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EMP Testing of UL489 Circuit Breakers

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Executive Summary

Sandia National Laboratories (SNL) is performing a test campaign for the Department of Energy (DOE) Office of Cybersecurity, Energy Security, and Emergency Response (CESER) to address high-altitude electromagnetic pulse (HEMP) vulnerability of critical components of generation stations, with focus on early-time (E1) HEMP. The campaign seeks to establish response and damage thresholds for these critical elements in response to reasonable HEMP threat levels as a means for determining where vulnerabilities may exist or where mitigations may be needed. This report provides component vulnerability test results that will help to inform site vulnerability assessments and HEMP mitigation planning.

This work entails conducted pulse testing of Altech UL489 molded-case circuit breakers, the primary way that circuit breakers are expected to experience E1 HEMP. The circuit breakers selected were D-trip UL489, which are rated from 5 to 60 Amps (A) as representative of common plant circuit breakers, and tested on the conducted electromagnetic pulse (EMP) testbed at SNL. Circuit breakers are protective devices that prevent damage from overcurrents by opening a circuit using a thermal response for prolonged high current or magnetic action for very high current. Inadvertent circuit breaker action removes power from critical equipment and circuit breakers that do not function, leave equipment unprotected from common hazards, leading to possible equipment damage.

The circuit breakers were tested in common mode with conducted HEMP insults up to the pulser's maximum capacity of 660 A, or an equivalent open circuit voltage exceeding 300 kilovolt (kV). The breaker trip responses were checked with 2 times (x) and 10x the rated current between each shot and on each phase at the beginning and end of the overall test series. Voltage withstand tests consistent with the UL489 standard were applied across the breaker casing at the beginning and end of the test series as well.

A single, non-repeatable instance of the breaker tripping in response to the conducted pulse occurred for a 10 A breaker in response to a ~54 kV equivalent open circuit voltage insult (18% of the maximum test voltage). Two, non-repeatable, instances were measured of reduced trip time during the 10x rated current test following a conducted pulse test, and the breaker returned to typical trip levels once they were allowed time to cool off. These exceed the 40 kV maximum coupled open circuit voltage expected for a 25 kV/meter (m) threat based on previous estimations of instrumentation and control cable coupling.

No other events recorded during testing were attributable to a breaker responding to the HEMP insult, and state of health (SOH) tracking determined consistent trip behavior within the acceptable trip response times across all breakers. As a result, the UL489 breakers were determined to be highly resilient to very high EMP insults with respect to direct damage and degradation. The breakers simultaneously do not provide any significant mitigation to a conducted HEMP insult, even in the case where a breaker trip occurred beyond the time frame of the initial pulse. Other mitigations should be considered besides solely circuit breakers for E1 protection. Additional investigation of critical components on generation facility circuits is necessary to determine what level of protection is appropriate for HEMP mitigation.

SNL conducted testing on Altech UL489 molded case circuit breakers to 660A or exceeding 300kV open circuit voltage. No permanent damage occured; however, some anomalous, unrepeated disruptions were noted.

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Glossary of Terms

Abbreviation	Definition
APELC	Applied Physical Electronics, L.C.
CESER	Office of Cybersecurity, Energy Security, and Emergency Response
CVR	Current-viewing resistor
CVT	Current-viewing transformer
DOE	Department of Energy
DUT	Device under test
E1	Early-time HEMP
EMP	Electromagnetic pulse
HEMP	High-altitude electromagnetic pulse
LV	Low voltage
MOV	Metal-oxide varistor
SNL	Sandia National Laboratories
SOH	State of health

Introduction

High-altitude electromagnetic pulse (HEMP) events generate strong electromagnetic fields at the earth's surface, which can cause damage or interruptions to electronic equipment via direct radiation or coupled insults on conductors. Critical power systems components are of particular interest in assessing this vulnerability due to potential connections to the long conductors associated with electric power. This work presents results of a broader testing campaign developed by Sandia National Laboratories (SNL) for the Department of Energy (DOE) Office of Cybersecurity, Energy Security, and Emergency Response (CESER) to assess the effects of conducted HEMP on power generation equipment. Conducted insults on these components arise from coupling onto power transmission or instrumentation and control cables in substations and generation facilities. The results in this work focus on HEMP vulnerability testing of circuit breakers as a potentially critical component in a generation facility. The individual component vulnerability test results in this report will help to inform site vulnerability assessments and HEMP mitigation planning.

Low voltage (LV) circuit breakers installed in facility components and cabinetry provide a basic level of protection to electrical systems by switching components in and out of energized circuits. A breaker changing states from 'open' (non-conducting) to 'closed' (conducting) can be a manual operation to connect or disconnect different equipment, or it can be an automatic response to high current or some other signal. Damage to a LV breaker from HEMP could cause a variety of effects. One is an unintended operation where a breaker opens in response to the conducted HEMP, which can take critical components offline during an emergency even if no damage occurs.

HEMP events may also create arcs across the dielectric material between the breaker terminals, or from a breaker terminal to the nearby ground. These arcs may decrease the dielectric breakdown threshold of the breaker casing to future events and provide a conducting path for a station battery or some other voltage source to do additional damage. Another potential arc effect is a permanent low impedance path through the dielectric. A pulsed insult with a high enough instantaneous current could also cause contacts to stick together in an already closed breaker due to metal heating or arc residue, which could require operator intervention to correct.

Experimental Overview

Objectives

The objectives of this work were to:

- Establish an experimental test to determine the effects of conducted E1 HEMP on molded case LV circuit breakers typically found in a power generation facility.
- Determine and document SOH metrics for the breakers based on any unintended operations, loss of breaker trip function, or change in device impedance.

Test Articles

The devices under test (DUTs) were UL489 listed Altech Miniature Molded Case Circuit Breakers shown in Figure 2-1. These breakers have current trip ratings up to 60 A and typical breakdown ratings of 10 kA. Five ratings of UL489 breakers were installed in a breaker panel for EMP pulse testing as shown in Figure 2-2. The breaker continuous ratings are as follows:

- Two – Three-pole, 5 A, 240 Vac breakers, designated SN001 and SN007
- Two – Three-pole, 10 A, 240 Vac breakers, designated SN002 and SN008
- Two – Three-pole, 20 A, 240 Vac breakers, designated SN003 and SN009
- Two – Three-pole, 50 A, 240 Vac breakers, designated SN004 and SN010
- Two – Three-pole, 60 A, 240 Vac breakers, designated SN005 and SN011

Figure 2-1. UL489 circuit breakers from Altech

Figure 2-2. Circuit breakers installed in breaker panel

Additional components not related to the test circuit were removed for EMP testing to prevent inadvertent testing of disconnected devices, leaving the DUT, the main 250 A breaker at the panel input, and the terminal block for the parallel rails. The three-phase parallel connection block on each rail was also removed such that the three phases coming from the terminal block were connected directly to the three phases of the breaker under test. Electrical points of entry were created at the bottom and side of the breaker panel to accommodate the electrical cable for the setup. The breaker panel setup used in testing is shown in Figure 2-3.

Figure 2-3. Breaker panel configured for EMP testing

Pulse Test Setup

Pulse testing of the circuit breakers was performed with the breakers closed and energized near their continuous voltage and current rating. This was accomplished via a three-phase generator providing approximately 0.9x of the current rating of the breaker. The general test setup for the breakers is depicted in Figure 2-4. The generator neutral was internally grounded and was also connected to a common return plane of the experimental setup. The steady-state current level in the circuit was set using two three-phase load banks at the other end of the circuit. The 100 kW and 400 kW load banks were initially chosen to provide more flexibility and accuracy in setting the steady-state and trip currents. The 100 kW load bank was initially used for 5, 10, and 20 A breaker tests, but a 400 kW load bank with more precise load control was used in later tests of these breakers and all tests of the 50 and 60 A breakers. The conducted EMP insult was applied in common mode to the center of the cable between the generator and the breaker panel. Metal oxide varistors (MOVs) were used to isolate the pulser from the AC power in the breaker circuit. Filters were used to isolate the generator and load bank from the EMP pulser. The physical layout of the test setup is depicted in Figure 2-5. The electrical lengths in the system between the different elements of the circuit were selected such that the components were electrically separated and the transient response at the breaker was dependent on the breaker characteristics alone. This also ensured that measurements of the transient pulse could distinguish between incident and reflected signals in the time domain.

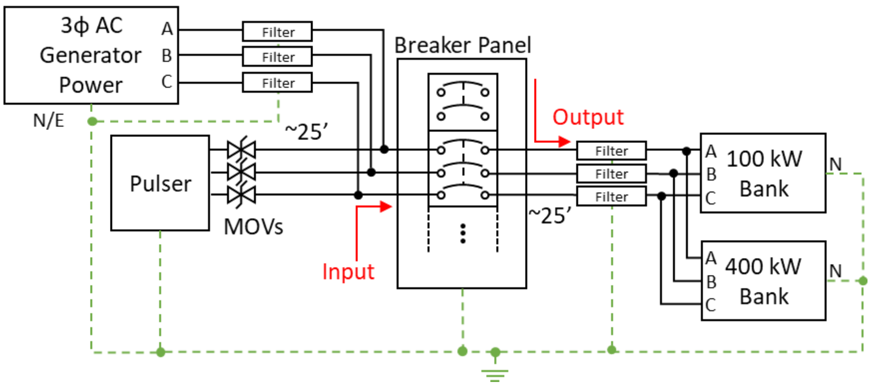

Figure 2-4. Test circuit diagram for three-pole AC circuit breaker testing in an energized state.

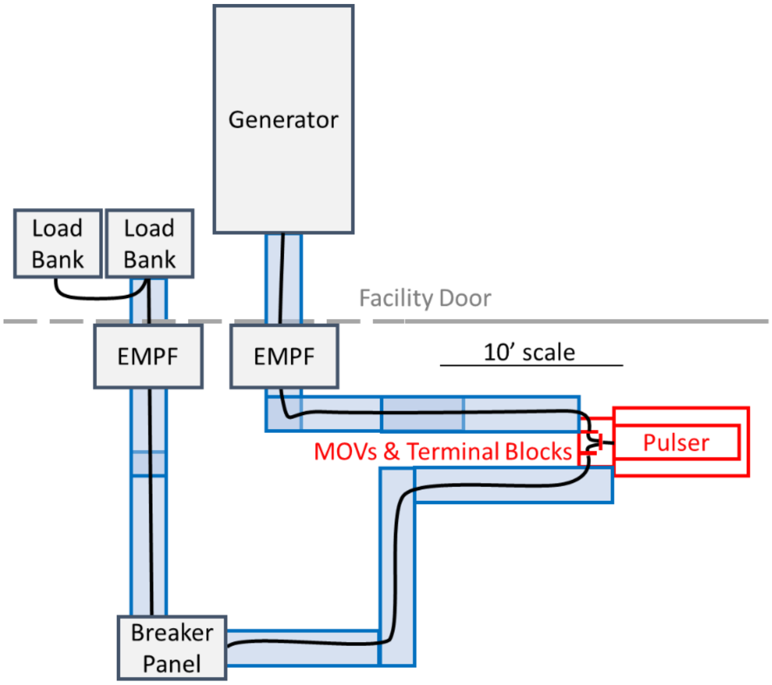

Figure 2-5. Test layout diagram for circuit breaker testing in a breaker panel, with return planes and cable runs for electrical separation of components during test.

Photographs of the experimental setup are shown in Figure 2-6 through Figure 2-8. Figure 2-6 shows the overall test configuration connected by a common return plane.

The power cable in the setup was a 4-conductor 6 AWG cable with three conductors used for the power and one conductor left open. The neutral of the generator and load bank was passed along the common return plane that was grounded to the local building ground at the EM pulser. The cable was mounted at 4 inches over the return plane in a similar setup to the RF testing configuration defined by the UL489 standard for circuit breakers [1]. This orientation of the cable provides an approximate cable impedance of 230 Ω [2].

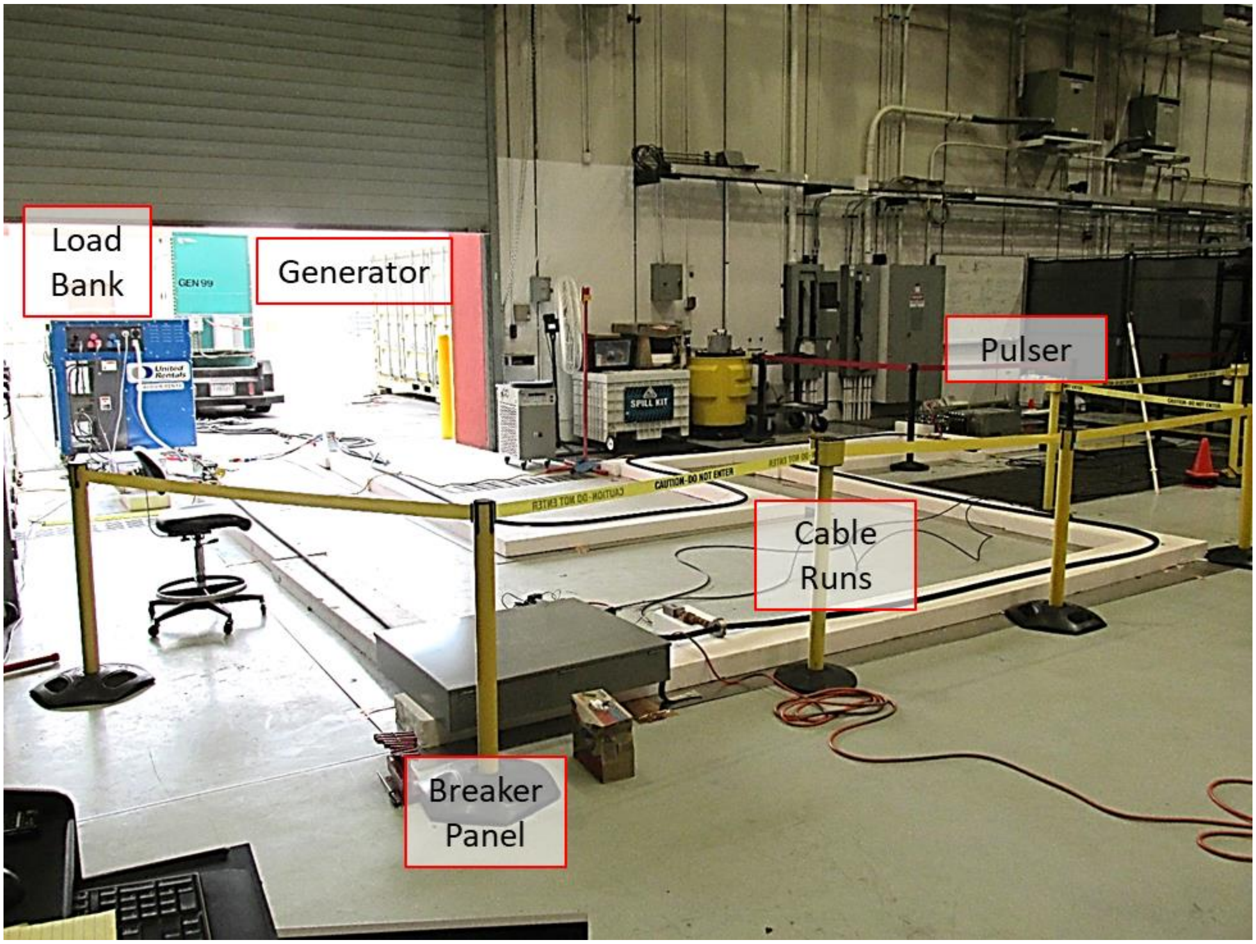

Figure 2-6. Photograph of breaker test setup

Figure 2-7 shows the 100 kW and 400 kW load banks used in testing. Each load bank was connected using camlocks at the end of the multiconductor cable with filters in series for low current tests and filters bypassed for high current tests. Figure 2-8 shows the 200 kW/250 kVA generator connections at the other end of the circuit, which were also connected via camlocks. It was determined during testing that the 200 kW generator could not reliably produce the high current levels needed for SOH testing of the 50 A and 60 A breakers; hence, a 300 kW generator was then used to facilitate testing of the higher breaker ratings.

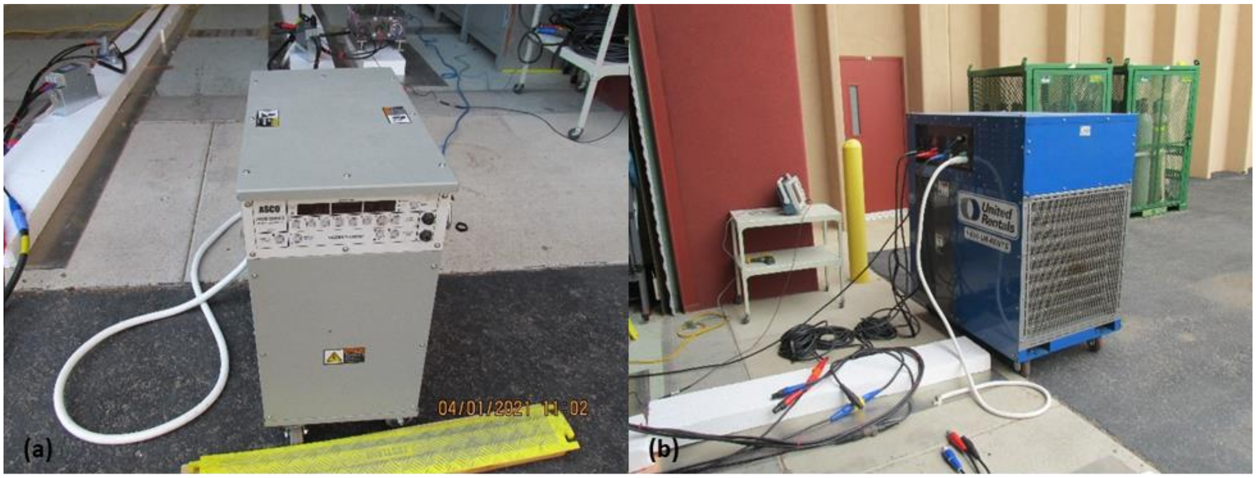

Figure 2-7. (a) 100 kW and (b) 400 kW load banks used during testing

Figure 2-8. Generator power connections

Pulse Generator

The conducted pulse generator was a Marx pulser designed by Applied Physical Electronics, L.C. (APELC). The APELC pulser is divided into a coaxial-structured Marx bank and an oil-insulated peaking section. The pulser was originally designed to feed into a wire waveguide structure; however, for the E1 HEMP testing, the pulser’s peaking section was closed and the output was fed directly into the conducted environment. The basic electrical parameters of the Marx generator are given in Table 2-1. A photograph of the pulser is given in Figure 2-9.

Table 2-1. Basic Electric Parameters of APELC Pulser

Parameter	Definition	Value
V_{marx}	Erected voltage of the Marx generator	195 – 520 kV*
V_{ch}	Stage charge voltage	15 – 40 kV*
N	Number of stages in the Marx generator	13
E_{st}	Stored energy	49 J
C_{erect}	Erected capacitance	361 pF
C_{stage}	Stage capacitance	4.7 nF
L_{marx}	Series Marx inductance	650 nH
C_{peak}	Peaking capacitance	50 pF
L_{peak}	Peaking inductance	100 nH
R_{peak}	Peaking section water resistor	10 Ω

*While rated to 40 kV, engineering controls limit the stage charge voltage to 39.5 kV (513.5 kV erected voltage).

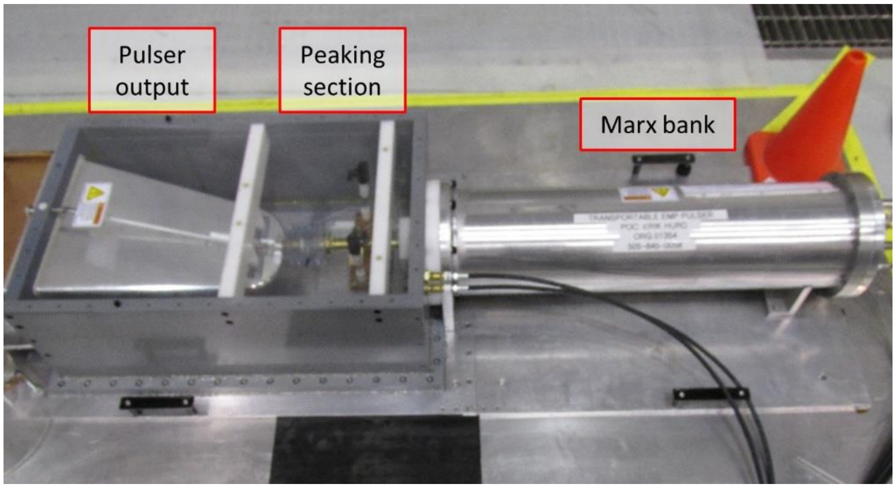

Figure 2-9. Conducted EMP Pulser

The conducted E1 waveform for a substation environment is anticipated to have a voltage peak in tens of kV based on coupling calculations. An example waveform from the generator output is given in Figure 2-10. The waveform has a 10 to 90% rise time of 8-10 nanoseconds (ns) and a pulse width of ~30 ns, which has an appropriate rise time for the expected conducted waveform with a slightly lower duration.

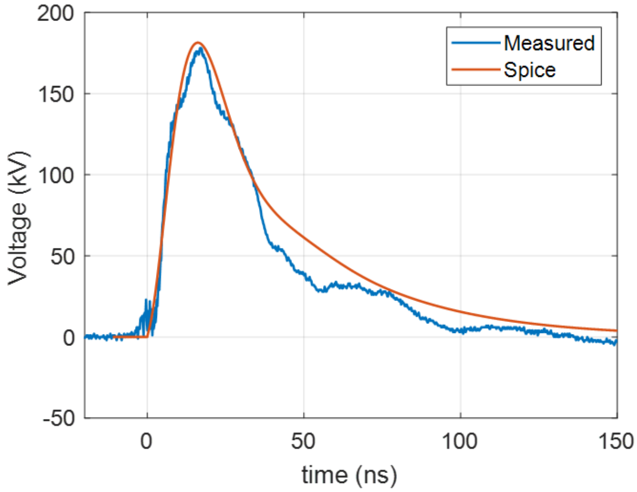

Figure 2-10. Marx bank output pulse at junction between pulser and Filter 2 with open circuit load.

Resistive filter networks are implemented to attenuate the output voltage of the pulser with enough overlap to achieve a peak voltage range from 10s of kV to the maximum erected voltage. All filters use a pi-network configuration and are reciprocal except for filter 4, which is left open. Additionally, the input impedance is kept as close to 100 Ω as possible to avoid reflections back into the pulser. Multiple resistors are used in parallel to reduce the loop inductance for each branch of the network, with each resistor estimated to have a self-inductance of 70 nH. The current in the two shunt branches of the pi-network were measured with 2.5 mΩ current-viewing resistors (CVRs). Analysis of the two CVRs can also provide an analytical approach to defining the voltage and current going into a load on the filter output. The diagram for implementing the output filter is shown in Figure 2-11, and the photograph of an output filter on the pulser is shown in Figure 2-12. The filter values and predicted ranges of the open circuit output voltage are given in Table 2-2. The design in Figure 2-12 was selected to minimize any risk of arcing from the pulser to ground from the filter.

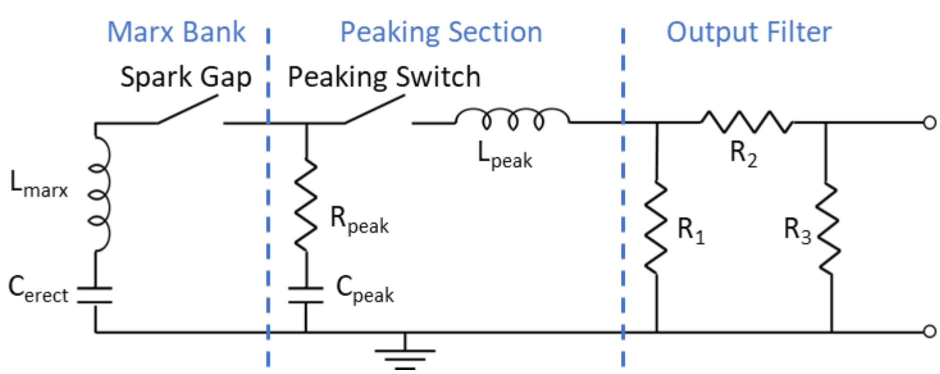

Figure 2-11. Marx circuit for filter output analysis

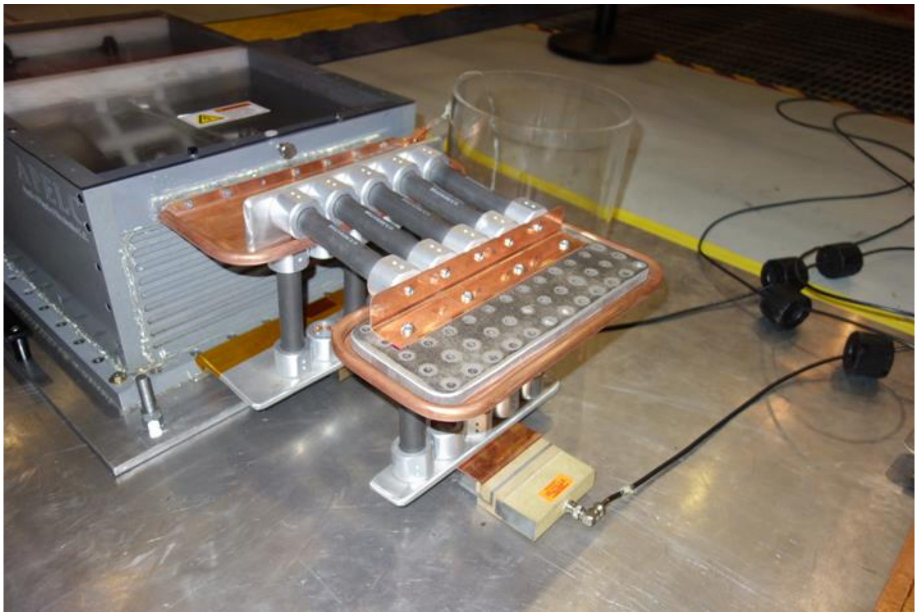

Figure 2-12. Filter fixturing on pulser output

Table 2-2. Filter Network Designs and Estimated Open Circuit Output Voltage

Filter	Resistance (# in parallel × Ω)			Calculated Voc	Simulated Voc	Measured Voc
	R1	R2	R3			
1	100 Ω (5 × 500)	1 kΩ (1 × 1000)	100 Ω (5 × 500)	15.8–41.7 kV	11.7–30.7 kV	22.0[1]–57.7 kV
2	125 Ω (4 × 500)	500 Ω (2 × 1000)	125 Ω (4 × 500)	35.4–93.3 kV	27.3–71.7 kV	41.3[1]–75.0 kV
3	167 Ω (3 × 500)	200 Ω (5 × 1000)	167 Ω (3 × 500)	81.5–214.6 kV	64.8–170.4 kV	84.1[1]–162.6 kV
4	125 Ω (4 × 500)	Short	Open	181.0–476.5 kV	147.7–388.3 kV	N/A

[1] Measurement data was taken down to 20 kV/stage during characterization. Values for 15 kV/stage can be estimated along a linear trend.

Only stage charge voltages of 15 kV, 20 kV, 25 kV, and 30 kV were used for this test series due to higher charge voltages increasing the chances for arcing across R1.

Test Instrumentation

Initial system tests measured common mode currents at the middle of the line between the injection point and the breaker panel, at the cable input to the panel, and between the panel and load bank using Prodyn I-125-2E 1 Ω current-viewing transformers (CVTs). All CVTs in the system were floated using Montena fiberoptic links to send the measured signal to the meter. Additional dielectric was added between the cable and

CVTs when potential discharge through the cable insulation was detected. An additional 0.01 Ω CVT was used on phase A of the cable between the breaker panel and load bank to determine the single-phase current during SOH checks and for setting the rated current during pulse tests. The various CVT positions used throughout testing are indicated in Figure 2-13. CVRs with a 2.5 mΩ resistance were placed at the bottom of each leg of the resistive filter on the pulser output to monitor the pulser output during testing.

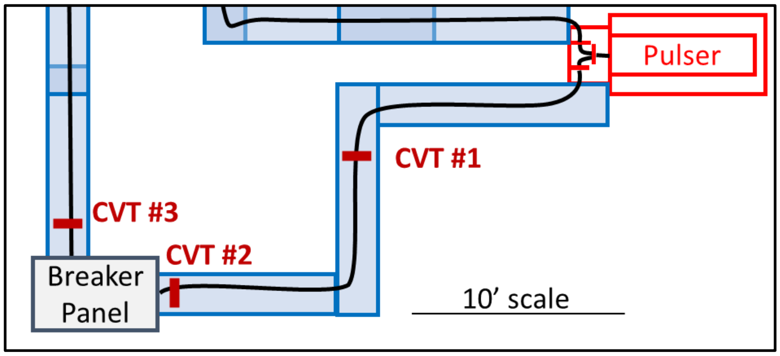

Figure 2-13. CVT measurement positions during testing

Test Procedure

The following test procedure was conducted for all configurations:

1. At the start of the day, perform pulser test shots with open circuit and CVRs on the filter legs to ensure pulser settings provide consistent discharge and output.
    a. Adjust pressure levels as necessary to ensure Marx bank discharge.
    b. Adjust the stage voltage to ensure the output voltages are sufficiently close to the desired peak values.

    NOTE: It is necessary to make these adjustments on the day of testing because of variation in pulser behavior with atmospheric pressure. Some scalability can be assumed for voltage levels once a baseline is established.
2. Assemble the DUT and pulser connection.
    a. Prior to the full testing sequence, disconnect any CVTs, CVRs, or voltage probes near the circuit breaker and fire disconnected pulser to measure any electric field effects.
3. SOH:
    a. Conduct SOH checks per the procedure given in the SOH Summary section below.
4. Ensure DUT is properly connected per Figure 2-4, installed in the breaker cabinet, and the breaker cabinet door is closed.

5. Insult the circuit for the desired open circuit voltage peak values.
6. Repeat SOH checks between each insult and document the results.
    a. If the device passes (no visible damage, breaker trips with correct timing in SOH per Figure 2-15, and no arcing occurred), proceed to the next voltage level for testing. Otherwise, proceed to the following steps, depending on device state.
    b. If the device tripped during testing (changed from closed to open state), repeat the same voltage level to determine consistency of breaker response.
    c. If the device showed arcing but no permanent reduction in open breaker impedance, repeat the same voltage level to determine whether a reduction in breakdown voltage occurred.

If the breaker fails (i.e., permanent damage is observed, breakers fail to open during SOH test, or if it has a low impedance path across any pole while in the open position), denote the breaker as having failed and proceed to the next breaker.

SOH Summary

The circuit breaker SOH was defined based on the Z-sequence of testing listed in UL489 [1] with modifications to the process based on feedback from Altech engineers and experimental needs. These modifications were needed to account for current and voltage demands in the UL489 standard that were not feasible to integrate into the experimental space with the conducted pulse testbed and would have resulted in a significant prolonging of the test sequence. All modifications were determined to meet the same functional need for assessing breaker health and were approved by DOE CESER prior to implementation. The full details of the SOH tests and the adjustments to the steps used during testing are provided in Appendix B.

The following checks were applied to each breaker:

- Between each shot:
    - Breaker visually inspected for evidence of arcing or device damage
    - 2x rated rms current applied to breaker in common mode and trip time recorded
    - 10x rated rms current applied to breaker in common mode and trip time recorded
    - Breaker opened and closed manually to confirm change in state
- At the beginning and end of the test series:
    - 2x rated rms current applied to breaker on each pole and trip time recorded
    - 10x rated rms current applied to breaker on each pole and trip time recorded

- 1500 V applied across the dielectrics of the breaker for 1 min
  - On each side of the same pole with the breaker open
  - Between each pair of poles with the breaker closed
  - Between each pole and the underlying chassis ground with the breaker closed
- Breaker open and closed impedances checked with a multimeter

Initially, the trip time was performed on each pole for each shot. However, due to the amount of time required to reconfigure for individual tests this was reduced to just a common mode test for each shot and a test on each phase at the end of the test sequence. SN001 through SN005 were pulsed once prior to the first SOH check due to delays in the generator and load bank setup, and SN007 through SN011 received SOH checks prior to any pulsing. The trip time of each breaker was defined as the amount of time between the applied current first exceeding the 2x or 10x level and the current dropping back to zero (defined as <10% of the 2x or 10x level). An example of these two trips is shown in Figure 2-14 for the 20 A breaker SN009 during the initial SOH check.

While there are time requirements established by the UL489 standard for breaker response for each test, the trip curve data from Altech shown in Figure 2-15 provides more strict boundaries for the breaker behavior and will be the reference point for typical breaker behavior [3]. All breakers tested were type D breakers. The provided 20 A breaker example had a calculated common mode 2x current trip of 8.486s and 10x current trip of 0.325s, both well within the D trip bounds established by the manufacturer in Figure 2-15. The ranges of acceptable trip times are approximated in Table 2-3 from the trip curve data and the UL489 standard, where UL489 defines the interrupting trip time (>>10x rated current) as whatever the manufacturer states.

Table 2-3. Approximate Acceptable Trip Ranges Per Type D Breaker Rating

Trip Requirement	5 A	10 A	20 A	50 A	60 A
UL489 200% Current	<2 min	<2 min	<2 min	<4 min	<6 min
Altech Spec. 2x I_{rated}	5-90 sec	5-90 sec	2-45 sec	2-45 sec	2-45 sec
Altech Spec. 10x I_{rated}	0.017-6 sec	0.017-6 sec	0.017-6 sec	0.017-4 sec	0.017-4 sec

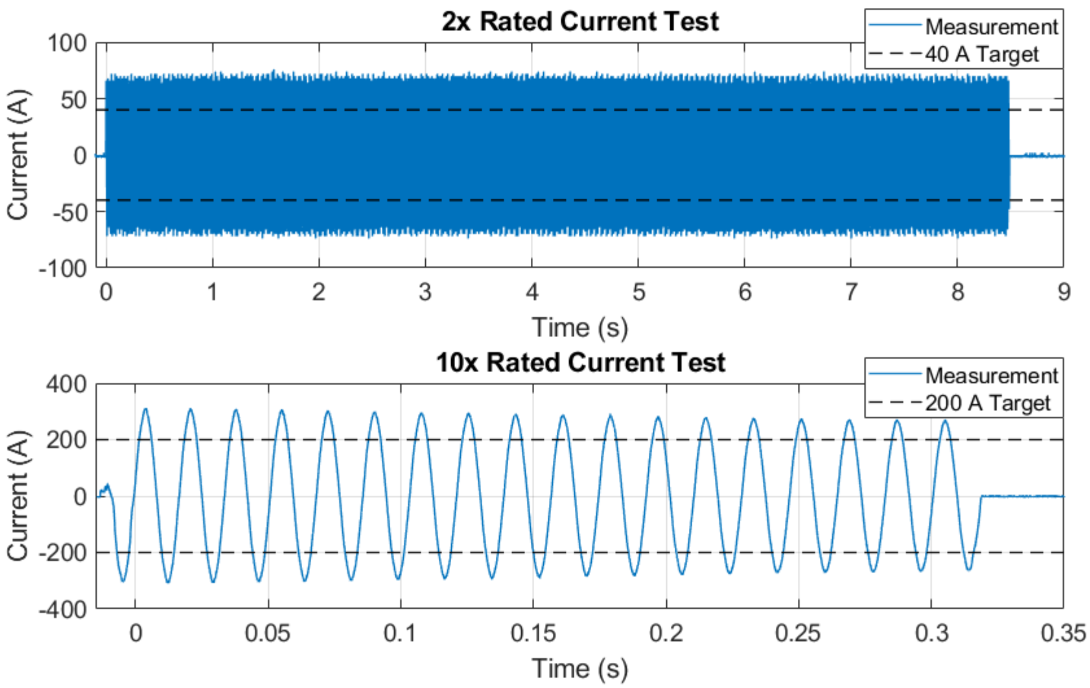

Figure 2-14. Common mode trip signal examples for SN009 (rated 20 A) breaker SOH at 2x and 10x rated current

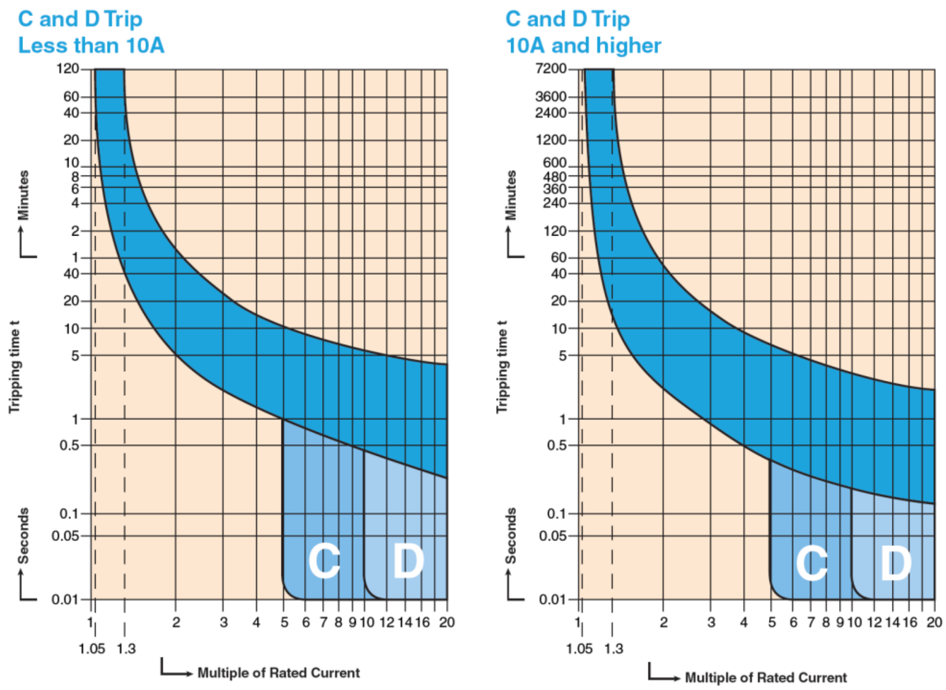

Figure 2-15. Example Thermal and Magnetic Time/Current Characteristic Curves for a UL489 Breaker [3]

Test Results

Shot Progression Summary

A total of 151 pulser shots were applied to the ten breakers tested in this work. A full account of every shot is provided in Appendix A with maximum test levels and notable results indicated in this section. Over the course of testing, no damage was observed in the breakers, and only a few cases of unexpected breaker responses arose. SN001 through SN005 were tested after the first shot due to a delay in the generator and load bank equipment needed to test the trip response, while SN007 through SN011 received SOH checks prior to EMP testing. The maximum insult for each breaker without observable damage (using filter 4 and a 30 kV/stage charge voltage) is indicated in Table 3-1. For tests with an energized circuit at 0.9x rated current, the pulse was not inherently coincident with the maximum of the underlying 60 Hz signal.

Table 3-1. Maximum Insult Applied to Each DUT

S/N	I_{rated} (A)	Shot #	Injected Pulse Current, CVT #1 (A)	Equivalent Coupled Pulse V_{oc} (kV)	Breaker Panel Pulse Current, CVT #2 (A)	Post-Breaker Pulse Current, CVT #3 (A)
SN001	5	148	668.06	307.31	1039.03	101.79
SN002	10	149	660.55	303.85	1041.79	92.12
SN003	20	150	665.45	306.11	1043.16	97.72
SN004	50	151	665.37	306.07	1045.50	99.65
SN005	60	134	670.06	308.23	1044.29	94.74
SN007	5	140	669.27	307.87	1042.78	64.67
SN008	10	141	662.36	304.68	1042.74	89.78
SN009	20	142	665.31	306.04	1041.62	89.02
SN010	50	143	669.55	307.99	1043.72	92.67
SN011	60	135	675.44	310.70	1043.00	95.90

Maximum values of the peak injected current consistently reached values greater than 660 A for all breakers. The measured current just before the breaker panel (CVT #2) in each case was consistently higher than the injected current on the cable. This is a known effect caused by reflection of the transient signal entering the grounded enclosure of the breaker panel, which changes the cable impedance. The overlapping incident and reflected signals cause a much higher current reading than the actual injected current. This effect has been previously seen at the aperture of a termination cabinet when testing protective relays [2] as a result of realistic changes in ground plane distances.

The peak current passing through to the breaker output was measured by CVT #3 and was contingent on reflections at both the input and output of the breaker panel as well as the devices within the panel.

The injected current was correlated to a coupled open circuit voltage using the equation $V_{oc} = 2I_{meas}Z_{cable}$, where $Z_{cable} = 230\ \Omega$ is the characteristic impedance of the cable. This open circuit voltage will be used consistently throughout the results as a description of insult levels as it directly correlates to the common practice of defining coupling simulations by the open circuit voltage on the cable. This approach provides a reference to system assessments involving coupling calculations. A reasonable maximum of approximately 80 kV has been predicted via calculations for coupling of 50 kV/m to substation and generation plant cables [2], [4], which falls well below the test values that exceed 300 kV in this work. A similar value of 40 kV can be estimated for a 25 kV/m threat level. As a result, it is unlikely that the EMP pulse would result in damage to the LV breakers. Some additional effects are nevertheless detailed in the Test Results, EMP Propagation Effects and Unexpected Operations section.

Breaker Trip Time with Respect to Insult Level

Measured trip behaviors for the ten tested breakers are shown in Figure 3-1 for the 2x rated current and Figure 3-4 for the 10x rated current. These results are also organized by breaker and compared to the number of trip tests in Appendix A. Over the course of testing, the trip response was seen to vary from shot to shot but demonstrated few observable trends from the beginning to end of tests. For the 5 A breakers in Figure 3-1a, Figure 3-1f, Figure 3-4a, and Figure 3-4f, the trip time was seen to trend upward for the low level shots and flatten for later shots, which can be attributed to challenges of low precision in setting the test current from the 100 kW load bank during early testing of the 5 to 20 A breakers. This improved later in testing as the 400 kW load bank with better step precision was introduced with the testing of the 50 A and 60 A breakers. Similarly, the later 10x rated current trip tests of the 50 A and 60 A breakers shown in Figure 3-4d, Figure 3-4e, Figure 3-4i, and Figure 3-4j were consistently lower than the initial tests. Starting with shot 104, a larger generator (240 kW/300 kVA) was brought in to exceed the 600 A necessary for the 60 A breaker tests, which also made testing above 500 A for the 50 A breaker more reliable. Applying a full 10x rated current in these cases decreased the trip time accordingly. Similar comparisons of the trip time to the number of times the trip response was tested (shown in detail in Appendix 0) showed no notable trends in the data outside of these updates to the test configuration over the course of testing.

In all cases, the trip times for each breaker fell within the acceptable trip times detailed in Test Results, SOH Summary, with the possible exception of two points. In Figure 3-4a and Figure 3-4b, a single trip time value was measured as being significantly lower (24 ms and 12 ms, respectively). These trip responses were not repeatable and are addressed in greater detail in the section Test Results, Shots 14 and 17 – Early Trip during 10x Rated Current Test. Overall, there is no indication of the EMP insults causing any detrimental change to the trip behavior of the breakers.

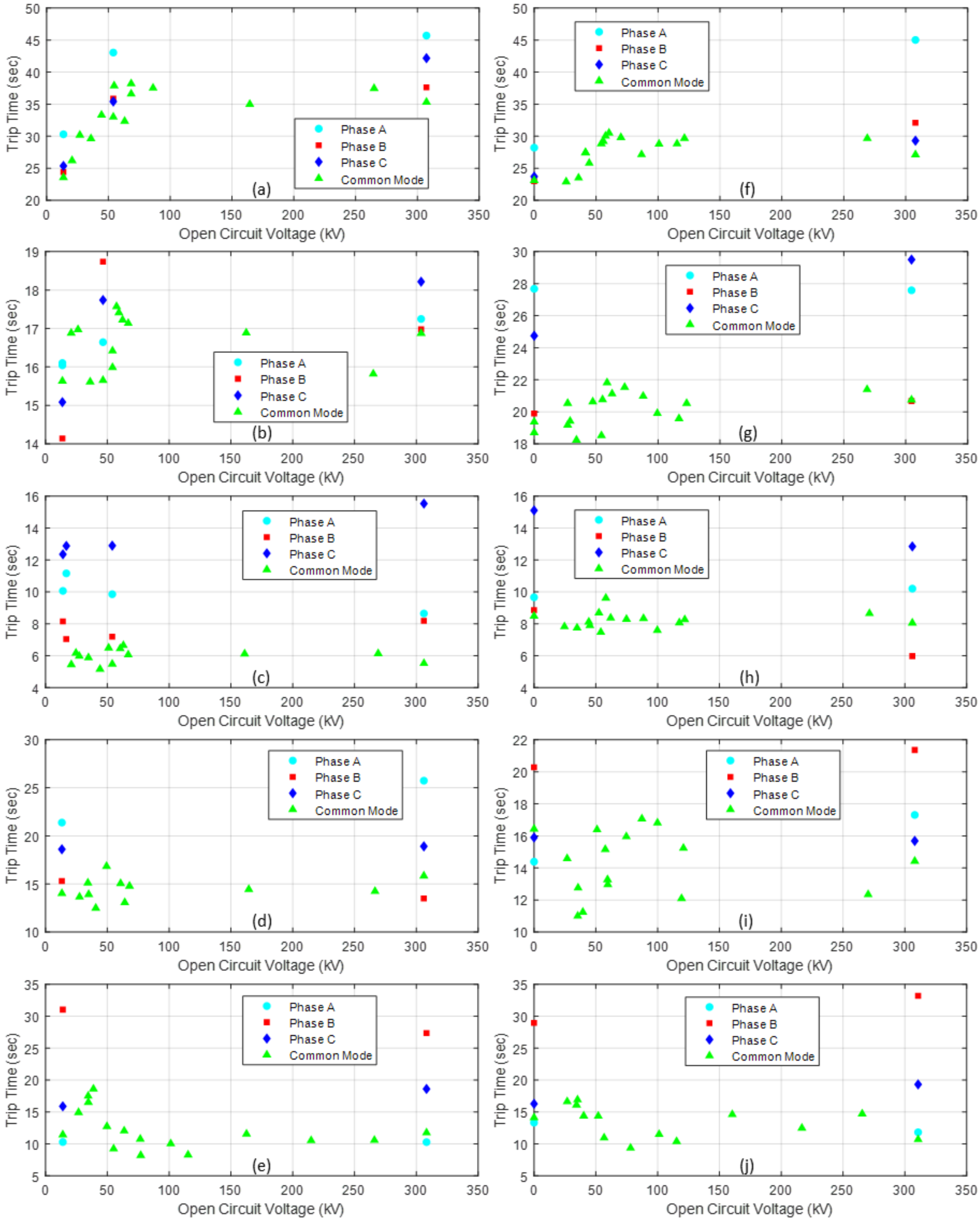

Figure 3-1. 2x I_{rated} trip tests versus conducted pulse open circuit voltage for (a) SN001, (b) SN002, (c) SN003, (d) SN004, (e) SN005, (f) SN007, (g) SN008, (h) SN009, (i) SN010, and (j) SN011.

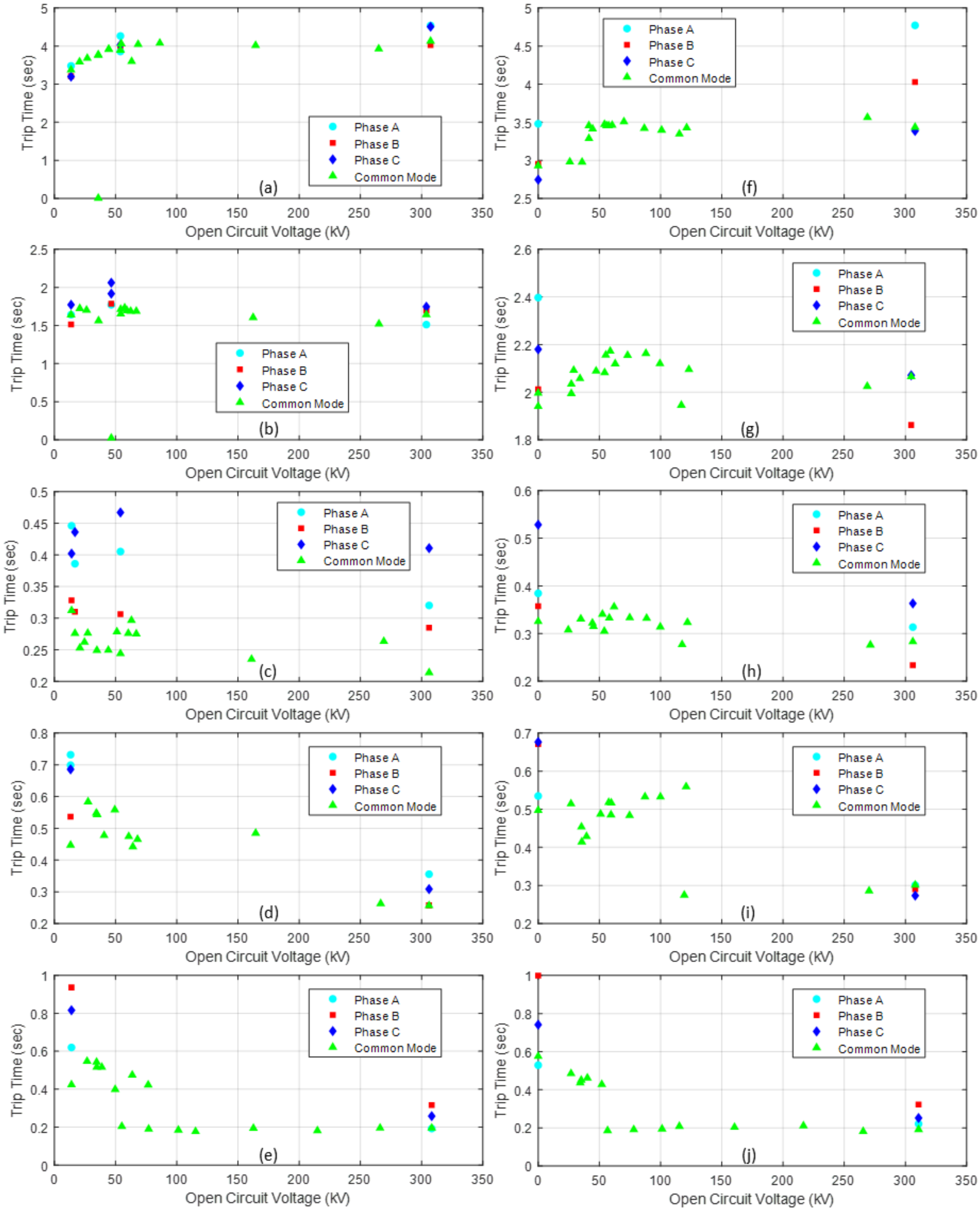

Figure 3-2. 10x I_{rated} trip tests versus conducted pulse open circuit voltage for (a) SN001, (b) SN002, (c) SN003, (d) SN004, (e) SN005, (f) SN007, (g) SN008, (h) SN009, (i) SN010, and (j) SN011.

EMP Propagation Effects and Unexpected Operations

Shots 1 and 69 – Open Breaker Shots

Two shots during testing occurred while the breaker had not been closed prior to applying the EMP insult: Shot 1 (SN001, 5 A, 12.54 kV) and Shot 69 (SN008, 10 A, 51.28 kV). These were immediately followed by shots in the same configuration with the breaker closed: Shot 2 (13.61 kV) and Shot 70 (55.19 kV). Comparison of the shots with the breakers open and closed provides some insight on the effect of the breaker state on the pulse propagation. This is shown in Figure 3-3 for shots 1 and 2 and Figure 3-4 for shots 69 and 70 comparing the midline current (CVT #1) and current after the breaker panel (CVT #3).

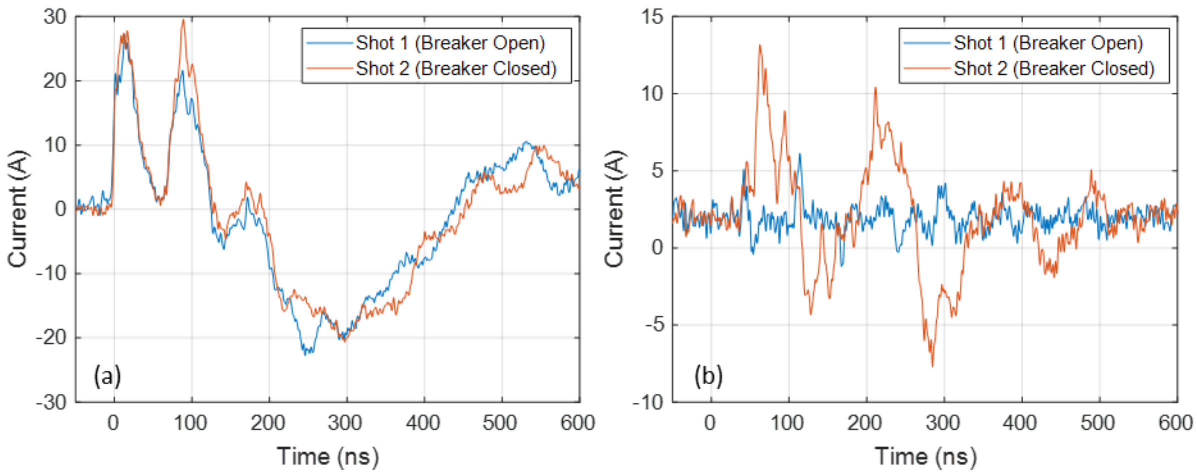

Figure 3-3. Comparison between shot 1 and shot 2 for (a) midline current and (b) current after the breaker panel.

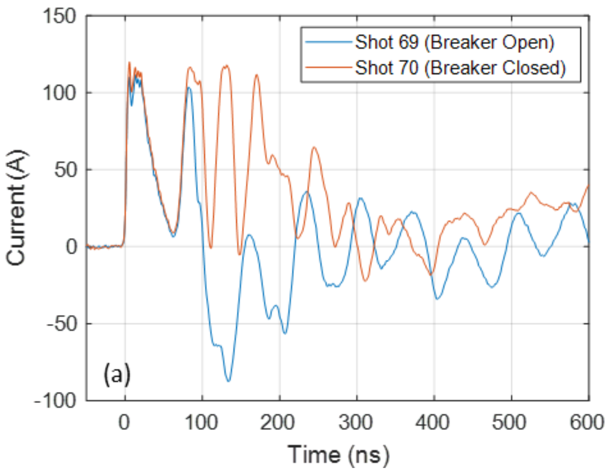

Figure 3-4. Comparison between shot 69 and shot 70 for (a) midline current and (b) current after the breaker panel.

The comparison between these shots shows that an open breaker does increase the signal reflected into the cable carrying the EMP insult. However, some amount of the insult still passes through the open breaker to the secondary cable.

Shots 14 and 17 – Early Trip during 10x Rated Current Test

Two instances occurred of a significant change in the trip response of a breaker during the 10x rated current test following an EMP pulse: shot 14 (SN002, 10 A, 46.50 kV) and shot 17 (SN001, 5 A, 35.87 kV). However, it was not clear whether this effect was due to the shots occurring directly, or due to a residual thermal effect of the SOH test sequence. Following these shots, the 10x rated current trip was reduced to about a single cycle. This is shown for SN001 in Figure 3-5. In both cases the trip test was repeated after allowing 2 minutes for the breaker to cool, and the trip time had reverted to typical levels. This effect was not reproducible, and the breakers were tested to higher levels without any similar changes.

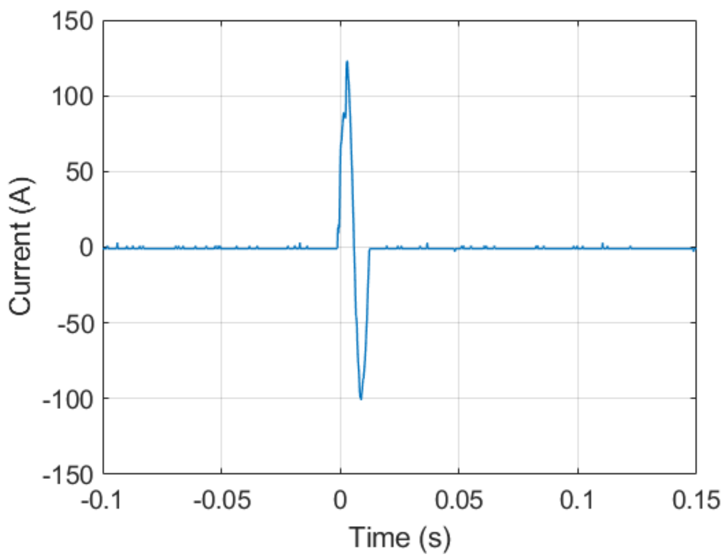

Figure 3-5. Reduced trip time for SN001 following Shot 17. Trip response returned to normal levels after 2 minutes.

Shots 18 and 25 – Immediate Thermal Trips

During the SOH tests following shot 18 (SN001, 5 A, 44.42 kV) and shot 25 (SN007, 5 A, 35.83 kV), the breakers could not be manually closed following the 2x rated current test and had to be permitted to cool for several minutes before the breaker would allow for a manual close. Neither the 2x nor the 10x rated current tests showed any significant change in the trip behavior otherwise.

Shot 32 – Breaker Trip in Response to Pulse

Shot 32 (SN008, 10 A, 54.30 kV) was the only instance observed across all testing in which the breaker tripped in response to the EMP insult. Similar trips were not observed for the breaker with the same rating, SN002, at similar levels, and SN008 was tested to higher levels following the trip event without incident. The results of this shot can be compared to the other shots on the same breaker and to the same shot level on other breakers to determine whether there was any indication of the breaker tripping in the measured data. Other shots on the same breaker leading up to shot 32 are shown in Figure 3-6 for the three CVT positions (CVT #1 on the midline, CVT #2 at the breaker panel, and CVT #3 after the breaker). The measured current at the midline and at the breaker panel show appropriate scaling as the stage charge voltage increases and insignificant late time variations. The current after the breaker panel in Figure 3-6c does not show that the initial peak scaled according to the charge voltage, which may indicate that a short occurred in the test setup; nonetheless, no damage to the breaker dielectric was determined in direct observation or subsequent voltage withstand tests that would indicate arcing. There is no clear indication of the trip occurring within the measurement window.

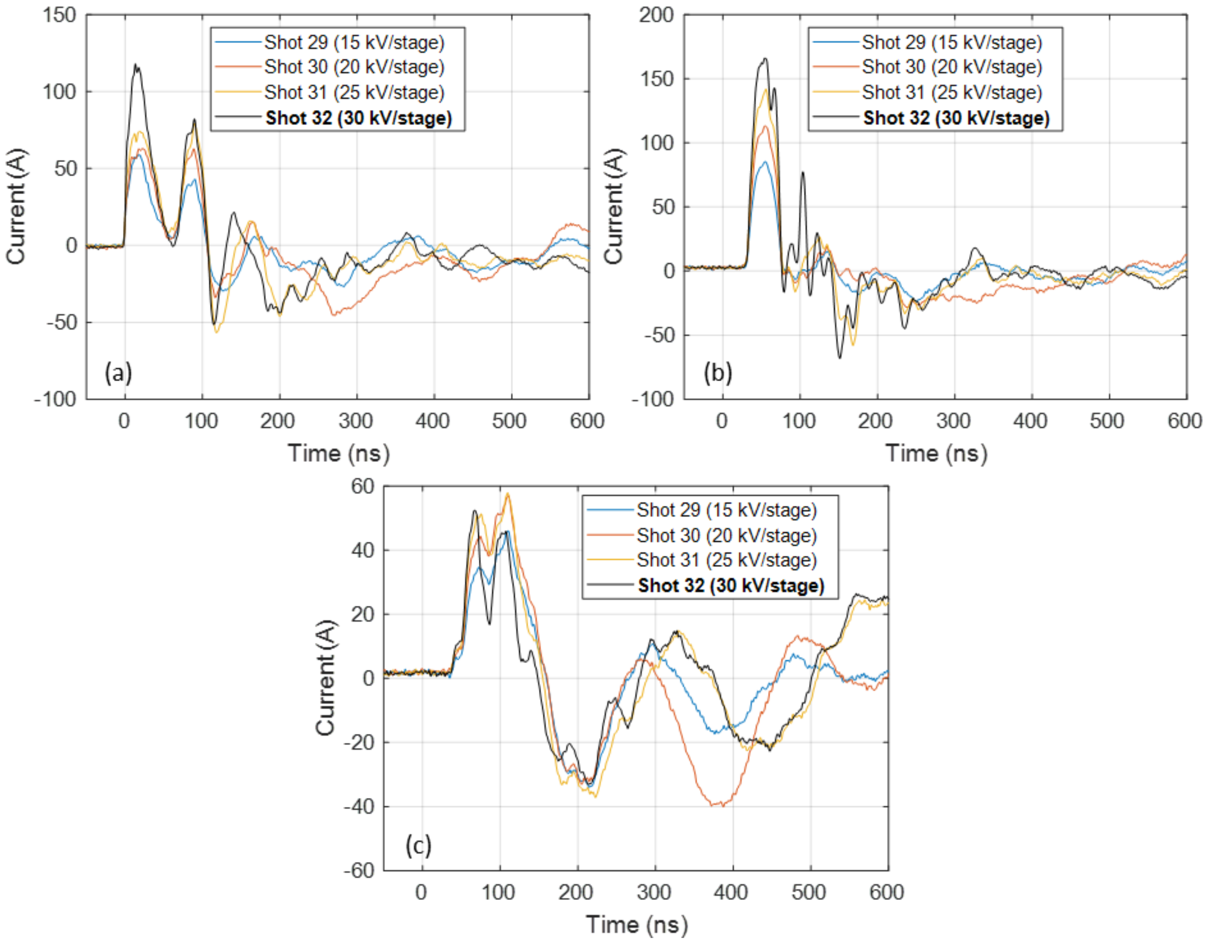

Figure 3-6. Comparison of series of shots using filter 2 on SN008 leading to breaker trip on shot 32 measuring (a) injection current (CVT #1), (b) current at breaker panel (CVT #2), and (c) current after breaker panel (CVT #3).

Additional context is gained by comparing the results of shot 32 to other shots using the same output configuration (filter 2, 30 kV/stage) on different breakers. This comparison is shown for the three CVTs in Figure 3-7. The results here for shot 32 appear to be very typical compared to other shots of the same level, and the additional oscillations identified in Figure 3-6 appear to be a result of the increasing current in the system as opposed to unique occurrences to shot 32. Any effect of the tripping breaker is not seen in the initial EMP insult since the breaker trip operation is much slower than the EMP propagation. Simultaneously, there was no observable impact on the breaker's continued operation or trip characteristics, despite the breaker tripping in response to the conducted EMP. It is notable that the trip did not occur concurrently with the highest voltage pulse on breaker SN008, but in the lower range of the voltages applied. The exact reason why shot 32 specifically tripped the breaker is not clear from the obtained data alone.

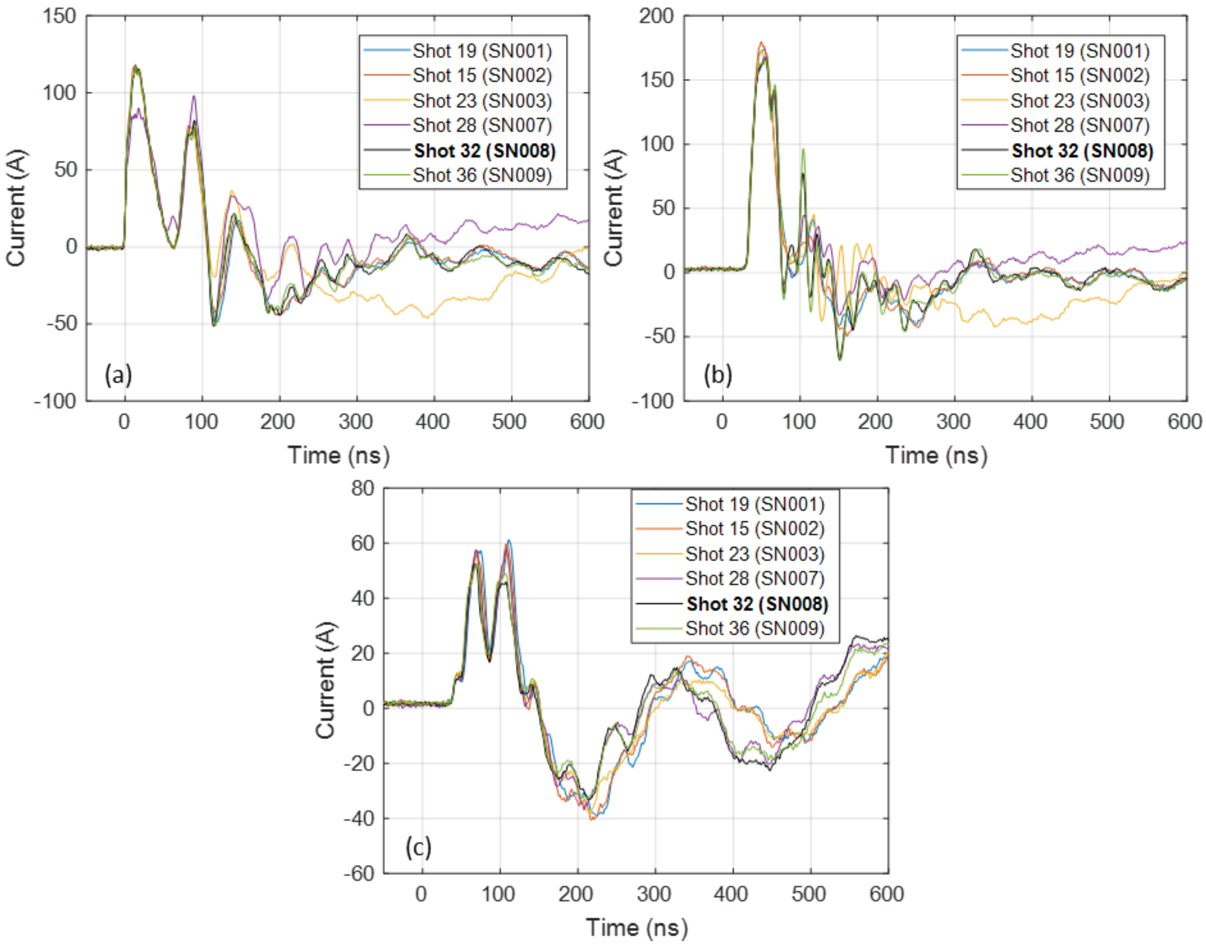

Figure 3-7. Comparison of series of shots using filter 2 and 30 kV/stage (average 51.98 kV open circuit voltage) on all 5 A, 10, A, and 20 A breakers, with the only breaker trip on shot 32, measuring (a) injection current, (b) current at breaker panel, and (c) current after breaker panel.

Shot 61 – Filter Arc Damage

Shot 61 caused an arc from phase C to the grounded chassis on the power line filter between the conducted pulser and the generator, as shown in Figure 3-8, resulting in the filter being removed from service. Testing from shot 62 onward did not have the circuit energized for all testing and switched in the generator and load banks to perform SOH checks only because the susceptibility of the generator to each conducted pulse was not known. Since the arc occurred between the generator and circuit breaker, no breaker response occurred.

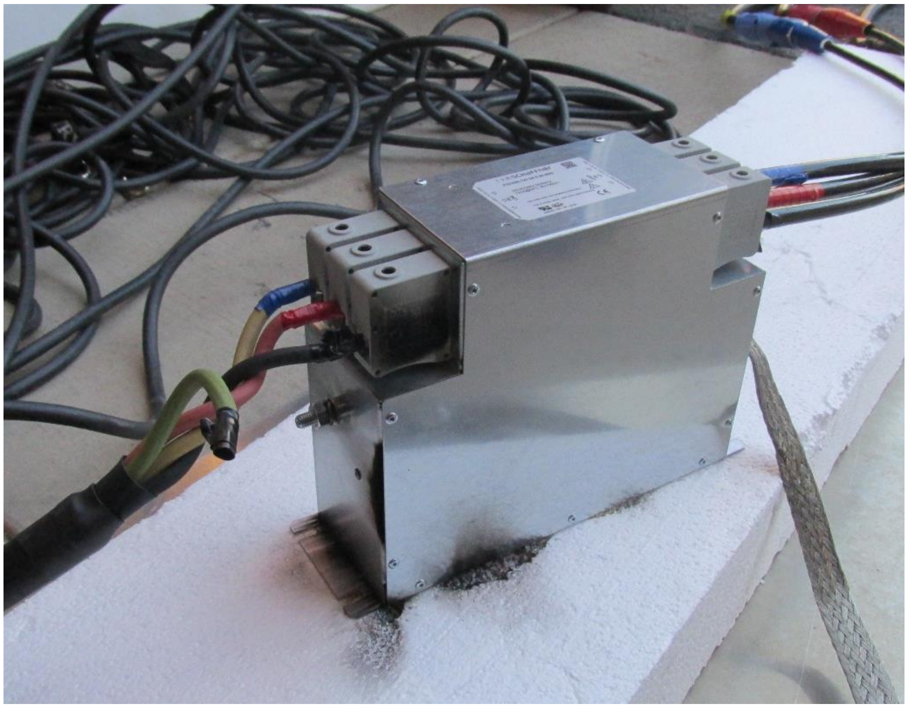

Figure 3-8. Arc damage to power line filter after shot 61.

Shots 87-113 – Potential Arcing at CVT #1 and Open Wire

During shot 113, an arc was observed from the cable being injected to CVT #1 at the midline. Subsequent troubleshooting also identified an arc from the unused wire of the 4-conductor cable to the chassis ground of the breaker panel. Assessment of the data leading up to shot 113 showed potential signs of arcing in the CVT #1 measurements as early as shot 87, and protective dielectric was applied to the setup at the two identified arcing points as shown in Figure 3-9. As a result of these discharges, the full insult reaching the breaker may not have been as high as testing with the same configuration on other breakers. Nevertheless, readings from CVT #3 show that significant impulses still passed through the breaker. Later testing with the same breakers at higher insult levels showed no indication of damage or unintended operation that might have been missed during this sequence of shots. As a result, the LV circuit breakers were still tested to the maximum value with no damage or degradation of the breakers.

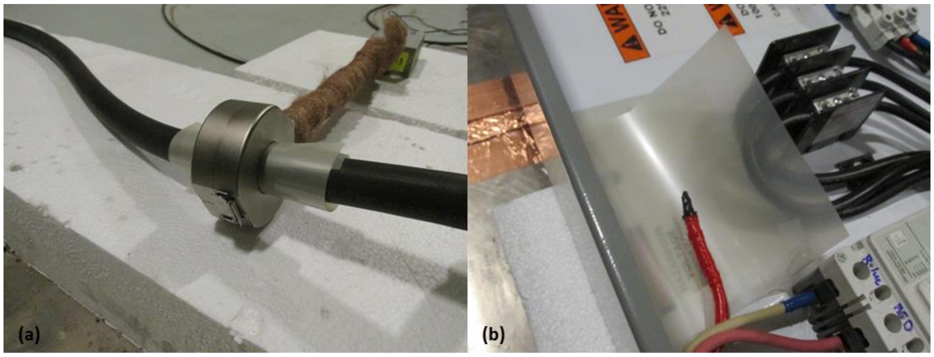

Figure 3-9. Additional insulation added to prevent arcing after shot 113.

Conclusions

Conducted EMP tests of UL489 circuit breakers were performed up to equivalent coupled open circuit voltages of 300 kV with no notable damage to the breakers or degradation in the breakers' ability to trip within manufacturer-defined parameters. Damage to the power line filters supporting the experiments occurred for one shot but did not cause the breakers to respond. None of the events noted during testing or unintended operation of the breaker constituted a violation of the UL489 standard or continued operability of the breaker. Both single phase and common mode trip behaviors were consistent across the entire test sequence aside from a single event, and all breakers passed their voltage withstand tests before and after testing. This testing far exceeds typical peak coupling values estimated to be around 80 kV on an open-terminated cable for a 50 kV/m field or 40 kV for a 25 kV/m field.

A single instance of the breaker tripping in response to the EMP insult was observed for an open circuit voltage of 54.30 kV, with the trip occurring well after the pulse had passed. This trip behavior was not replicable for other breakers tested under the same configuration or for the same breaker tested to even higher insult levels. Therefore, while there is a possibility for the breakers to trip in response to a HEMP event, it would be highly unlikely to the point of being an outlying response. Similarly, a single case of the breaker trip behavior changing after an EMP response was observed but was not replicable. Other observed effects during testing were attributed to thermal effects on the breaker from SOH tests or from arcing in the circuit away from the DUT.

Based on the above outcomes, it is highly unlikely that E1 HEMP would directly damage a circuit breaker in a typical grid installation. At the same time, circuit breakers do not offer any significant mitigation against EMP traveling through a system while they are closed, and some amount of the conducted pulse can still pass through the breakers when they are open. Additional investigation of critical components on generation facility circuits is necessary to determine what level of protection is appropriate for HEMP mitigation.

References

1. Standard for Safety – Molded-Case Circuit Breakers, Molded-Case Switches and Circuit-Breaker Enclosures, UL489, Underwriters Laboratories Inc., April 22, 2019.

2. A. Baughman, T. Bowman, R. Guttromson, M. Halligan, T. Minteer, T. Mooney, and C. Vorse, "HEMP Testing of Substation Yard Circuit Breaker Control and Protective Relay Circuits," Sandia National Laboratories, Albuquerque, NM, Rep. SAND2020-9872, September 2020.

3. "Circuit Protection Devices and Busbars," Altech Corp., [https://www.altechcorp.com/breakers/Altech-Breakers-ONLY.pdf]

4. B. J. Pierre, R. T. Guttromson, J. Eddy, R. Schiek, J. Quiroz, and M. Hoffman, "A framework to evaluate grid consequences from high altitude EMP events," Sandia National Laboratories, Albuquerque, NM, Technical Paper SAND2020-7323C, July 2020.

Appendix A: Data Tables

This section highlights details that may not be relevant to the testing result summary. The details include setup anomalies, setup deviations, protective relay settings changes, wiring changes, etc. The following subsections are organized by the date and activity.

Shot Log

The full shot log of the conducted EMP testing is detailed in Table A-1. In order of shot number, the log records the date of test, the stage voltage and resistive output filter configuration from Table 2-2, serial number and current rating of the breaker, pulser output, pulser open circuit voltage (Pulser V_{oc}) the three CVT current peaks, and the equivalent coupled open circuit voltage (Equivalent Coupled V_{oc}) from CVT #1. All breakers were rated for 240 Vac and were differentiated by the current rating. The two V_{oc} values are differentiated by Pulser V_{oc} indicating the theoretical pulser output after the resistive filter if no load circuit were present, whereas Equivalent Coupled V_{oc} indicates the voltage on the cable itself if it were terminated in an open circuit. The Equivalent Coupled V_{oc} is, by definition, double (twice) the traveling wave voltage.

Table A-1. Sequential Shot Log of All Breaker Tests

Shot #	Test Date	Stage Voltage (kV)	Output Filter	S/N	Breaker Irated (A)	Pulser Output (kV)	Pulser Voc (kV)	Injected Current, CVT #1 (A)	Equivalent Coupled Voc (kV)	Breaker Panel Current, CVT #2 (A)	Breaker Output Current, CVT #3 (A)
1	3/19	15	1	SN001	5	115.58	10.51	27.25	12.54	41.67	6.13
2	3/19	15	1	SN001	5	125.59	11.42	27.79	13.61	46.40	13.17
3	3/19	15	1	SN002	10	125.38	11.40	28.93	13.64	47.57	10.71
4	3/19	15	1	SN003	20	123.96	11.27	28.06	14.06	48.23	11.63
5	3/19	15	1	SN004	50	123.69	11.24	27.18	13.24	47.88	11.11
6	3/19	15	1	SN005	60	124.46	11.31	28.76	13.98	47.16	11.66
7	4/1	20	1	SN003	20	177.08	16.10	36.57	16.82	58.34	25.69
8	4/1	25	1	SN003	20	222.76	20.25	45.30	20.84	70.00	27.61
9	4/1	30	1	SN003	20	267.29	24.30	53.47	24.60	82.67	30.71
10	4/7	25	1	SN001	5	223.84	20.35	44.75	20.58	68.68	28.29
11	4/7	25	1	SN002	10	222.80	20.25	45.15	20.77	68.96	28.29
12	4/7	15	2	SN002	10	134.90	26.98	57.14	26.29	89.39	34.45
13	4/7	20	2	SN002	10	187.85	37.57	78.46	36.09	121.26	43.89
14	4/7	25	2	SN002	10	235.76	47.15	101.09	46.50	153.09	52.17
15	4/8	30	2	SN002	10	285.99	57.20	117.84	54.20	179.89	57.67
16	4/8	15	2	SN001	5	133.66	26.73	58.47	26.90	91.79	36.45
17	4/8	20	2	SN001	5	188.92	37.78	77.98	35.87	123.13	44.50
18	4/8	25	2	SN001	5	227.68	45.54	96.56	44.42	148.03	52.32

Shot #	Test Date	Stage Voltage (kV)	Output Filter	S/N	Breaker Irated (A)	Pulser Output (kV)	Pulser Voc (kV)	Injected Current, CVT #1 (A)	Equivalent Coupled Voc (kV)	Breaker Panel Current, CVT #2 (A)	Breaker Output Current, CVT #3 (A)
19	4/8	30	2	SN001	5	281.18	56.24	117.30	53.96	174.36	57.31
20	4/8	15	2	SN003	20	133.61	26.72	59.29	27.27	90.59	34.21
21	4/8	20	2	SN003	20	179.77	35.95	75.53	34.74	119.27	43.18
22	4/8	25	2	SN003	20	232.78	46.56	95.79	44.06	148.61	51.55
23	4/8	30	2	SN003	20	281.86	56.37	117.34	53.98	173.35	55.23
24	4/14	15	2	SN007	5	133.37	26.67	56.15	25.83	86.45	36.67
25	4/14	20	2	SN007	5	185.02	37.00	77.90	35.83	115.49	46.40
26	4/14	25	2	SN007	5	230.00	46.00	96.32	44.31	140.91	53.66
27	4/14	25	2	SN007	5	230.43	46.09	96.64	44.45	140.10	53.57
28	4/14	30	2	SN007	5	284.35	56.87	90.10	41.45	167.95	57.25
29	4/14	15	2	SN008	10	133.48	26.70	58.80	27.05	85.29	34.67
30	4/14	20	2	SN008	10	182.37	36.47	62.73	29.01	113.27	44.36
31	4/14	25	2	SN008	10	230.93	46.19	74.21	34.14	142.01	51.31
32	4/14	30	2	SN008	10	285.45	57.09	118.03	54.30	166.19	52.44
33	4/14	15	2	SN009	20	123.75	24.75	53.45	24.59	76.44	33.58
34	4/14	20	2	SN009	20	182.26	36.45	75.66	34.80	111.00	44.02
35	4/14	25	2	SN009	20	230.90	46.18	96.30	44.30	139.71	50.53
36	4/14	30	2	SN009	20	284.65	56.93	117.41	54.01	165.87	52.53
37	4/16	15	2	SN004	50	135.82	27.16	59.82	27.52	84.42	36.00
38	4/16	15	2	SN005	60	135.42	27.08	58.07	26.71	84.18	36.12
39	4/16	15	2	SN010	50	133.74	26.75	58.22	26.78	83.52	35.62
40	4/16	15	2	SN011	60	133.65	26.73	58.30	26.82	85.68	36.09
41	4/16	20	2	SN004	50	181.58	36.32	75.89	34.91	114.79	46.94
42	4/16	20	2	SN005	60	181.72	36.34	75.30	34.64	112.29	47.03
43	4/16	20	2	SN010	50	182.45	36.49	76.79	35.32	112.21	47.44
44	4/16	20	2	SN011	60	180.68	36.14	74.72	34.37	110.52	46.77
45	4/19	25	2	SN004	50	229.97	45.99	72.60	34.26	140.72	54.32
46	4/19	25	2	SN005	60	232.56	46.51	73.88	34.50	141.60	55.33
47	4/19	25	2	SN010	50	229.41	45.88	75.86	35.61	141.01	54.55
48	4/19	25	2	SN011	60	231.05	46.21	75.29	35.17	142.07	55.47
49	4/19	30	2	SN004	50	282.15	56.43	88.36	40.65	167.79	56.01
50	4/19	30	2	SN005	60	282.72	56.54	84.26	38.76	167.36	58.84
51	4/19	30	2	SN010	50	282.18	56.44	85.87	39.50	164.94	56.86
52	4/19	30	2	SN011	60	286.00	57.20	87.34	40.18	167.92	56.86
53	4/19	20	3	SN004	50	188.00	85.55	137.25	63.13	213.49	53.58
54	4/19	20	3	SN005	60	186.51	84.87	135.54	62.35	208.82	53.92
55	4/19	20	3	SN003	20	187.24	85.20	136.86	62.96	207.73	51.97
56	4/19	20	3	SN002	10	186.71	84.96	139.36	64.10	205.88	50.41
57	4/19	20	3	SN001	5	185.79	84.54	138.29	63.61	209.47	49.20
58	4/20	25	3	SN005	60	237.72	108.17	118.79	54.64	235.39	54.68
59	4/20	25	3	SN004	50	236.11	107.44	129.03	59.35	234.72	54.84

Shot #	Test Date	Stage Voltage (kV)	Output Filter	S/N	Breaker Irated (A)	Pulser Output (kV)	Pulser Voc (kV)	Injected Current, CVT #1 (A)	Equivalent Coupled Voc (kV)	Breaker Panel Current, CVT #2 (A)	Breaker Output Current, CVT #3 (A)
60	4/20	25	3	SN003	20	239.75	109.09	131.29	60.40	233.13	53.55
61	4/20	25	3	SN002	10	234.25	106.60	132.04	60.74	232.54	52.71
62	4/20	25	3	SN001	5	242.47	110.33	166.63	76.65	238.30	50.13
63	4/21	30	3	SN005	60	290.44	132.16	187.20	86.11	263.77	52.37
64	4/21	30	3	SN004	50	293.58	133.59	124.93	57.47	165.82	53.70
65	4/21	30	3	SN003	20	289.42	131.70	111.03	51.07	161.35	57.38
66	4/21	30	3	SN002	10	292.08	132.91	107.31	49.36	159.92	60.07
67	4/21	30	3	SN001	5	294.18	133.86	107.98	49.67	156.63	58.99
68	4/21	30	3	SN007	5	307.04	139.71	121.47	55.88	160.79	58.96
69	4/21	30	3	SN008	10	298.81	135.97	111.47	51.28	152.99	15.13
70	4/21	30	3	SN008	10	298.34	135.76	119.98	55.19	167.37	55.67
71	4/21	30	3	SN009	20	300.51	136.75	114.12	52.50	161.17	52.72
72	4/21	30	3	SN010	50	295.07	134.27	110.80	50.97	161.36	57.96
73	4/21	30	3	SN011	60	298.21	135.70	112.94	51.95	160.87	53.20
74	4/27	15	3	SN007	5	122.07	55.55	82.70	38.04	94.71	39.79
75	4/27	15	3	SN007	5	134.63	61.26	117.80	54.19	159.47	53.44
76	4/27	15	3	SN008	10	138.21	62.89	102.84	47.31	139.64	47.88
77	4/27	15	3	SN009	20	138.70	63.11	98.11	45.13	130.57	47.45
78	4/27	15	3	SN010	50	138.72	63.12	129.25	59.46	185.10	53.43
79	4/27	20	3	SN007	5	193.23	87.93	125.23	57.60	151.11	57.37
80	4/27	20	3	SN008	10	195.31	88.87	136.71	62.89	167.99	48.36
81	4/27	20	3	SN009	20	193.53	88.06	126.24	58.07	155.42	48.08
82	4/27	20	3	SN010	50	184.04	83.74	125.29	57.63	146.43	51.01
83	4/28	25	3	SN007	5	245.87	111.88	131.36	60.42	150.89	57.31
84	4/28	25	3	SN008	10	247.24	112.50	127.91	58.84	149.80	58.68
85	4/28	25	3	SN009	20	247.77	112.75	134.76	61.99	152.58	51.33
86	4/28	25	3	SN010	50	246.45	112.14	129.71	59.67	151.90	58.76
87	4/28	15	4	SN007	5	94.78	94.78	152.24[5]	70.03	224.79	61.62
88	4/28	15	4	SN008	10	106.46	106.46	158.77[5]	73.03	207.62	52.32
89	4/28	15	4	SN009	20	96.64	96.64	162.56[5]	74.78	228.93	57.19
90	4/28	15	4	SN010	50	94.32	94.32	162.28[5]	74.65	227.80	55.70
91	4/29	20	4	SN007	5	134.21	134.21	188.43[5]	86.68	297.59	58.15
92	4/29	20	4	SN008	10	133.99	133.99	191.29[5]	87.99	294.88	61.12
93	4/29	20	4	SN009	20	123.45	123.45	194.77[5]	89.59	270.75	63.72
94	4/29	20	4	SN009	20	134.31	134.31	192.54[5]	88.57	295.52	63.54
95	4/29	20	4	SN010	50	135.86	135.86	189.64[5]	87.24	296.30	64.47
96	4/29	25	4	SN007	5	167.12	167.12	219.17[5]	100.82	359.22	61.31
97	4/29	25	4	SN008	10	165.80	165.80	216.18[5]	99.44	359.84	65.48
98	4/29	25	4	SN009	20	165.30	165.30	216.81[5]	99.73	357.76	66.66
99	4/29	25	4	SN010	50	167.38	167.38	217.09[5]	99.86	363.51	66.56
100	5/3	30	4	SN007	5	215.79	215.79	263.72[5]	121.31	413.54	60.94

Shot #	Test Date	Stage Voltage (kV)	Output Filter	S/N	Breaker Irated (A)	Pulser Output (kV)	Pulser Voc (kV)	Injected Current, CVT #1 (A)	Equivalent Coupled Voc (kV)	Breaker Panel Current, CVT #2 (A)	Breaker Output Current, CVT #3 (A)
101	5/3	30	4	SN008	10	214.91	214.91	267.63[5]	123.11	420.22	65.67
102	5/3	30	4	SN009	20	212.08	212.08	265.09[5]	121.94	418.53	64.11
103	5/3	30	4	SN010	50	214.36	214.36	262.72[5]	120.85	415.60	67.26
104	5/5	15	4	SN001	5	90.65	90.65	148.72[5]	68.41	226.00	61.11
105	5/5	15	4	SN002	10	91.26	91.26	145.49[5]	66.92	227.36	58.74
106	5/5	15	4	SN003	20	96.26	96.26	145.51[5]	66.93	228.69	58.17
107	5/5	15	4	SN004	50	91.61	91.61	147.70[5]	67.94	227.79	57.61
108	5/5	20	4	SN001	5	134.82	134.82	357.32[5]	164.37	523.66[1]	79.48
109	5/5	20	4	SN002	10	135.36	135.36	352.96[5]	162.36	523.98[1]	81.55
110	5/5	20	4	SN003	20	135.00	135.00	350.13[5]	161.06	520.08[1]	82.46
111	5/5	20	4	SN004	50	135.38	135.38	357.48[5]	164.44	519.95[1]	83.62
112	5/5	25	4	SN001	5	172.62	172.62	448.76[5]	206.43	523.16[1]	82.16
113	5/5	25	4	SN002	10	173.04	173.04	447.80[5]	205.99	338.46[2]	28.20
114	5/7	15	3	SN005	60	170.19	77.44	119.77	55.09	204.78	53.34
115	5/7	15	3	SN011	60	222.68	101.33	123.23	56.68	202.20	49.12
116	5/7	20	3	SN005	60	254.21	115.67	167.46	77.03	275.10	55.35
117	5/7	20	3	SN011	60	233.05	106.05	169.73	78.07	278.59	52.78
118	5/7	25	3	SN005	60	330.00	150.16	220.19	101.29	348.95	58.68
119	5/7	25	3	SN011	60	247.26	112.51	219.95	101.18	347.40	57.55
120	5/7	30	3	SN005	60	378.98[3]	172.45	250.73	115.34	391.19	52.20
121	5/7	30	3	SN011	60	347.01[3]	157.90	250.73	115.34	224.98[4]	-81.97[4]
122	5/7	30	3	SN005	60	412.10[3]	187.52	250.73	115.34	220.30[4]	-86.13[4]
123	5/10	30	3	SN007	5	350.59[3]	159.53	250.73	115.34	391.19	52.20
124	5/10	30	3	SN008	10	313.93[3]	142.85	254.19	116.93	394.05	58.84
125	5/10	30	3	SN009	20	402.59[3]	183.19	255.55	117.55	392.28	61.26
126	5/10	30	3	SN010	50	360.99[3]	164.27	259.42	119.33	395.77	60.36
127	5/11	15	4	SN005	60	100.23	100.23	353.48	162.60	530.90	75.27
128	5/11	15	4	SN011	60	98.61	98.61	348.62	160.36	522.31	75.44
129	5/11	20	4	SN005	60	135.15	135.15	471.59	216.93	526.46[1]	81.81
130	5/11	20	4	SN005	60	133.19	133.19	467.08	214.86	760.98	87.04
131	5/11	20	4	SN011	60	134.79	134.79	471.03	216.68	759.88	87.06
132	5/11	25	4	SN005	60	175.32	175.32	578.40	266.06	930.81	89.64
133	5/11	25	4	SN011	60	175.32	175.32	577.08	265.46	935.00	93.28
134	5/11	30	4	SN005	60	217.91	217.91	670.06	308.23	1044.29	94.74
135	5/11	30	4	SN011	60	219.05	219.05	675.44	310.70	1043.00	95.90
136	5/12	25	4	SN007	5	176.16	176.16	584.72	268.97	929.60	92.16
137	5/12	25	4	SN010	50	178.17	178.17	587.58	270.29	934.81	94.44
138	5/12	25	4	SN009	20	176.68	176.68	589.89	271.35	928.93	89.18
139	5/12	25	4	SN008	10	177.22	177.22	584.36	268.81	933.28	85.68
140	5/12	30	4	SN007	5	218.66	218.66	669.27	307.87	1042.78	64.67
141	5/12	30	4	SN008	10	218.80	218.80	662.36	304.68	1042.74	89.78

Shot #	Test Date	Stage Voltage (kV)	Output Filter	S/N	Breaker Irated (A)	Pulser Output (kV)	Pulser Voc (kV)	Injected Current, CVT #1 (A)	Equivalent Coupled Voc (kV)	Breaker Panel Current, CVT #2 (A)	Breaker Output Current, CVT #3 (A)
142	5/12	30	4	SN009	20	220.84	220.84	665.31	306.04	1041.62	89.02
143	5/12	30	4	SN010	50	217.99	217.99	669.55	307.99	1043.72	92.67
144	5/12	25	4	SN001	5	175.68	175.68	575.97	264.95	935.89	84.80
145	5/12	25	4	SN002	10	174.21	174.21	576.40	265.15	933.50	88.49
146	5/12	25	4	SN003	20	173.00	173.00	585.03	269.11	938.52	91.90
147	5/12	25	4	SN004	50	171.68	171.68	579.46	266.55	931.93	88.47
148	5/12	30	4	SN001	5	217.73	217.73	668.06	307.31	1039.03	101.79
149	5/12	30	4	SN002	10	220.07	220.07	660.55	303.85	1041.79	92.12
150	5/12	30	4	SN003	20	220.49	220.49	665.45	306.11	1043.16	97.72
151	5/12	30	4	SN004	50	221.27	221.27	665.37	306.07	1045.50	99.65

Notes:

1. Data clipped
2. Possible misfire
3. Peaking switch discharged
4. Osciliscope triggered late
5. Possible arcing to CVT in measurements

Full SOH Log

The full SOH log for all breakers is shown in Table A-2. Columns for every SOH trip test are provided, though not every test was applied after every pulse, and SOH tests that were not performed for the shot are grayed out. In general, the individual pole trip tests were performed only at the beginning and end of testing on that breaker, with some exceptions for interim checks, while common mode tests were performed after every shot, excluding a few early shots before the 2x common mode was adopted over individual pole tests with every shot. Some shots where the SOH tests were skipped are individually noted in the table. In some instances, the trip tests were repeated for the same configuration, in which case, the additional entries are added on the next line of the same cell of the table. The trip time was defined as the amount of time between the current first exceeding its rms value (or the target current for the test) until the signal drops to zero from the breaker tripping the circuit. This calculation is accurate to within one quarter of the 60 Hz cycle, or approximately 5 ms. **Every breaker passed every application of the SOH tests.**

Table A-2. Sequential SOH Log across All Testing

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
1	3/19	5	SN001	No										1
2	3/19	5	SN001	No	30.308	24.412	25.376	23.568	3.48	3.206	3.198	3.373	Yes	2
3	3/19	10	SN002	No	16.104 16.044	14.144	15.086	15.636	1.6416	1.514	1.772	1.639	Yes	2
4	3/19	20	SN003	No	10.062	8.156	12.354		0.446	0.328	0.402	0.312	Yes	2
5	3/19	50	SN004	No	21.384	15.300	18.608	14.028	0.732 0.699	0.537	0.686	0.447	Yes	3
6	3/19	60	SN005	No	10.292	31.020	15.880	11.440	0.620	0.936	0.816	0.424	Yes	3
7	4/1	20	SN003	No	11.16	7.04	12.88		0.386	0.31	0.436	0.276		
8	4/1	20	SN003	No				5.448				0.253		
9	4/1	20	SN003	No				6.168				0.262	Yes	
10	4/7	5	SN001	No				26.216				3.585	Yes	

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
11	4/7	10	SN002	No				16.882				1.724	Yes	
12	4/7	10	SN002	No				16.972				1.703		
13	4/7	10	SN002	No				15.614				1.564		
14	4/7	10	SN002	No				15.654				0.024		
15	4/8	10	SN002	No	16.644	18.736	17.74	16.418 15.988	1.772	1.787	1.918 2.062	1.712 1.652	Yes	4
16	4/8	5	SN001	No				30.180				3.680		
17	4/8	5	SN001	No				29.636				0.012 3.771 3.761		5
18	4/8	5	SN001	No				33.312				3.918 3.911		6
19	4/8	5	SN001	No	43.050	35.840	35.410	33.000	3.857 4.264	4.005	4.030	3.895	Yes	4
20	4/8	20	SN003	No				5.980				0.276		
21	4/8	20	SN003	No				5.881				0.249		
22	4/8	20	SN003	No				5.164				0.249		
23	4/8	20	SN003	No	9.852	7.196	12.894	5.481	0.405	0.306	0.467	0.244	Yes	4
SOH	4/12	5	SN007	N/A	28.220	22.990	23.710	23.112	3.480	2.955	2.748	2.930	Yes	
SOH	4/12	10	SN008	N/A	27.676	19.896	24.748	19.376 18.708	2.397	2.012	2.18	1.941 1.996	Yes	
SOH	4/12	20	SN009	N/A	9.662	8.860	15.102	8.486	0.3844	0.357	0.528	0.325	Yes	
24	4/14	5	SN007	No				22.912				2.980		
25	4/14	5	SN007	No				23.504				2.978		6
26	4/14	5	SN007	No										7
27	4/14	5	SN007	No				25.804				3.414		
28	4/14	5	SN007	No				27.460				3.288		

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
								27.428				3.456		
29	4/14	10	SN008	No				19.176 20.536				2.034 1.995		
30	4/14	10	SN008	No				19.420				2.092		
31	4/14	10	SN008	No				18.244				2.058		
32	4/14	10	SN008	Yes				18.520				2.082		
33	4/14	20	SN009	No				7.822				0.308		
34	4/14	20	SN009	No				7.742				0.331		
35	4/14	20	SN009	No				8.120				0.322		
36	4/14	20	SN009	No				7.472				0.305		
SOH	4/15	50	SN010	N/A	14.392	20.284	15.900	16.436	0.535	0.671	0.676	0.497		
SOH	4/15	60	SN011	N/A	13.324	28.928	16.280	14.112	0.529	0.999	0.741	0.576		
37	4/16	50	SN004	No				13.656				0.5836		
38	4/16	60	SN005	No				14.928				0.5472		
39	4/16	50	SN010	No				14.588				0.5144		
40	4/16	60	SN011	No				16.624				0.4852		
41	4/16	50	SN004	No				13.924				0.5436		
42	4/16	60	SN005	No				16.524				0.5164		
43	4/16	50	SN010	No				11.004				0.4536		
44	4/16	60	SN011	No				16.096				0.4364		
45	4/19	50	SN004	No				15.116				0.548		
46	4/19	60	SN005	No				17.492				0.5428		
47	4/19	50	SN010	No				12.76				0.4144		
48	4/19	60	SN011	No				16.904				0.4508		
49	4/19	50	SN004	No				12.5				0.4776		
50	4/19	60	SN005	No				18.608				0.516		

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
51	4/19	50	SN010	No				11.244				0.4288		
52	4/19	60	SN011	No				14.38				0.462		
53	4/19	5	SN001	No				32.36				3.596		
54	4/19	10	SN002	No				17.224				1.688		
55	4/19	20	SN003	No				6.646				0.29648		
56	4/19	50	SN004	No				13.08				0.442		
57	4/19	60	SN005	No				12.044				0.4748		
58	4/20	5	SN001	No				37.872				4.062		
59	4/20	10	SN002	No				17.412				1.6948		
60	4/20	20	SN003	No				6.448				0.276		
61	4/20	50	SN004	No				15.056				0.4744		
62	4/20	60	SN005	No				10.76				0.4228		
63	4/21	5	SN001	No				37.520				4.078		
64	4/21	10	SN002	No				17.572				1.732		
65	4/21	20	SN003	No				6.493				0.278		
66	4/21	50	SN004	No				16.844				0.558		
67	4/21	60	SN005	No				12.740				0.399		
68	4/21	5	SN007	No				29.204				3.456		
69	4/21	10	SN008	No										1
70	4/21	10	SN008	No				20.768				2.156		
71	4/21	20	SN009	No				8.686				0.341		
72	4/21	50	SN010	No				16.388				0.488		
73	4/21	60	SN011	No				14.348				0.428		
74	4/27	5	SN007	No										8
75	4/27	5	SN007	No				28.844				3.473		

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
76	4/27	10	SN008	No				20.628				2.0892		
77	4/27	20	SN009	No				7.895				0.31496		
78	4/27	50	SN010	No				13.272				0.4856		
79	4/27	5	SN007	No				30.036				3.456		
80	4/27	10	SN008	No				21.128				2.1196		
81	4/27	20	SN009	No				9.615				0.33264		
82	4/27	50	SN010	No				15.16				0.518		
83	4/28	5	SN007	No				30.504				3.462		
84	4/28	10	SN008	No				21.82				2.1724		
85	4/28	20	SN009	No				8.365				0.35616		
86	4/28	50	SN010	No				12.968				0.5168		
87	4/28	5	SN007	No				29.812				3.508		
88	4/28	10	SN008	No				21.536				2.1548		
89	4/28	20	SN009	No				8.29				0.3332		
90	4/28	50	SN010	No				15.956				0.4836		
91	4/29	5	SN007	No				27.144				3.422		
92	4/29	10	SN008	No				20.98				2.1632		
93	4/29	20	SN009	No										8
94	4/29	20	SN009	No				8.338				0.332		
95	4/29	50	SN010	No				17.068				0.533		
96	4/29	5	SN007	No				28.788				3.398		
97	4/29	10	SN008	No				19.904				2.120		
98	4/29	20	SN009	No				7.593				0.314		
99	4/29	50	SN010	No				16.812				0.532		
100	5/3	5	SN007	No				29.688				3.428		

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
101	5/3	10	SN008	No				20.532				2.096		
102	5/3	20	SN009	No				8.261				0.323		
103	5/3	50	SN010	No				15.236				0.559		
104	5/5	5	SN001	No				38.204 36.600				4.044		
105	5/5	10	SN002	No				17.136				1.688		
106	5/5	20	SN003	No				6.063				0.275		
107	5/5	50	SN004	No				14.784				0.466		
108	5/5	5	SN001	No				34.99				4.017		
109	5/5	10	SN002	No				16.888				1.606		
110	5/5	20	SN003	No				6.120				0.235		
111	5/5	50	SN004	No				14.444				0.4848		
112	5/5	5	SN001	No										
113	5/5	10	SN002	No										
114	5/7	60	SN005	No				9.228				0.2044		
115	5/7	60	SN011	No				10.952				0.186		
116	5/7	60	SN005	No				8.208				0.1906		
117	5/7	60	SN011	No				9.348				0.1912		
118	5/7	60	SN005	No				10.032				0.1852		
119	5/7	60	SN011	No				11.5				0.1948		
120	5/7	60	SN005	No										9
121	5/7	60	SN011	No				10.388				0.2086		
122	5/7	60	SN005	No				8.284				0.1772		
123	5/10	5	SN007	No				28.832				3.347		
124	5/10	10	SN008	No				19.584				1.9456		
125	5/10	20	SN009	No				8.072				0.277		

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
126	5/10	50	SN010	No				12.092				0.2748		
127	5/11	60	SN005	No				11.548				0.1944		
128	5/11	60	SN011	No				14.608				0.2036		
129	5/11	60	SN005	No										8
130	5/11	60	SN005	No				10.532				0.1818		
131	5/11	60	SN011	No				12.476				0.2112		
132	5/11	60	SN005	No				10.576				0.1954		
133	5/11	60	SN011	No				14.712				0.1818		
134	5/11	60	SN005	No	10.276	27.336	18.608	11.744	0.1928	0.3168	0.2584	0.1954	Yes	
135	5/11	60	SN011	No	11.824	33.192	19.316	10.688	0.2212	0.3224	0.252	0.192	Yes	
136	5/12	5	SN007	No				29.672				3.564		
137	5/12	50	SN010	No				12.344				0.286		
138	5/12	20	SN009	No				8.645				0.27616		
139	5/12	10	SN008	No				21.396				2.0248		
140	5/12	5	SN007	No	45.02	32.1	29.31	27.124	4.771	4.028	3.387	3.436	Yes	
141	5/12	10	SN008	No	27.584	20.676	29.496	20.748	2.446	1.8624	2.0712	2.0656	Yes	
142	5/12	20	SN009	No	10.204	5.974	12.846	8.054	0.31348	0.23376	0.3632	0.283	Yes	
143	5/12	50	SN010	No	17.308	21.356	15.688	14.428	0.3008	0.2904	0.2736	0.3012	Yes	
144	5/12	5	SN001	No				37.47				3.928		
145	5/12	10	SN002	No				15.82				1.5212		
146	5/12	20	SN003	No				6.137				0.26324		
147	5/12	50	SN004	No				14.244				0.2632		
148	5/12	5	SN001	No	45.7	37.62	42.18	35.33	4.538	4.028	4.506	4.129	Yes	
149	5/12	10	SN002	No	17.248	16.98	18.216	16.876	1.512	1.696	1.7472	1.642	Yes	
150	5/12	20	SN003	No	8.644	8.178	15.53	5.519	0.3201	0.2848	0.4106	0.21392	Yes	

Shot #	Test Date	I_{rated} (A)	S/N	Trip From Shot?	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)	Passed Voltage Withstand Check?	Notes
151	5/12	50	SN004	No	25.74	13.5	18.912	15.844	0.3556	0.2576	0.3088	0.2568	Yes	

Notes:

1. Breaker was open during test
2. SN001, SN002, and SN003 were tested once before the first SOH test. Trip times were measured on 4/1.
3. SN004 and SN005 were tested once before the first SOH test. Trip times were measured on 4/15.
4. Individual pole trip times were checked on 4/12 for these shots instead of on the same day.
5. Breaker SN001 experienced a single cycle trip after shot 17. This effect was not replicable in subsequent SOH tests.
6. Following the health checks coinciding with shots 18 and 25, the breaker did not allow a manual close for a few minutes, until the breaker cooled off.
7. Load bank settings were off for shot 26; thus, shot was repeated without stopping to check SOH.
8. Due to partial discharges of the pulser on shots 74, 93, and 129, these shots were repeated without checking SOH.
9. Data was not captured for this shot due to an unexplained early trigger on the CVTs that was being diagnosed.

Sequential SOH Logs for Each Breaker

Table A-3 through Table A-12 contain the SOH trip data from Table A-2 organized by the serial number of the breaker and presented in shot order, with the injected pulse information taken from Table A-1.

Table A-3. Sequential SOH Log for SN001, 5 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
2	29.58	13.61	30.308	24.412	25.376	23.568	3.480	3.206	3.198	3.373
10	44.75	20.58				26.216				3.585
16	58.47	26.90				30.180				3.680
17	77.98	35.87				29.636				0.012 3.771 3.761
18	96.56	44.42				33.312				3.918 3.911
19	117.30	53.96	43.050	35.840	35.410	33.000	3.857 4.264	4.005	4.030	3.895
53	137.25	63.13				32.360				3.596
58	118.79	54.64				37.872				4.062
63	187.20	86.11				37.520				4.078
104	148.72	68.41				38.204 36.600				4.044
108	357.32	164.37				34.990				4.017
144	575.97	264.95				37.470				3.928
148	668.06	307.31	45.700	37.620	42.180	35.330	4.538	4.028	4.506	4.129

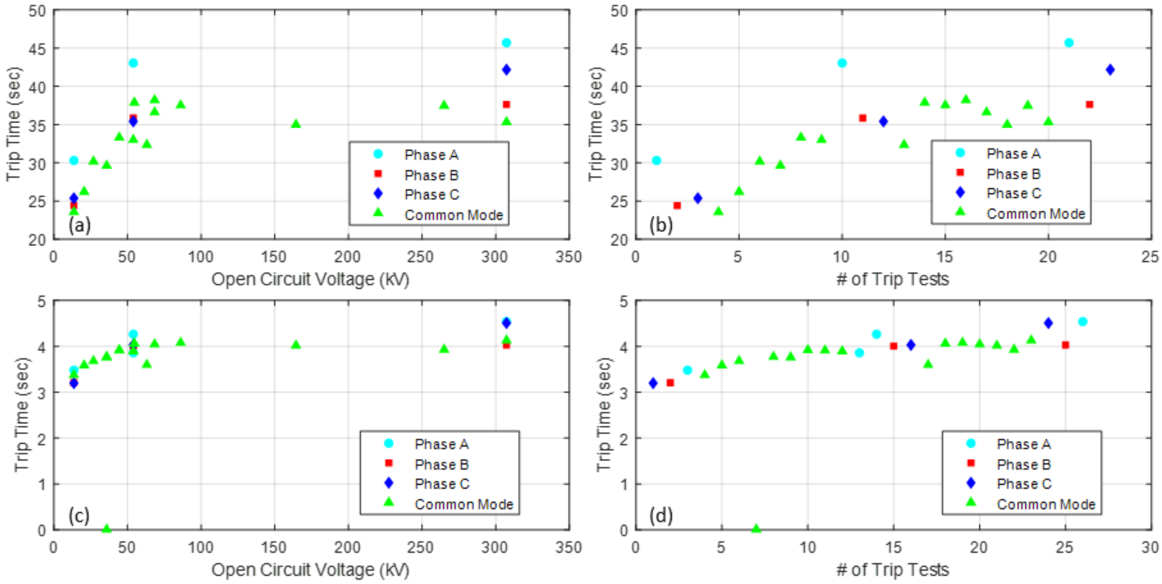

Figure A-1. SN001 trip responses at (a) 2x Irated versus previous shot voltage, (b) 2x Irated versus number of trips, (c) 10x Irated versus previous shot voltage, and (d) 10x Irated versus number of trips.

Table A-4. Sequential SOH Log for SN002, 10 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
3	29.64	13.64	16.104 16.044	14.144	15.086	15.636	1.642	1.514	1.772	1.639
11	45.15	20.77				16.882				1.724
12	57.14	26.29				16.972				1.703
13	78.46	36.09				15.614				1.564
14	101.09	46.50	16.644	18.736	17.740	15.654	1.772	1.787	1.918 2.062	0.024
15	117.84	54.20				16.418 15.988				1.712 1.615
54	135.54	62.35				17.224				1.688
59	129.03	59.35				17.412				1.695
64	124.93	57.47				17.572				1.732
105	145.49	66.92				17.136				1.688
109	352.96	162.36				16.888				1.606
145	576.40	265.15				15.820				1.521
149	660.55	303.85	17.248	16.980	18.216	16.876	1.512	1.696	1.747	1.642

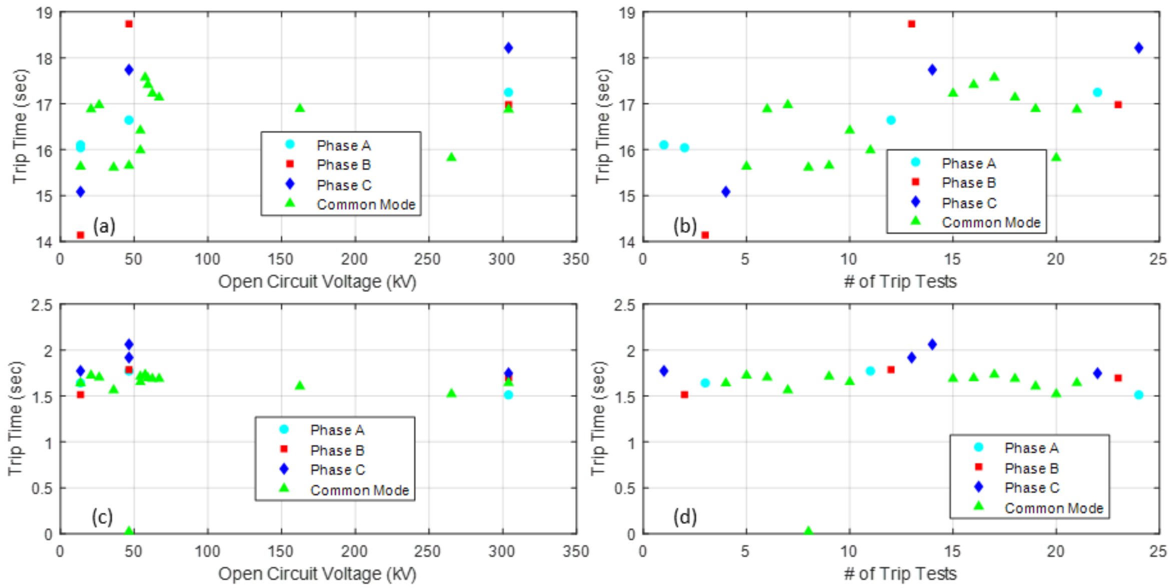

Figure A-2. SN002 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-5. Sequential SOH Log for SN003, 20 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
4	30.57	14.06	10.062	8.156	12.354		0.446	0.328	0.402	0.312
7	36.57	16.82	11.160	7.040	12.880		0.386	0.310	0.436	0.276
8	45.30	20.84				5.448				0.253
9	53.47	24.60				6.168				0.262
20	59.29	27.27				5.980				0.276
21	75.53	34.74				5.881				0.249
22	95.79	44.06				5.164				0.249
23	117.34	53.98	9.852	7.196	12.894	5.481	0.405	0.306	0.467	0.244
55	136.86	62.96				6.646				0.296
60	131.29	60.40				6.448				0.276
65	111.03	51.07				6.493				0.278
106	145.51	66.93				6.063				0.275
110	350.13	161.06				6.120				0.235
146	585.03	269.11				6.137				0.263
150	665.45	306.11	8.644	8.178	15.530	5.519	0.320	0.285	0.411	0.214

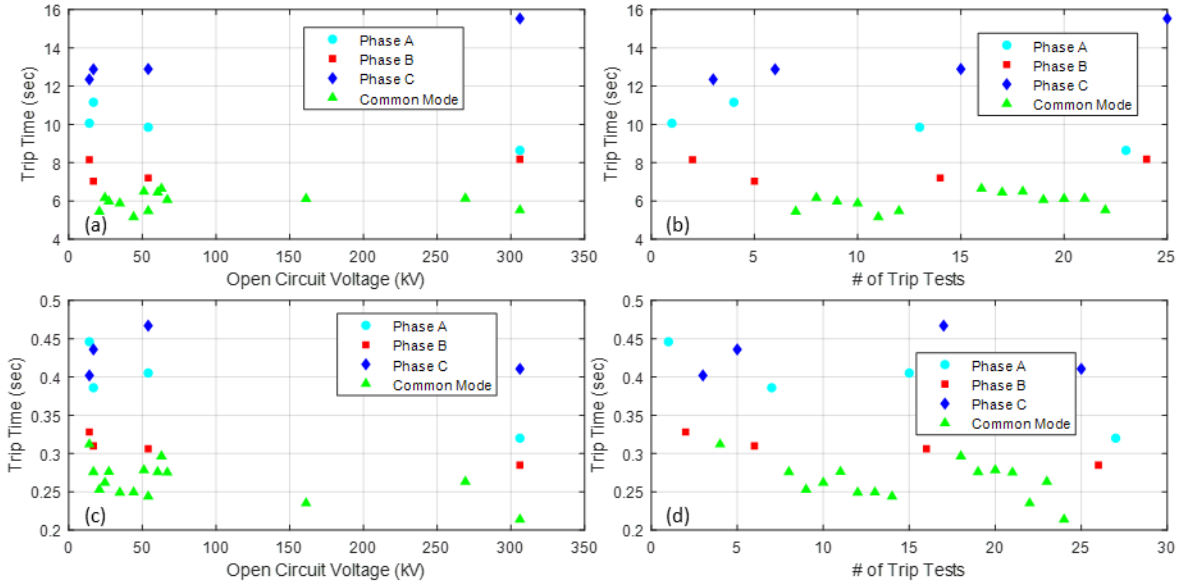

Figure A-3. SN003 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-6. Sequential SOH Log for SN004, 50 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
5	28.79	13.24	21.384	15.300	18.608	14.028	0.732 0.699	0.537	0.686	0.447
37	59.82	27.52				13.656				0.584
41	75.89	34.91				13.924				0.544
45	74.47	34.26				15.116				0.548
49	88.36	40.65				12.500				0.478
56	139.36	64.10				13.080				0.442
61	132.04	60.74				15.056				0.474
66	107.31	49.36				16.844				0.558
107	147.70	67.94				14.784				0.466
111	357.48	164.44				14.444				0.485
147	579.46	266.55				14.244				0.263
151	665.37	306.07	25.740	13.500	18.912	15.844	0.356	0.258	0.309	0.257

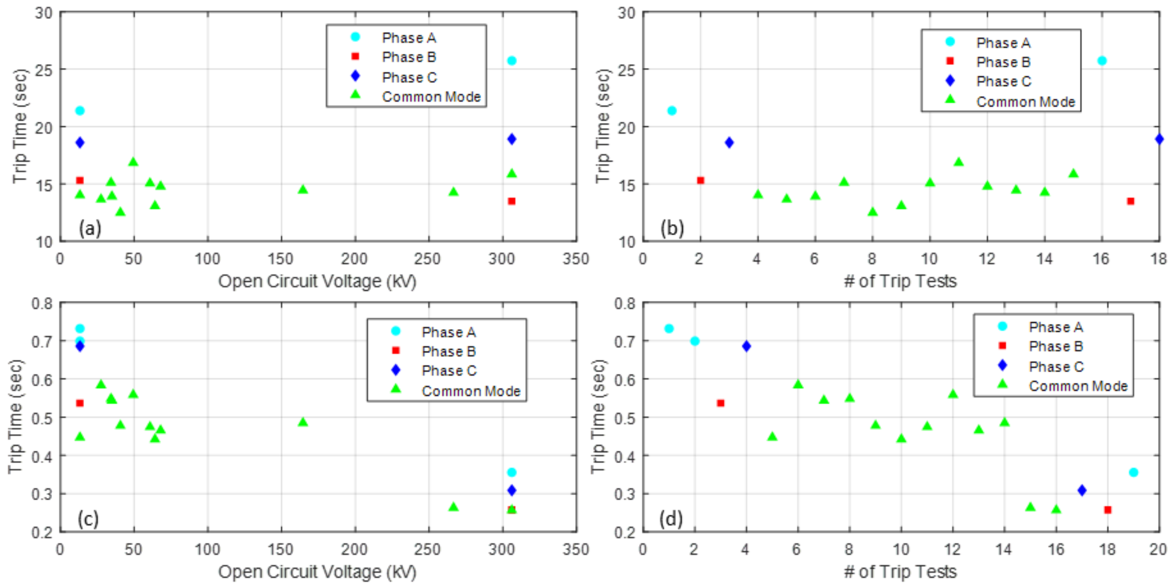

Figure A-4. SN004 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-7. Sequential SOH Log for SN005, 60 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
6	30.39	13.98	10.292	31.020	15.880	11.440	0.620	0.936	0.816	0.424
38	58.07	26.71				14.928				0.547
42	75.30	34.64				16.524				0.516
46	75.01	34.50				17.492				0.543
50	84.26	38.76				18.608				0.516
57	138.29	63.61				12.044				0.475
62	166.63	76.65				10.760				0.423
67	107.98	49.67				12.740				0.399
114	119.77	55.09				9.228				0.204
116	167.46	77.03				8.208				0.191
118	220.19	101.29				10.032				0.185
122	250.73	115.34				8.284				0.177
127	353.48	162.60				11.548				0.194
130	467.08	214.86				10.532				0.182
132	578.40	266.06				10.576				0.195
134	670.06	308.23	10.276	27.336	18.608	11.744	0.193	0.317	0.258	0.195

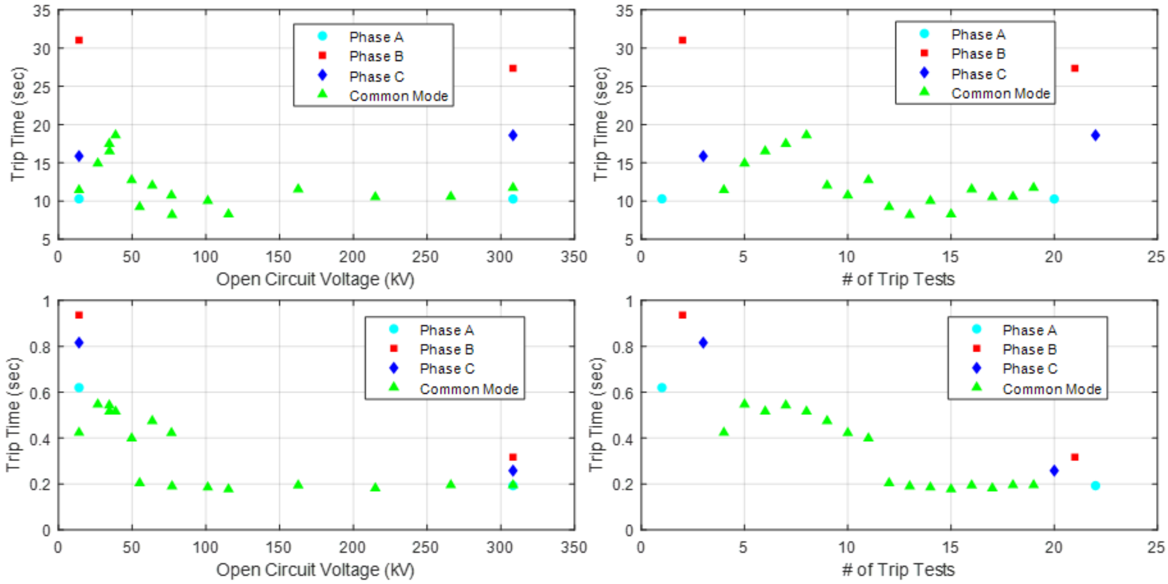

Figure A-5. SN005 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-8. Sequential SOH Log for SN007, 5 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
SOH	N/A	N/A	28.220	22.990	23.710	23.112	3.480	2.955	2.748	2.930
24	56.15	25.83				22.912				2.980
25	77.90	35.83				23.504				2.978
27	96.64	44.45				25.804				3.414
28	90.10	41.45				27.460 27.428				3.288 3.456
68	121.47	55.88				29.204				3.456
75	117.80	54.19				28.844				3.473
79	125.23	57.60				30.036				3.456
83	131.36	60.42				30.504				3.462
87	152.24	70.03				29.812				3.508
91	188.43	86.68				27.144				3.422
96	219.17	100.82				28.788				3.398
100	263.72	121.31				29.688				3.428
123	250.73	115.34				28.832				3.347
136	584.72	268.97				29.672				3.564
140	669.27	307.87	45.020	32.100	29.310	27.124	4.771	4.028	3.387	3.436

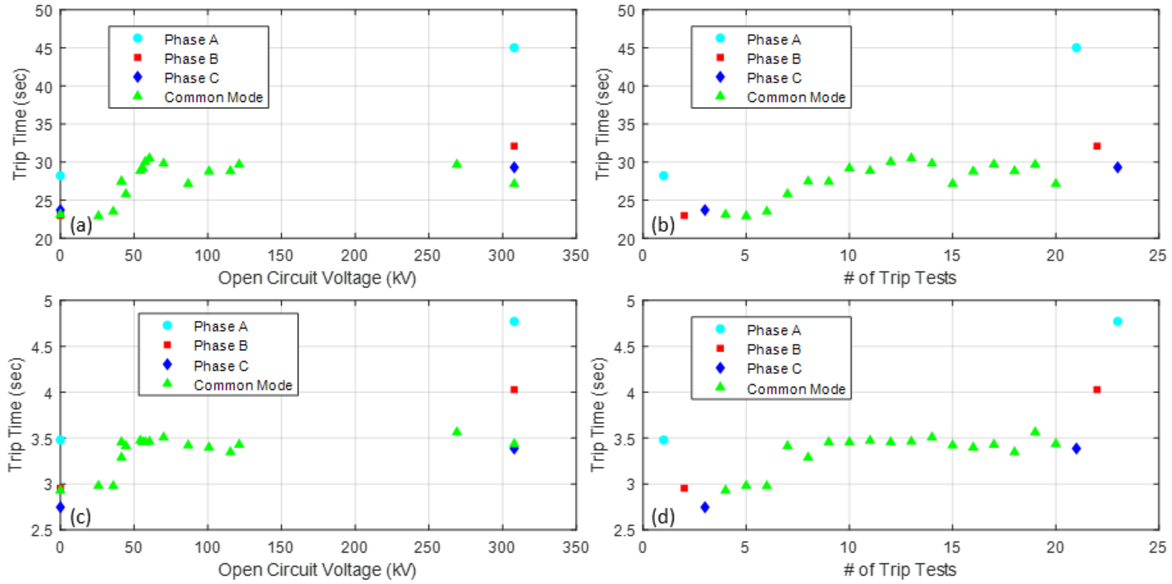

Figure A-6. SN007 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-9. Sequential SOH Log for SN008, 10 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
SOH	N/A	N/A	27.676	19.896	24.748	19.376 18.708	2.397	2.012	2.180	1.941 1.996
29	58.80	27.05				19.176 20.536				2.034 1.995
30	63.06	29.01				19.420				2.092
31	74.21	34.14				18.244				2.058
32	118.03	54.30				18.520				2.082
70	119.98	55.19				20.768				2.156
76	102.84	47.31				20.628				2.089
80	136.71	62.89				21.128				2.120
84	127.91	58.84				21.820				2.172
88	158.77	73.03				21.536				2.155
92	191.29	87.99				20.980				2.163
97	216.18	99.44				19.904				2.120
101	267.63	123.11				20.532				2.096
124	254.19	116.93				19.584				1.946
139	584.36	268.81				21.396				2.025
141	662.36	304.68	27.584	20.676	29.496	20.748	2.446	1.862	2.071	2.066

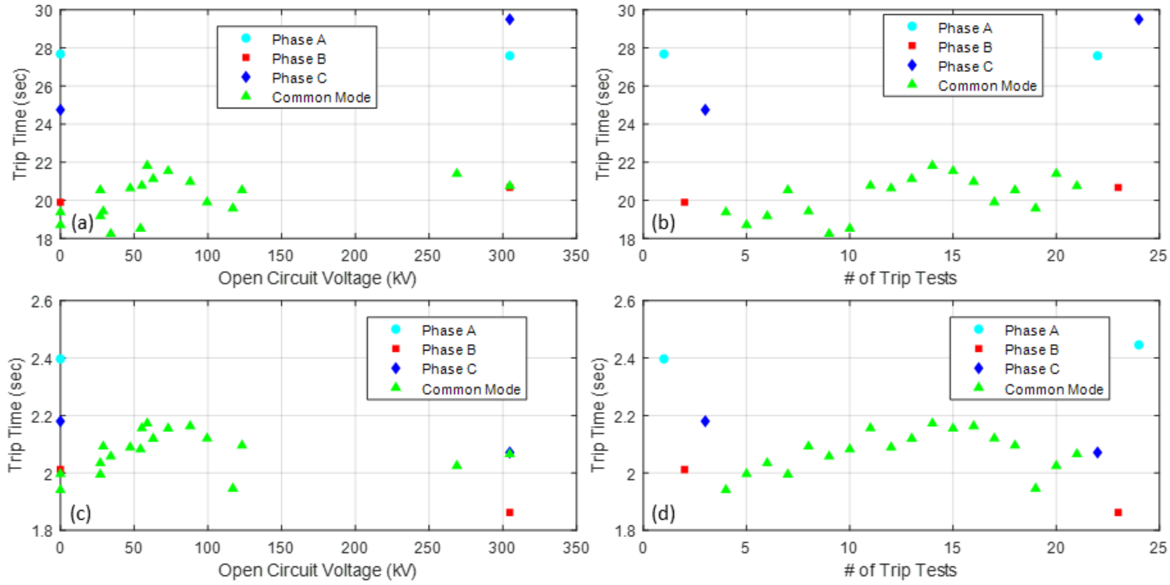

Figure A-7. SN008 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-10. Sequential SOH Log for SN009, 20 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
SOH	N/A	N/A	9.662	8.860	15.102	8.486	0.384	0.357	0.528	0.325
33	53.45	24.59				7.822				0.308
34	75.66	34.80				7.742				0.331
35	96.30	44.30				8.120				0.322
36	117.41	54.01				7.472				0.305
71	114.12	52.50				8.686				0.341
77	98.11	45.13				7.895				0.315
81	126.24	58.07				9.615				0.333
85	134.76	61.99				8.365				0.356
89	162.56	74.78				8.290				0.333
94	192.54	88.57				8.338				0.332
98	216.81	99.73				7.593				0.314
102	265.09	121.94				8.261				0.323
125	255.55	117.55				8.072				0.277
138	589.89	271.35				8.645				0.276
142	665.31	306.04	10.204	5.974	12.846	8.054	0.313	0.234	0.363	0.283

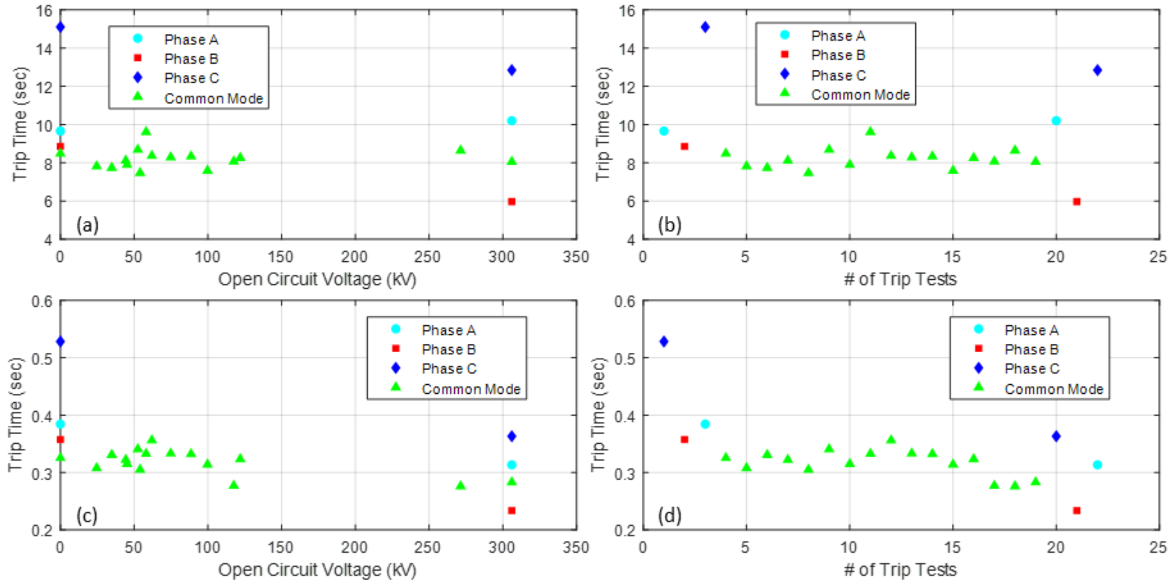

Figure A-8. SN009 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-11. Sequential SOH Log for SN010, 50 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
SOH	N/A	N/A	14.392	20.284	15.900	16.436	0.535	0.671	0.676	0.497
39	58.22	26.78				14.588				0.514
43	76.79	35.32				11.004				0.454
47	77.41	35.61				12.760				0.414
51	85.87	39.50				11.244				0.429
72	110.80	50.97				16.388				0.488
78	129.25	59.46				13.272				0.486
82	125.29	57.63				15.160				0.518
86	129.71	59.67				12.968				0.517
90	162.28	74.65				15.956				0.484
95	189.64	87.24				17.068				0.533
99	217.09	99.86				16.812				0.532
103	262.72	120.85				15.236				0.559
126	259.42	119.33				12.092				0.275
137	587.58	270.29				12.344				0.286
143	669.55	307.99	17.308	21.356	15.688	14.428	0.301	0.290	0.274	0.301

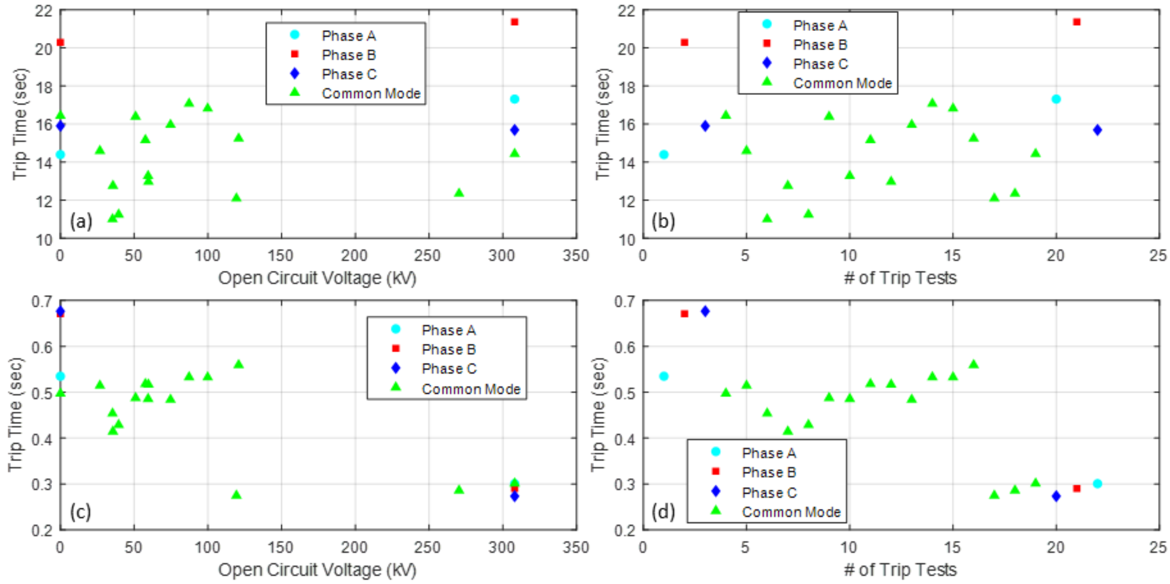

Figure A-9. SN010 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Table A-12. Sequential SOH Log for SN011, 60 A breaker

Shot #	Injected Current (A)	Equivalent Coupled V_{oc} (kV)	2x I_{rated} A Pole Trip (s)	2x I_{rated} B Pole Trip (s)	2x I_{rated} C Pole Trip (s)	2x I_{rated} Common Trip (s)	10x I_{rated} A Pole Trip (s)	10x I_{rated} B Pole Trip (s)	10x I_{rated} C Pole Trip (s)	10x I_{rated} Common Trip (s)
SOH	N/A	N/A	13.324	28.928	16.280	14.112	0.529	0.999	0.741	0.576
40	58.30	26.82				16.624				0.485
44	74.72	34.37				16.096				0.436
48	76.46	35.17				16.904				0.451
52	87.34	40.18				14.380				0.462
73	112.94	51.95				14.348				0.428
115	123.23	56.68				10.952				0.186
117	169.73	78.07				9.348				0.191
119	219.95	101.18				11.500				0.195
121	250.73	115.34				10.388				0.209
128	348.62	160.36				14.608				0.204
131	471.03	216.68				12.476				0.211
133	577.08	265.46				14.712				0.182
135	675.44	310.70	11.824	33.192	19.316	10.688	0.221	0.322	0.252	0.192

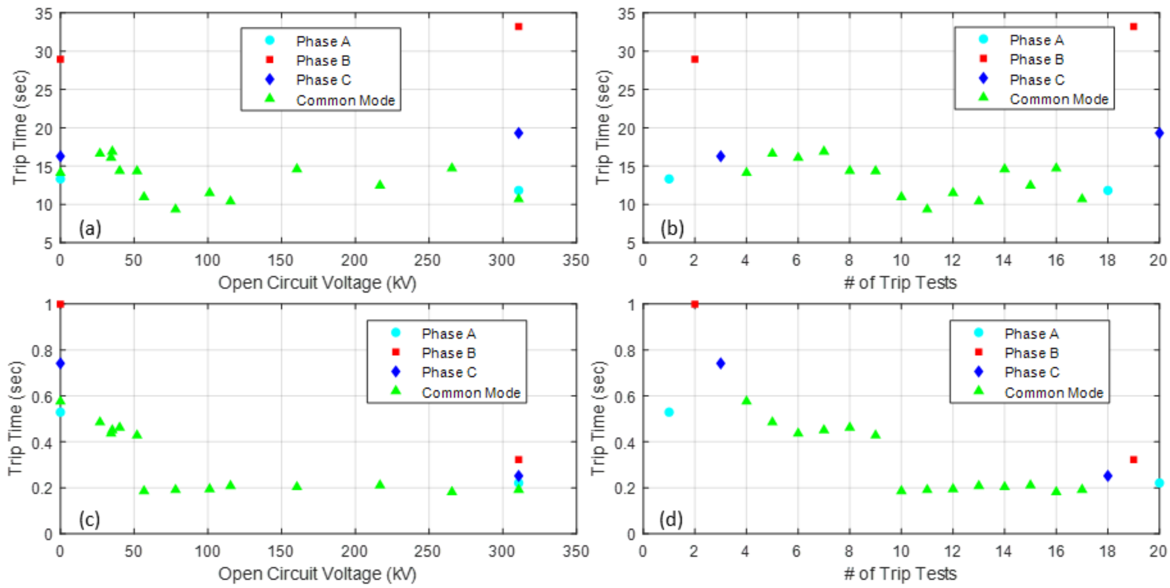

Figure A-10. SN011 trip responses at (a) 2x I_{rated} versus previous shot voltage, (b) 2x I_{rated} versus number of trips, (c) 10x I_{rated} versus previous shot voltage, and (d) 10x I_{rated} versus number of trips.

Appendix B: SOH Tests

SOH Justification

The circuit breaker SOH was defined based on the Z-sequence of testing listed in UL489 [1] with modifications to the process based on feedback from Altech engineers and experimental needs. The UL489 Z-sequence is defined as follows:

1. 200% calibration test at 25 °C
    a. 2x rated current
    b. All poles tested individually
    c. Pass criteria: breaker trips within maximum trip times for current rating:
        i. 0 – 30 A: 2 minutes
        ii. 31 – 50 A: 4 minutes
        iii. 51 – 100 A: 6 minutes
2. Interrupting test
    a. Short circuit current capacity exceeding 5 kA
    b. Limiting impedances in-line with breaker inputs and outputs shorted
    c. Cotton indicator around breaker switch
    d. Test sequence:
        i. All poles tested individually switching circuit on with breaker closed
        ii. All poles tested individually switching breaker closed on energized circuit
        iii. Common mode test switching circuit on with breaker closed
        iv. 2 minutes between every test
    e. Pass criteria: breaker trips according to trip times defined by the breaker manufacturers
3. 200% trip-out at 25 °C
    a. Same as the calibration test
4. Dielectric voltage withstand

a. 2x rated voltage (240 Vac) plus 1000 V applied across breaker dielectric for 1 minute
    i. Each pole input to output with breaker open
    ii. Each pole to adjacent poles with breaker closed
    iii. Each pole to ground metal with breaker closed
b. Pass criteria: no current detected from high voltage supply

Following discussion with engineering contacts at Altech, the following compromises to the SOH justification were made to the interrupting test above:

- 10x rated current used instead of 5 kA short circuit current. This level is sufficient to check the magnetic trip response instead of the thermal response addressed by the 200% calibration test.
- Impedance controlled by load bank.
- No cotton indicator used.
- Switching breaker into live circuit was not done for electrical safety concerns.

Following the initial set of tests and discussion with DOE, the following adjustments were made to the frequency of the SOH tests:

- 2x rated current individual pole testing reduced to the beginning and end of the overall test sequence.
- 2x rated current common mode test replaced individual pole testing between shots.
- 10x rated current individual pole testing reduced to the beginning and end of the overall test sequence.
- 200% trip-out test not performed.
- Dielectric voltage withstand test reduced to the beginning and end of the overall test sequence. A 1500 Vdc source was used instead of 1500 Vac rms.

SOH Steps

The full SOH sequence is defined below. Certain steps were defined as being performed only at the beginning and end of the test sequence, and are denoted as part of the sequence. The remaining steps were performed between every shot of the pulser.

1. Open the breaker panel and inspect for visual damage or tracking on the circuit breaker exterior.

   a. If any arc was heard at the breaker panel during testing, indicate this in the shot logs even if no physical damage is observed. Direct visual observation of the breaker is unlikely during testing given the closed breaker panel.
2. Record whether the breaker tripped during the pulsed test.
   a. If breaker tripped, close breaker and confirm that it does not trip at 0.9x rated current for 1000 seconds.
3. Disconnect the EMF filters and connect the parallel circuit to connect the generator directly to the circuit breakers and load.
4. 2x Rated Current Test
   a. <u>Test Series Beginning/End Only:</u> Connect a single pole of the breaker under test to one of the generator phases, leaving two of the breaker poles unconnected to the source. Connect one phase of the load bank to the output of the breaker pole being tested, and the other two load phases directly to the remaining generator phases, bypassing the breaker under test.
   b. Apply 2x rated current. Confirm that the breaker trips within the acceptable trip curve values defined by Altech in Figure 2-15.
   c. <u>Test Series Beginning/End Only:</u> Repeat Step 4b for the remaining poles of the same breaker. Allow 2 minutes of cooldown between trip tests.
   d. Connect all three poles in parallel and repeat the 2x rated current test.

      NOTE: This is the only configuration of this test performed between individual shots in the middle of the test series.
5. 10x Rated Current Test
   a. <u>Test Series Beginning/End Only:</u> Connect a single pole of the breaker under test to one of the generator phases, leaving two of the breaker poles unconnected to the source. Connect one phase of the load bank to the output of the breaker pole being tested, and the other two load phases directly to the remaining generator phases, bypassing the breaker under test.
   b. Apply 10x rated current. Confirm that the breaker trips within the acceptable trip curve values defined by Altech in Figure 2-15.
   c. <u>Test Series Beginning/End Only:</u> Repeat Step 5b for the remaining poles of the same breaker. Allow 2 minutes of cooldown between trip tests.
   d. Connect all three poles in parallel and repeat the 10x rated current test.

NOTE: This is the only configuration of this test performed between individual shots in the middle of the test series.

6. <u>Test Series Beginning/End Only:</u> Voltage Withstand Test
    a. Disconnect the breaker from the generator/load cables and open the breaker.
    b. Using a high voltage supply for breaker poles I1-I2-I3, apply 1500 Vdc for 1 minute:
        i. With breaker open
            1. I1 input to I1 output
            2. I2 input to I2 output
            3. I3 input to I3 output
        ii. With breaker closed
            1. I1 input to I2 input
            2. I2 input to I3 input
            3. I1 input to grounded panel chassis
            4. I2 input to grounded panel chassis
            5. I3 input to grounded panel chassis
    c. Check that closed impedance of breaker falls within multimeter precision limits for short circuit (≤0.2 Ω) and that the open breaker reads as an open circuit.
    d. Reconnect the breaker.
7. Manual Trip
    a. Confirm that the breaker opens and closes fully.
8. Reconnect the EMF filter

In the case of breaker failures, breaker casings would have been opened for diagnostics and determination of the reason for failure. However, no failures were identified in the course of testing, and therefore, no destructive evaluation of the breakers was performed.