tag all voltage sources.

   b. Connect the MX -45 power amplifier for single-phase mode to utilize the full capacity of the amplifier.

   c. Install and connect the primary of the split-phase transformer to the output of the power amplifier.

      i. Make certain the neutral connection of the secondary of the transformer is properly bonded to the ground.

   d. Connect the input of the 200-amp voltage sag generator to the output of the transformer and the output of the array of 240V/120V distribution panels that contain the GFCIs for the testing.

e. Connect the first 240-volt GFCI to the compressor unit. Also connect the 120-volt GFCI to the air handler if required.

f. Verify the ground paths and make sure the test unit's refrigerant lines and wiring is isolated from the ground connections of the test chamber.

g. Connect the Hioki 3198 power meter to the output of the voltage sag generator.

   i. Configure the power meter to monitor a split-phase residential power system as shown in Section 3 "Power Measurement instrumentation" of this report.

h. Connect the Nicolet Gen 3i to the output voltages and currents as shown in Figure A-3.

i. Connect the current probe around the refrigerant lines and connect to the Nicolet.

j. Set up the Nicolet as shown in Table A-6.

Table A-7
Nicolet Configuration

Connector, TB, Board	Description	Symbol	Nicolet Channel
	I_1, Line 1 current	**$L1_{input}$**	1
	I_2, Line 2 current	**$L2_{input}$**	2
	LC_1, Leakage Current 1	**LC_1**	3
	LC_2, Leakage Current 2	**LC_2**	4
	LC_3, Leakage Current 3	**LC_3**	5
	LC_4, Leakage Current 4	**LC_4**	6
	$Line_1$-Neutral Input Voltage	**L_1-n Volts**	7
	$Line_2$-Neutral Input Voltage	**L_2-n Volts**	8
	$Line_1$-$Line_2$ Input Voltage	**L_1-L_2 Volts**	9
	VFD DC Bus	**VFD DC Bus**	10
	$Line_1$-$Line_2$ GFCI Output Voltage	**L_1-L_2 GFCI**	11
	$Line_1$-Neutral Input Voltage (Indoor)	**Indoor L_1-n Volts**	12

Channels are differentially isolated, and measure signals up to 1000 volts with the proper isolation modules. Additional monitoring points may be added at the time of testing.

a. Set up the data acquisition of the voltage sag generator as shown in Table A-7.

Additional information about the sag generator may be seen in the beginning of the PQ Conditions section of the test protocol.

Table A-8
Voltage Sag DAQ Configuration

Connector, TB, Board	Number	Description	Symbol	Porto-Sag Channel
		Ia, phase L1 current	Ia_{input}	1
		Ib, phase L2 current	Ib_{input}	2
				3
				4
				5
				6
				7
				8
		L1-Neutral Input Voltage	L_1-n Volts	9
		L2-Neutral Input Voltage	L_2-n Volts	10
		L1-L2 Input Voltage	L_1-L_2 Volts	11
				12
				13
				14
		L1-L2 GFCI Output Voltage		15
		Drive DC Bus (If Applicable)		16

Normal Operation Test Protocol

The test procedures for this section describe the tests shown in test Table A-3. The Normal Operation Testing Protocol is written with the intention that testing is conducted sequentially by the designated test number in the table. The setup for all the tests may be conducted using the same physical setup shown in Figure A-3. Each of the "Normal Operation" tests shall be conducted with the Indoor and Outdoor Simulation Chambers configured in the three different test conditions shown in Table A-8.

Table A-9
Chamber Test Conditions

Test Condition Designation	Outdoor Air Temp (db)	Indoor Air Temp (db)	Test Condition Simulates
1	**75 °F**	**75 °F**	**Nominal Base Line (75 degrees)**
2	**95 °F (Nominal + 20 °F)**	**75 °F**	**Full Nominal Cooling Conditions**
3	**47 °F (Nominal - 28 °F)**	**75 °F**	**Full Nominal Heating Conditions**

Test 1 Power Applied Test

The purpose of the Power Applied test is to determine if the GFCI trips depending on the point-on-wave where the 60-Hertz sine wave power is applied to the EUT.

The procedure for the test is as follows:

1) Connect the Compressor Unit to the GFCI Test Specimen.
    a. Lockout and tag all voltage sources.
    b. Connect the 240V power terminals of the compressor (outdoor) unit to the output of the GFCI.
        i. If this is the beginning of all tests, then install GFCI sample 1.
        ii. If testing of the first GFCI is complete connect the compressor unit to GFCI sample N+1.
    c. If the indoor unit requires external power connect it to another GFCI of the same series.
        i. The GFCI will be different depending on the 120 volts or 240 volts is required for the indoor unit. The indoor units of some HVAC systems are

powered from the outdoor units and do not require an additional power source.

2) Test Setup Verification Procedure.

    a. Make certain the monitoring connects for the data acquisition systems are connected as per Figure A-3 and initial test setup procedure.

    b. Make certain the voltage sag generator is configured and ready to create three-phase voltage interruptions.

    c. Remove lockout tag out.

    d. Configure the power amplifier to operate at 240 volts, 60 Hz, and turn on enable the output.

    e. Verify the HVAC system powers as it should.

    f. Set the thermostat of the HVAC system to allow it to run.

    g. Synchronize the time of the computer, power monitor(s), and any other data collection with NIST official timer server.

        i. https://timegov.boulder.nist.gov/

        ii. Set for Eastern Standard Time (UTC-5).

    h. Verify the Hioki 3198 is measuring voltage, current, and power correctly.

    i. Press “play” on the Nicolet Gen 3i and collect measurements for about 5 seconds and press stop.

    j. Verify the waveforms are scaled, phased, and the general waveshapes appear correct.

    k. Turn off the HVAC system in an orderly fashion.

    l. Turn off the output of the power amplifier.

3) Testing Procedure

    a. Set the indoor and outdoor chamber to test condition designation 1, or designation N+1 if all tests in Table A-3 have been conducted in test condition 1 of Table A-8.

    b. If all tests in Table 1-3 have been conducted in all chamber test conditions shown in Table A-8 then go to the PQ Condition Test Protocol Section of the document.

c. Wait for the chambers to reach the designated temperature in Table A-8.

d. Configure the voltage sag generator to create a 3-second voltage interruption.

    i. Set the Point-on-wave (POW) slide bar to 0 degrees.

    ii. Reference the voltage sag to Channel 0 of the data acquisition system "240 Vac Output".

    iii. Set the voltage sag duration to 180 cycles.

    iv. Connect the tap jumpers of all 3 transformers to 0%.

    v. Configure a sag activity log labeled "Test 1_GFCI Specimen<#>_HVAC Unit".

e. Press the record button on the Hioki 3198.

f. Press the play button on the Nicolet.

g. Press trigger on the voltage sag generator.

h. Enable the output of the amplifier and press the "Start" pushbutton on the front of the voltage sag generator within 2 seconds of triggering the sag generator.

i. Observe and record the response of the EUT.

    i. GFCI Tripped?

    ii. HVAC Powered?

j. Press the stop button on the Nicolet.

k. Record the time, Nicolet File name, and Voltage sag test number.

l. Turn off the amplifier output.

m. Wait 5 minutes for any stored energy sources in the HVAC units to discharge.

n. If the 0-degree POW test has been conducted go to step o.

o. If the 0-degree POW and the 45-degree POW test is complete skip to step q.

p. Set the point-on-wave slide bar to 90 degrees and return to step e.

q. If the 0-, 45-, and 90-degree POW test has been conducted go to step s.

r. Set the point-on-wave slide bar to 90 degrees and return to step e.

s. Stop the log file in the sag generator.

t. End of test 1.

Test 2 HVAC Running Test

The purpose of the HVAC Running Test is to observe the unit is able to bring the conditioned area from an initial temperature of 85 degrees F to a set temperature 67 degrees F (ASHRE 55-2017) and less than 65% humidity (ASHRE 62.1-2016) without tripping the GFCI.

The procedure for the test is as follows:

1) Conduct the test contiguously with the previous test using the same GFCI Test Specimen.
2) The test setup should remain the same as the previous test.
3) Test Procedure.
    a. Set the indoor and outdoor chamber to the test condition from the previous test.
    b. Wait for the chambers to reach the designated temperature in Table A-8
    c. Turn on the control power for the voltage sag generator.
    d. Turn the mode switch on the front of the voltage sag to "Inhibit."
    e. Press the green start button on the front of the voltage sag generator until the "Load On" lamp illuminates.
    f. Verify the power amplifier is set to operate at 240 volts, 60Hz.
    g. Press start on the Hioki if not still running from the previous test.
    h. Press the play button on the Nicolet.
    i. Turn on the output of the power amplifier.
    j. Set the temperature on the thermostat to 67 degrees F.
    k. Observe and document the condition of the EUT while the HVAC is running.
        i. GFCI tripped?
        ii. HVAC powered?
    l. Press the stop button on the Nicolet once the indoor thermal chamber has reached the set temperature or the GFCI trips.
    m. Record the time, Nicolet file name, and the Test number.
    n. End of test

Test 3 Thermostat Cycling Test

The purpose of the Thermostat Cycling Test is to determine if the GFCI trips at any time while the HVAC is cycling on and off every 5 minutes for an hour.

The procedure for the test is as follows:

1) Conduct the test contiguously with previous test using the same GFCI Test Specimen.

2) The test setup should remain the same as the previous test with the following exception.

    a. Remove and replace the thermostat with a cycling circuit similar to the one shown in Figure A-4- to allow the HVAC unit to cycle on a timed signal and nota temperature setpoint.

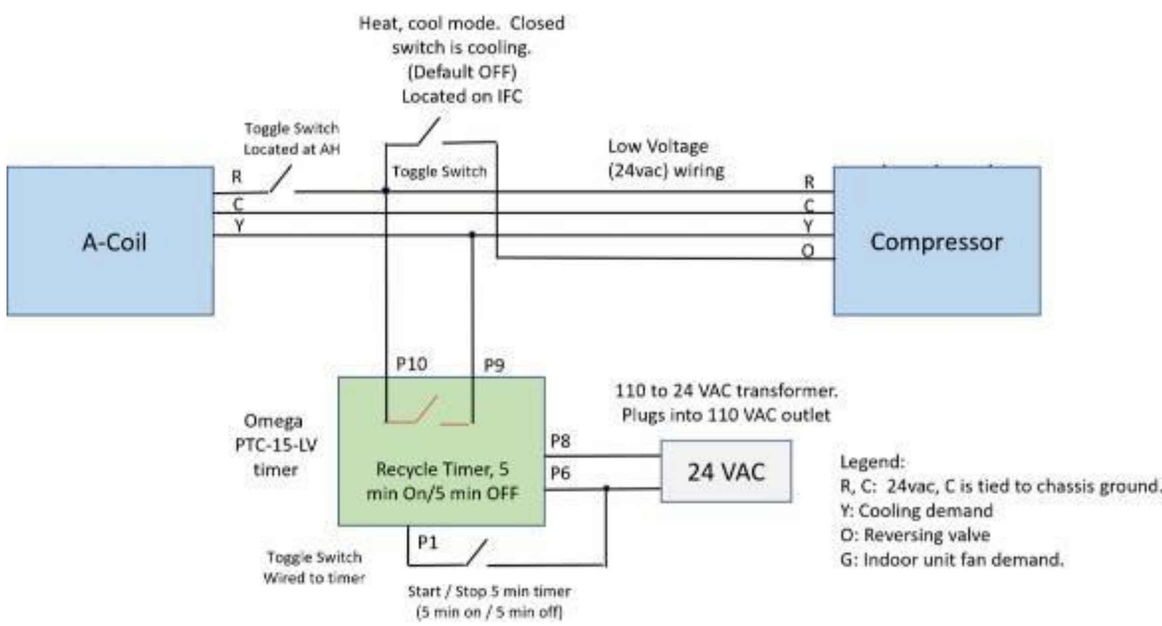


Figure A-4
Timed Cycling Circuit

1) Testing Procedure

    a. Set the indoor and outdoor chamber to the test condition from the previous test.

    b. Wait for the chambers to reach the designated temperature in Table A-8

    c. Turn on the control power for the voltage sag generator.

    d. Turn the mode switch on the front of the sag generator to "Inhibit."

e. Press the green start button on the front of the voltage sage generator until the
"Load On" lamp
illuminates.

f. Verify the power amplifier is set to operate at 240volts, 60Hz.

g. Press "start" on the Hioki if not still running from previous test.

h. Press the play button on the Nicolet.

i. Turn on the output of the power amplifier.

j. Set the timing circuit to turn off and on in a 5-minute time interval in the appropriate cooling/heating mode.

k. Observe and document the condition of the EUT while the HVAC is running.

   i. GFCI tripped?

   ii. HVAC powered?

l. Press the stop button on the Nicolet once the unit has been permitted to operate for one hour or the GFCI trips.

m. Record the time, Nicolet file name, and Test number.

n. End of test

Test 4 Defrost Cycle Test

The purpose of the Defrost Cycle Test is to measure the potential for leakage current when the unit is operating in the defrost mode. The operation of the HVAC system in defrost mode does not appear to be much different than cooling mode, with the exception of the fan motor is not operating during defrost mode and the outdoor temperature is much lower than when in normal cooling mode.

This test will be conducted only in chamber test condition 3

in Table A-8. The procedure for the test is as follows:

1) Conduct the test contiguously with previous test using the same GFCI Test Specimen.

2) The test setup should remain the same as the previous test.

3) Testing procedure

a. Set the indoor and outdoor chamber to the test condition from the previous test.

b. Wait for the chambers to reach the designated temperature in Table A-8.

c. Turn on the control power for the voltage sag generator.

d. Turn the mode switch on the front of the sag generator to “Inhibit.”

e. Press the green start push button on the front of the voltage sag generator until the “Load On” lamp illuminates.

f. Verify the power amplifier is set to operation at 240 volts, 60 Hz.

g. Press “start” on the Hioki if not still running from the previous test.

h. Press the play button on the Nicolet.

i. Turn on the output of the power amplifier.

j. Start the HVAC system either manually or via a thermostat.

k. Allow the unit to operate for five minutes.

l. Observe and document the condition of the EUT while the HVAC is running.

    i. GFCI tripped?

    ii. HVAC powered?

m. Press the stop button on the Nicolet after five minutes or the GFCI trips.

n. Record the time, Nicolet file name, and Test number.

o. Open the knife switch and lockout.

p. If both open ground and high-resistance ground test are complete go to step t.

q. Insert a one-ohm resister between the ground connection of the compressor unit and ground.

r. Remove lockout and close the knife switch.

s. Return to step b.

t. Open the knife switch and lockout.

u. Remove the resistor and restore connection.

v. End of test 5

Test 6 Loose Neutral Test

The purpose of the Loose Neutral Test is to observe the behavior of the EUT when there is a loose neutral between the transformer and the circuit panel.

The procedure for the test is as follows:

1) Conduct the test contiguously with the previous test using the same GFCI Test Specimen.

2) The test setup should be shown in Figure A-3.

    a. In addition, disconnect the neutral connection from the transformer. This can be accomplished by simply removing the neutral connection from the voltage sag generator as shown in Figure A-5.

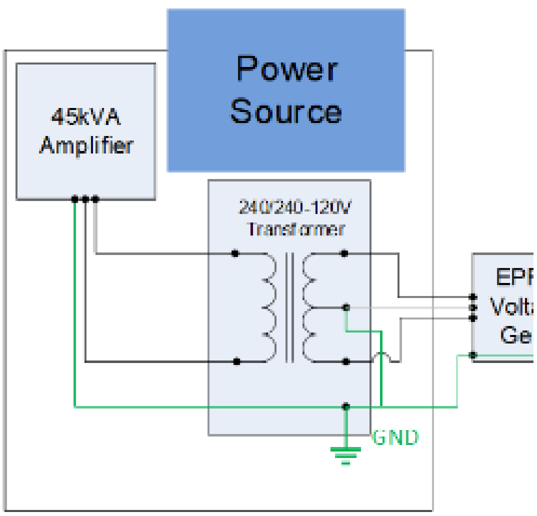


Figure A-5
Disconnect Neutral Conductor from Circuit

1) Testing procedure

    a. Set the indoor and outdoor chamber to the test condition from the previous test.

    b. Wait for the chambers to reach the designated temperature in Table A-8.

    c. Turn on the control power for the voltage sag generator.

d. Turn on the mode switch on the front of the voltage sag generator to "Inhibit."

e. Press the green start push button on the front of the voltage sag generator until the "Load On" lamp illuminates.

f. Verify the power amplifier is set to operate at 240 volts, 60 Hz.

g. Press start on the Hioki if not still running from previous test.

h. Press the play button on the Nicolet.

i. Turn on the output of the power amplifier.

j. Start the HVAC system either manually or via a thermostat.

k. Allow the unit to operate for five minutes.

l. Observe and document the condition of the EUT while the HVAC is running.
    i. GFCI tripped?
    ii. HVAC powered?

m. Press the stop button the Nicolet after five minutes or the GFCI trips.

n. Record the time, Nicolet file name, and Test number.

o. Open the knife switch and lockout.

p. Turn off amplifier.

q. Restore the neutral connection to the set up.

r. Remove lockout and close the knife switch.

s. End of test

t. Return to the Test 1 testing procedure step a.

PQ Conditions Test Protocol

The testing procedures for this section discuss the tests shown in Table A-4 and again in Table A-10 below. The PQ Test Condition Test section of this protocol is written with the intention that the testing is to be conducted sequentially by the designated test number in both Table A-

3 and Table A-4. The PQ Conditions testing is also designed to be conducted after the tests in the Normal Operation Test section have been exhausted. Each of the “PQ Condition” tests shall be conducted with the Indoor and Outdoor Simulation Chambers operated in test condition number 2 shown in Table A-8.

Table A-10
PQ Tests (Same as Table A-4—Repeated for Convenience)

Test No.	Test	Procedure	Purpose
7	Voltage Sag ***(defer to Phase 2)***	Inject Type I voltage sags into the input of the GFCI/HVAC Test Setup while the HVAC System is in a Normal Operating Condition utilizing IEEE 1668 Box-in-Method as a guide.	Determine if the response of the HVAC system to voltage sags that may cause the GFCI to trip using IEEE 1668 as a guide.
8	Voltage Swell ***(defer to Phase 2)***	Using the voltage sag/swell generator inject Type I voltage swells from 100% to 120% in 5% increments utilizing a modified version of IEEE 1668 Box-in-Method as a guide.	Determine if the response of the HVAC system to voltage swell may cause the GFCI to trip.
9	Voltage Interruption	Inject voltage interruptions into the EUT. Observe and document the performance of the EUT. Perform the test with all tap jumpers of the voltage sag generator on the 0% tap and again with the voltage tap jumpers removed.	Determine if the response of the HVAC system may cause the GFCI to trip for high impedance voltage interruptions (open circuit) and low impedance voltage interruptions (tap transformer set to 0%).
10	Steady-State Voltage Distortion (Eliminate)	Using a power amplifier inject voltage distortion levels in IEEE-519	Investigate the response of the EUT when voltage distortion within the bounds of IEEE-519 are observed.
11	High/Low Voltage Range Test (C84.1)	Using a power amplifier increases the nominal voltage to the maximum and minimum in three-volt increments until the EUT trips or the C84.1 Range B limits are reached. If the minimum/maximum voltage level is achieved allow the unit to operate for two 5-minute on/off cycles as described in the thermostat cycling test.	Investigate the response of the EUT when operating at the minimum and maximum "acceptable" voltage levels provided in the ANSI C84.1 standard.

Tests 7 through 9 in the PQ Test Matrix will require the use of a voltage sag generator, while tests 10 and 11 will require the use of a power amplifier. The voltage sag test instrument and the test setup, above and beyond what is shown in the test setup photo in Figure A-3, must be discussed prior to the test procedures for Tests 7 through 9.

Tests Requiring a Voltage Sag Generator

A 200-amp portable voltage sag generator (Porto-Sag) will be used for the testing. The electrical requirements for the unit are shown in Table A-10.

Table A-11
Electrical Requirements for Sag Gen

Component	Electrical Requirement
Portable Computer	120 Vac outlet < 1 amp/battery power
Solid State Switch/Contactor Box w/ Data Acquisition & Digital I/O Control Hardware	120 Vac outlet < 3 amps
Variac Voltage Source	Switched into the circuit during the voltage sag, the device will accept voltages up to 480Vac, 3 phase referenced to ground or neutral.

Single-phase power is connected through the Porto-Sag and passed to the electrical load as shown in Figure A-6.

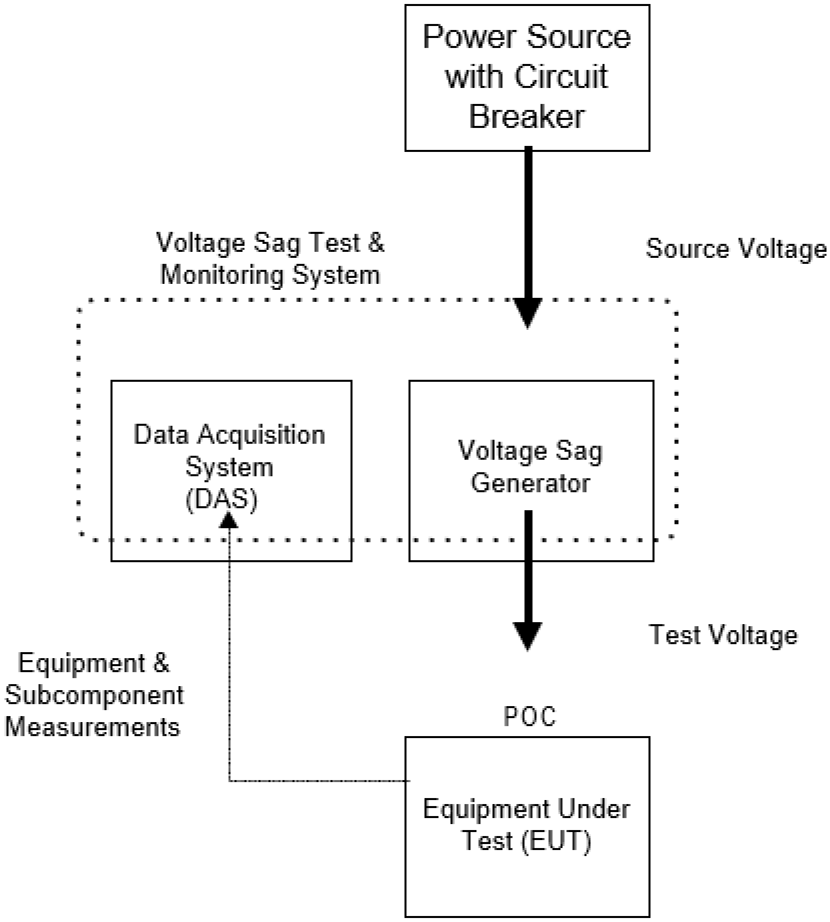


Figure A-6
Electrical Hook-up Diagram

Type I voltage sags and swells will be injected at varying depths and durations by switching in the autotransformers for a set time period. In order to monitor the status of the tool during the injected voltage sag, some of the data acquisition channels will be connected to various components of the EUT.

Safety Requirements

EPRI will follow these safety standards. Usual safety procedures are as follows:

- Lock, tag, and try procedures will be followed when the testing is conducted. No circuit shall be connected or wired when electricity is present unless rubber insulated gloves are worn. The immediately area surrounding the tool will be corded off and signs reading “Test in Progress” will be attached to the cord.
- Safety glasses or side-shields for those with prescription glasses will

be worn at all times.

- To reduce the chance of accidents, only essential personnel will be allowed within the corded test area.
- Work will be done in an orderly fashion as described in the test protocol. Circuits will be visually inspected before power is restored.

Testing Method

Testing will be conducted according to the "Box-In" methodology described in IEEE 1668™ Recommended Practice for Voltage Sag and Short Interruption Ride-through Testing for End Use Electrical Equipment Rated Less than 1,000 Volts. A detailed description of this test method may be found in Appendix C of this report.

General Strategy

The general test strategy is to characterize the EUT while the HVAC system operates in the temperature chambers that are set to configuration number 2 in Table A-8 in this report. The test mode and parameters will be thoroughly documented for completeness. During the tests, the HVAC systems will be operated as closely to the maximum current rating as possible to make sure that events are created when the system is in its most sensitive process state. The voltage sag generator has sixteen channels of data acquisition. The channels will be set up as per Table A-11. The waveforms for each test will be saved to record the performance of the tool.

Measurements

The measurement test points shown in Table A-11 below will be used during the test and in post processing.

Table A-12
Porto-Sag Measurement Points

Connector, TB, Board	Number	Description	Symbol	Porto-Sag Channel
		Ia, phase L1 current	$\mathbf{Ia}_{\mathbf{input}}$	1
		Ib, phase L2 current	$\mathbf{Ib}_{\mathbf{input}}$	2
				3
				4
				5

				6
				7
				8
		L1-Neutral Input Voltage	L1-n Volts	9
		L2-Neutral Input Voltage	L2-n Volts	10
		L1-L2 Input Voltage	L1-L2 Volts	11
				12
				13
				14
		L1-L2 GFCI Output Voltage		15
		Drive DC Bus (If Applicable)		16

Channels 1-8 are not isolated and measure from +/- 10 V. Channels 9-16 are differentially isolated, and measure signals up to 700 volts. Additional monitoring points may be added at the time of testing.

Test 7 Voltage Sag Test Procedure

The purpose of this test is to investigate the effects voltage sags may have on the EUT when voltage sags are conducted between the secondary of a split-phase transformer and the GFCI while the EUT is operating.
This procedure provides an example checklist of steps to be done prior to starting the actual voltage testing.

a) De-energize the EUT lockout/tagout at the point-of-connection (POC).
b) Connect the EUT into the test setup as shown in Figure A-3.
c) Synchronize time of the computer, power monitor(s), and any other data collection with NIST official time server
    a. https://timegov.boulder.nist.gov/
    b. Set for Eastern Standard Time (UTC-5)
d) Connect DAS monitoring channels per the test plan using Table A-12 as a general reference.
e) Visually inspect all connections prior to energizing the test setup.
f) Energize the power source and verify source voltage using a digital voltmeter.
g) Energize the voltage-sag generator, measure and record the phase voltages, and confirm the output of the sag generator.

a) Power up the EUT
b) Perform any final configuration and setup of the DAS channels and confirm their readings.
c) Ensure that the EUT is in a desired process state for voltage-sag testing. Tests should be conducted while the HVAC system operates under setpoint condition 2 defined in Table A-8. Tests may have to be repeated in various states to fully characterize the equipment.
d) Wait for the thermal chambers to reach temperature setpoint 2 in Table A-8.

e) Conduct Voltage Sag testing:
   a. Use “Box-in” test method described in IEEE 1668 and Appendix C of this report.
   b. Set the Point-on-wave (POW) slide bar to 0 degrees.
   c. Reference the voltage sag to Channel 9 of the data acquisition system “240Vac Output”
   d. Configure a sag activity log labeled “Test 6_GFCI Specimen <#>_HVAC Unit”.
   e. Maximum 60-cycle duration
f) De-energize the EUT lockout/tagout at the point-of-connection (POC)
g) End of Test 7

Test 8 Voltage Swell Test Procedure

This test is designed to help the investigator determine the effects voltage swells may have on the EUT when voltage swells are conducted between the secondary of a split-phase transformer and the GFCI while the EUT is operating.
This procedure provides an example checklist of steps ` done prior to starting the actual voltage testing. The test procedure is as follows:

a) De-energize the EUT lockout/tagout at the point-of-connection (POC).
b) Connect the EUT into the test setup as shown in Figure A-6.
c) Synchronize time of the computer, power monitor(s), and any other data collection with NIST official time server.
   a. https://timegov.boulder.nist.gov/
   b. Set for Eastern Standard Time (UTC-5)
d) Connect DAS monitoring channels per the test plan using Table A-11 as a general reference.
e) Visually inspect all connections prior to energizing the test setup.
f) Energize the power source and verify source voltage using a digital voltmeter.
g) Energize the voltage-swell generator, measure and record the phase voltages, and confirm the output of the swell generator.
h) Power up the EUT.
i) Perform any final configuration and setup of the DAS channels and confirm their readings.
j) Adjust and begin recording with the digital camcorder.
k) Ensure that the EUT is in a desired process state for voltage-sag testing. Tests should be conducted while the HVAC system operates under setpoint condition 2 defined in Table A-8. Tests may have to be repeated in various states to fully characterize the equipment.
l) Wait for the thermal chambers to reach temperature setpoint 2 in Table A-8.

m) Conduct Voltage Swell testing:

a. Use a modified version of “Box-in” test method described in IEEE 1668 and Appendix C of this report.
    i. Start at 105% and increase the voltage magnitude in 5% increments up to 125% nominal voltage.
b. Set the Point-on-wave (POW) slide bar to 0 degrees.
c. Reference the voltage sag to Channel 9 of the data acquisition system “240Vac Output”
d. Configure a sag activity log labeled “Test 7_GFCI Specimen <#>_HVAC Unit”.

n) De-energize the EUT lockout/tagout at the point-of-connection (POC).

Test 9 Voltage Interruption Test Procedures

The purpose of this test is to investigate the response voltage interruptions may induce on the GFCI when voltage sags are conducted between the secondary of a split-phase transformer and the GFCI while the EUT is operating.
This procedure provides an example checklist of steps to be done prior to starting the actual voltage testing.

a) De-energize the EUT lockout/tagout at the point-of-connection (POC)
b) Connect the EUT into the test setup as shown in Figure A-3.
c) Synchronize time of the computer, power monitor(s), and any other data collection with NIST official time server
    a. https://timegov.boulder.nist.gov/
    b. Set for Eastern Standard Time (UTC-5)
d) Connect DAS monitoring channels per the test plan using Table A-11 as a general reference.
e) Visually inspect all connections prior to energizing the test setup.
f) Energize the power source and verify source voltage using a digital voltmeter.
g) Energize the voltage-sag generator, measure and record the phase voltages, and confirm the output of the sag generator.
h) Power up the EUT.
i) Perform any final configuration and setup of the DAS channels and confirm their readings.
j) Tests should be conducted while the HVAC system operates
k) under setpoint condition 2 defined in Table A-8. Tests may have to be repeated in various states to fully characterize the equipment.
l) Wait for the thermal chambers to reach temperature setpoint 2 in Table A-8.

m) Conduct Voltage Interruption testing:
    a. Maximum 60-cycle duration
    b. Set the Point-on-wave (POW) slide bar to 0 degrees.

c. Reference the voltage sag to Channel 9 of the data acquisition system “240 Vac Output”
d. Configure a sag activity log labeled “Test 8_GFCI Specimen <#>_HVAC Unit”.
e. Conduct test with sag generator auto transformers set:
   i. 0% Tap (low-impedance interruptions)
   ii. Tap jumpers removed (high impedance interruptions)

n) De-Energize the EUT lockout/tagout at the point-of-connection (POC)

Tests 10 and 11 will require the use of a power amplifier. During this testing, the voltage sag generator will be turned on and operating in “Inhibit Mode.”

Tests Requiring a Power Amplifier

This section describes the setup and the test procedures for tests 10 and 11 shown in Table A-9.

Power Amplifier Test Setup

A 45 kVA California Instruments power amplifier will be used for the testing. The electrical requirements for the unit are shown in Table A-12.

Table A-13
Electrical Requirements for Power Amplifier

Component	Electrical Requirement
Portable Computer	120 Vac outlet <1amp/battery power
Amplifier Power Source	480 Vac outlet 100amps
High Speed Data Recorder	120 Vac outlet <3amps

Three-phase power is connected to the input of the amplifier. The output of the amplifier is connected to the input of the EUT. A Nicolet Vision high-speed data recorder will be used to capture the voltage and current waveforms as shown in Figure A-6.

Steady-state voltage distortion and High/Low voltage schemes will be created and uploaded to the amplifier and injected into the EUT. A high-speed data recorder will be utilized to monitor the status of the EUT during the tests.

Safety Requirements

EPRI will follow these safety standards. Usual safety procedures are as follows:

- Lock, tag, and try procedures will be followed when the testing is conducted. No circuit shall be connected or wired when electricity is present unless rubber insulated gloves are worn.

- The immediately area surrounding the tool will be corded off and signs reading "Test in Progress" will be attached to the cord.
- Safety glasses or side-shields for those with prescription glasses will be worn at all times.
- To reduce the chance of accidents, only essential personnel will be allowed within the corded test area.
- Work will be done in an orderly fashion as described in the test protocol. Circuits will be visually inspected before power is restored.

General Strategy

The general test strategy is to characterize the EUT while under load. The test mode and parameters will be thoroughly documented for completeness. During the tests, the HVAC system will be operated under test conditions shown in test condition 2 in Table A-8. The high-speed data recorder has sixteen channels of data acquisition. The channels will be set up as per Table A-11. The waveforms for each test will be saved to indicate the performance of the tool.

Test 9 Steady-state Voltage Distortion Test

This test is designed to investigate the response of the EUT when voltage distortion within the bounds of IEEE-519 is observed. IEEE-519 only addresses harmonic distortion at the point of common coupling (PCC) and not at the equipment level. According to IEEE 519, the total harmonic distortion must not exceed 8% and no individual harmonic frequency may exceed 5% for systems 1 kilovolts and less as shown in Table A-13. Unfiltered single-phase ASDs are going to emit predominantly 3rd and 5th harmonic currents. The impact these harmonic currents have on the voltage will depend on the "stiffness" of the voltage source. A voltage source with a high ratio of prospective short circuit current/rated current would be considered a "stiff" voltage source. The stiffer the voltage source the less likely the current harmonics will affect the voltage signature.

Table A-14
IEEE 519 Voltage Distortion Limit

Bus Voltage at the PCC	Individual Harmonic (%)	Total Harmonic Distortion (%)
V≤ 1.00 kV	5	8

This procedure provides an example checklist of steps to be done prior to starting the actual voltage testing.

a) De-energize the EUT lockout/tagout at the point-of-connection (POC).
b) Connect the EUT into the test setup as shown in Figure A-6.
c) Synchronize time of the computer, power monitor(s), and any other data collection with NIST official time server
    a. https://timegov.boulder.nist.gov/
    b. Set for Eastern Standard Time (UTC-5)
d) Connect Nicolet monitoring channels per the test plan using Table A-11 as a general reference.
e) Visually inspect all connections prior to energizing the test setup.
f) Energize the power source and verify source voltage using a digital voltmeter.
g) Energize the power source to the power amplifier.
h) Configure the power amplifier to supply 100% of the HVAC's rated voltage.
i) Turn on the output of the power amplifier.
j) Power up the EUT.
k) Tests should be conducted while the HVAC system operates under setpoint condition 2 defined in Table A-8.
l) Wait for the thermal chambers to reach temperature setpoint 2 in Table A-8.
m) Perform any final configuration and setup of the DAS channels and confirm their readings.
n) Start the high-speed data recorder.
o) Conduct the Steady-State Voltage Distortion testing:
    a. Upload sequence to the power amplifier.
    b. Start the high-speed data recorder.
    c. Inject the waveform into the EUT.
p) De-energize the EUT lockout/tagout at the point-of-connection (POC).

Test 11 High/Low Range Voltage Test

The purpose of this test is to investigate the response of the EUT when operating at the minimum and maximum "acceptable" voltage levels described in the ANSI C84.1 standard. ANSI C84.1 specifies the EUT must operate between 106% and 87% of the nominal voltage.
This procedure provides an example checklist of steps to be done prior to starting the actual voltage testing.

a) De-energize the EUT lockout/tagout at the point-of-connection (POC).
b) Connect the EUT into the test setup as shown in Figure A-3.
c) Synchronize time of the computer, power monitor(s), and any other data collection with NIST official time server
    a. https://timegov.boulder.nist.gov/
    b. Set for Eastern Standard Time (UTC-5)
d) Connect Nicolet monitoring channels per the test plan using Table A-11 as a general reference.
e) Visually inspect all connections prior to energizing the test setup.

f) Energize the power source to the power amplifier.
g) Configure the power amplifier to supply 100% of the HVAC's rated voltage.
h) Turn on the output of the power amplifier.
i) Power up the EUT.
j) Tests should be conducted while the HVAC system operates under setpoint condition 2 defined in Table A-8.
k) Wait 10 minutes for the chamber temperatures to normalize.
l) Perform any final configuration and setup of the DAS channels and confirm their readings.
m) Start the high-speed data recorder.
n) Increase the amplifier output to 106% of the nominal voltage.
o) Allow the equipment to operate for 5 minutes.
p) Reduce the amplifier voltage to the nominal voltage.
q) Allow the equipment to operate for 5 minutes.
r) Reduce the amplifier voltage to 95% of the nominal voltage.
s) Allow the equipment to operate for 5 minutes.
t) Reduce the amplifier voltage to 90% of the nominal voltage.
u) Allow the equipment to operate for 5 minutes.
v) Reduce the amplifier voltage to 86% of the nominal voltage.
w) Allow the equipment to operate for 5 minutes.
x) Stop the high-speed data recorder and record the file number.
y) De-energize the EUT lockout/tagout at the point-of-connection (POC)
z) If all GFCI samples have been tested, this is the end of

If all GFCI samples have not been tested, then Return to Test 1.

B POWER MEASUREMENT INSTUMENTATION

The power measurement component of the testing will be used to collect harmonic, energy efficiency, and inrush data. Some of the measurement tests may be conducted in tandem with the power quality testing phase of this protocol.

The power and energy of the equipment will be measured using a Hioki 3198 power analyzer shown in Figure B-1.

Figure B-1
Hioki Power Analyzer

The Hioki has the capability to measure many parameters. The meter will be configured to record all available measurement parameters. Figure B-2 is a list of all the recorded parameters.

Voltage measurement items (TIME PLOT Recording)	RMS voltage Frequency DC voltage Harmonic voltage (0 to 50th order) Inter-harmonic voltage (0.5 to 49.5th) Total harmonic voltage distortion factor	Waveform voltage peak Frequency (1 cycle, 10-sec) IEC Flicker (Pst, Plt) Harmonic voltage phase angle (0 to 50th) High order harmonic voltage component Voltage Unbalance factor (Zero-phase /Negative-phase)
Current measurement items (TIME PLOT Recording)	RMS current Waveform current peak Harmonic current phase angle (0 to 50th) Harmonic current (0 to 50th) Inter-harmonic current (0.5 to 49.5th)	High order harmonic current component Total harmonic current distortion factor Current Unbalance factor (Zero-phase /Negative-phase) K factor DC current (when using compatible sensor)
Power measurement items (TIME PLOT Recording)	Active power Reactive power Apparent power Power factor	Harmonic power (0 to 50th) Harmonic voltage-current phase angle (0 to 50th) Active energy Reactive energy

Figure B-2
Hioki Measured Parameters

Power-Measurement Test Procedures

This general procedure provides an example checklist of steps to be done while installing and performing power measurements. The meter is intended to be used during all twelve tests in the protocol.

a) Connect control power for power monitoring equipment to a local 120 Vac service outlet.
b) Configure power monitoring equipment for planned circuit connections.
c) Synchronize time of the power monitor(s) with NIST official time server.
    a. https://timegov.boulder.nist.gov/
    b. Set for Eastern Standard Time (UTC-5)
d) De-energize the EUT then lockout/tagout at the point-of-connection (POC).
e) Connect the power monitoring equipment as shown in the Figure B-3 below.

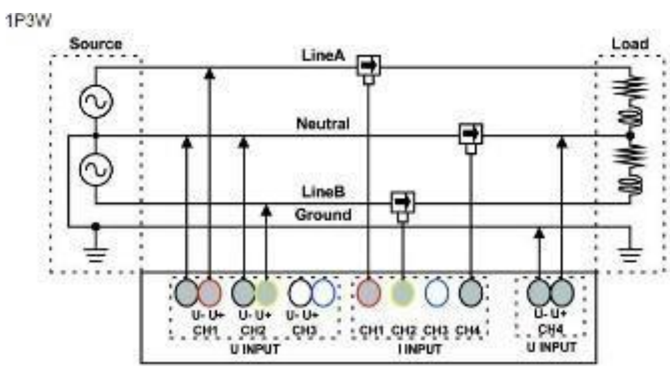


Figure B-3
Hioki 3198 Configuration

f) Visually inspect all connections prior to energizing the test setup.

g) Remove lockout/tagout and energize the EUT, measure and record the phase voltages, and verify power measurements are as expected.

h) Perform any final configuration and setup of the power monitor and confirm readings.

i) Wait 30 minutes to allow for power monitor and EUT stabilization.

j) Start data logging on power monitoring equipment, manually record time stamp as a backup.

k) Start the EUT and operate at full speed at the prescribed load level for 15 minutes.

l) Upon completion of monitoring period, manually record time stamp.

m) If additional measurement runs are desired, repeat from step j.

n) If testing is completed, de-energize the EUT and perform lockout/tagout at the point- of- connection (POC).

o) Remove the power measurement equipment and interconnect assembly from the circuit.

C IEEE 1668 BOX-IN CHARACTERIZATION TEST METHOD

This section will describe the Box-In test methodology described in IEEE 1668™ *Recommended Practice for Voltage Sag and Short Interruption Ride-through Testing for End Use Electrical Equipment Rated Less than 1,000 Volts.*

The "Box-In" test method involves creating a voltage sag at the shortest prescribed duration at 0% voltage magnitude. The next test point is the maximum prescribed duration; at 85% nominal magnitude and then reduce the voltage in 5% increments until the trip point or 0% magnitude is found. Reduce the duration to the next lowest level and increase the voltage sag magnitude 5% from the previous trip level and reduce the magnitude by 5% until the EUT trips again. Continue reducing the voltage sag duration as per the prescribed levels until all durations have been exhausted. The flow chart for this test method may be seen in Figure C-1. A graphical representation of the test procedure is shown in Figure C-2. If the EUT tripped during the initial minimum test, the test engineer must find the trip point at the minimum duration by following the previous procedure. Table C-1 is the test worksheet for 60-Hz testing, wherein the example parameters of the test plan are as follows:

- Maximum magnitude: 85% of nominal
- Minimum magnitude: 0% of nominal
- Maximum duration: 1 seconds
- Minimum duration: 0.02 seconds
- Magnitude interval: 5% of nominal (18 steps)
- Duration schedule (minimum): 1, 0.5, 0.2, and 0.0167 seconds (four loops)

For illustration purposes, steps 1 through 18 within loop 1 are explicitly shown. This method enables the investigator to find a trip point (should it exist) at all given test durations outlined in the plan. In the example single-phase test matrices shown in Table C-1, as many as six trip points for the EUT may be identified during the test. Of course, it is possible to include more or fewer duration values in the schedule, depending upon the test plan.

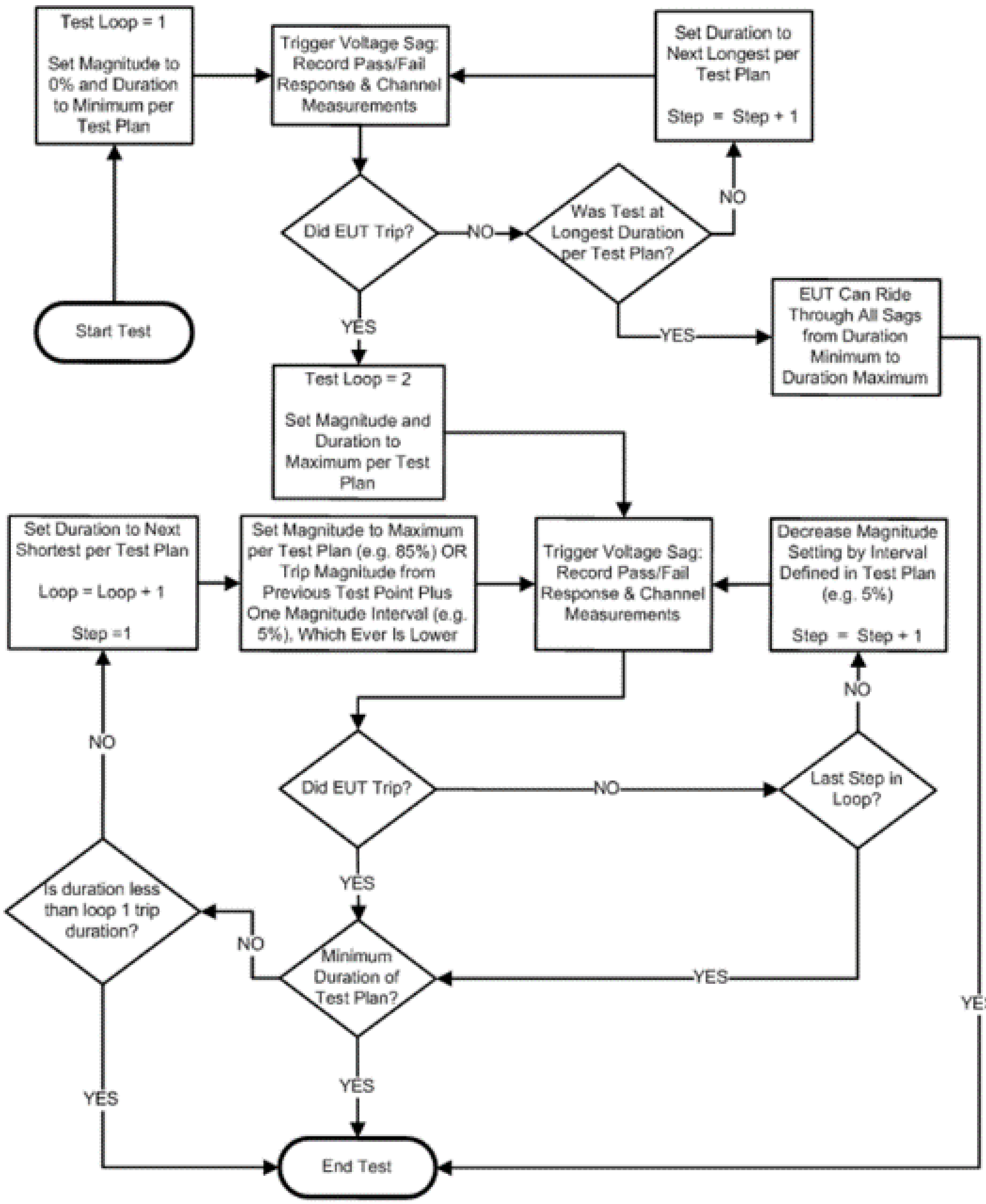


Figure C-1
Box-in voltage sag characterization test flow chart

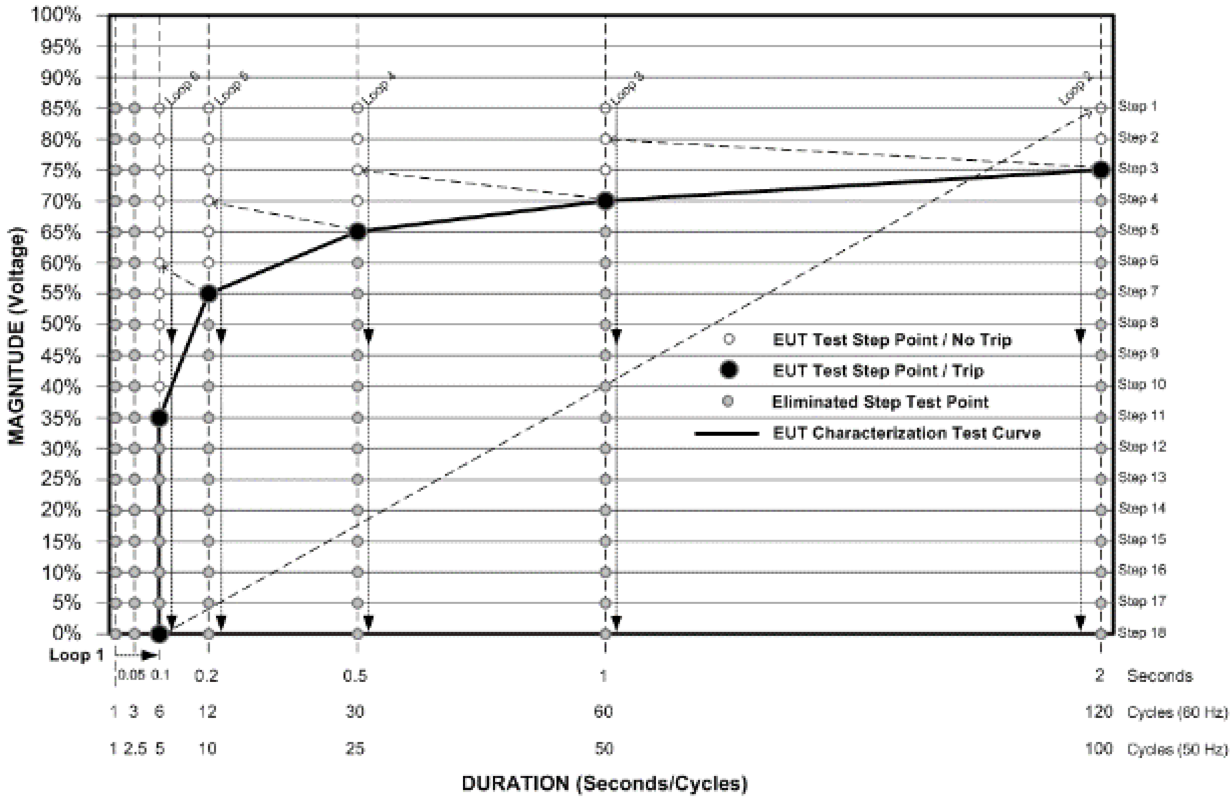


Figure C-2
Box-in voltage sag characterization test method (8 Loop Example)

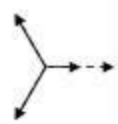
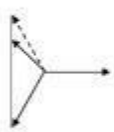
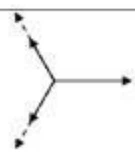
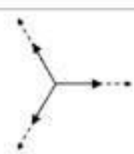
Table C-1
Box-in method equipment characterization test matrix, 60 HZ (8 Loops)

Test loop	Step No.	Voltage-sag duration		%Vnom. of PUT	Pass/fail response			Notes
		Secs	60-Hz cycles		Full operation	Self-recovery	Assisted recovery	
Loop 1	1	0.0167	1	0%				
	2	0.05	2	0%				
	3	0.1	6	0%				
	4	0.2	12	0%				
	5	0.5	30	0%				
	6	1	60	0%				
	7	2	120	0%				If EUT has not tripped at the maximum duration test point, testing can stop.
Loop 2	1	2	120	85%				
	2	2	120	80%				
	3	2	120	75%				
	4	2	120	70%				
	5	2	120	65%				
	6	2	120	60%				
	7	2	120	55%				
	8	2	120	50%				
	9	2	120	45%				
	10	2	120	40%				
	11	2	120	35%				
	12	2	120	30%				
	13	2	120	25%				
	14	2	120	20%				
	15	2	120	15%				
	16	2	120	10%				
	17	2	120	5%				
	1→17	1	60	85%→ 5%				
	1→17	0.5	30	85%→ 5%				
	1→17	0.2	12	85%→ 5%				
	1→17	0.1	6	85%→ 5%				
	1→17	0.05	3	85%→ 5%				
	1→17	0.0167	1	85%→ 5%				

Voltage Sag Test Vectors

Voltage sags occur in many ways. During a voltage sag, the voltage magnitudes are rarely balanced, and the phase angles do not change symmetrically with relationship to each other. Because it is not always practical to reproduce the voltage sags exactly as they occur in the field, approximations may need to be made to allow the use of available test equipment. For this reason, Table C-2 presents both recommended and allowed test vectors and important considerations.

Table C-2
Recommended and allowed voltage sag test vectors and considerations

Type description	Example test-vector method	Vector descriptions	Comments
Recommended Type I		$V_a = X$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jE\sqrt{3}$	This testing is most relevant to single-phase equipment or three-phase equipment with a neutral
Recommended Type II (IEC Type 3c)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}jV\sqrt{3}$	CIGRE C4.110 study indicated that this type of voltage sag makes up 82 to 91 percent of Type II events on HV and MV networks.[2]
Allowed Type II.A1 (IEC Type 3b)		$V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	CIGRE C4.110 study indicated that this type of voltage sag makes up 9 to 18 percent of Type II events on HV and MV networks.[2]
Allowed Type II.A2 (IEC Type 3d)		$V_a = E$ $V_b = -\frac{1}{2}X - \frac{1}{2}jX\sqrt{3}$ $V_c = -\frac{1}{2}X + \frac{1}{2}jX\sqrt{3}$	This type of voltage sag can occur when two phases are shorted to ground at the same time
Recommended Type III		$V_a = V$ $V_b = -\frac{1}{2}V - \frac{1}{2}jV\sqrt{3}$ $V_c = -\frac{1}{2}V + \frac{1}{2}jV\sqrt{3}$	This is a common type of voltage sag that occurs in 11% to 20% of the events recorded per EPRI[4] and CIGRE C4.110 studies.[2]

In many initial system compatibility tests, most Type II tests were completed using what is referred to as Type II.A2 because the first models of voltage-sag generators were based on referencing the voltage sag to a neutral conductor. This method has provided the most severe scenario for phase-vector magnitudes during tests and has been proven to lead to improvements in voltage-sag immunity of end-use equipment. However, Type II.A2 induces little phase shift for the phase-to-phase vectors and no phase shift for the phase-to-neutral vectors. For equipment with active front ends and phase-locked loop type of controls, testing by Type II.A2 could lead to a false sense of robustness for certain types of loads because no phase shifting occurs.

Likewise, testing with the Type II.A1 method can lead to a false sense of robustness for certain three-phase loads in that these loads do not trip during the test but could trip during actual voltage sags. Again, this is most critical for loads such as the diode-bridge AC drive. If tests are conducted for all Type II combinations (i.e., Type II, Type II.A1, and Type II.A2), the weakness of any one test can be offset. The most thorough approach would be to evaluate the EUT against all five test-vector scenarios.

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