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NUREG/CR-7229

Testing to Evaluate Battery and Battery Charger Short-Circuit Current Contributions to a Fault on the DC Distribution System

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ABSTRACT

On September 25, 2011, at the Palisades Nuclear Plant, both the battery and the battery charger on one DC Class 1E power division tripped on overcurrent when a fault occurred in a downstream DC panel (see NRC Information Notice 2013-17). The response to a fault on the DC distribution system at a nuclear power plant (NPP) can have a significant impact as seen by this event. Therefore, it is necessary to have proper DC fault calculations to design effective DC system fault protection with coordination that would minimize safety system impacts in a fault event. As a result of the significance, the U.S. Nuclear Regulatory Commission (NRC) contracted with Brookhaven National Laboratory (BNL) to investigate the interactions between a battery and a battery charger under fault conditions at the BNL Battery Test Facility. More specifically, BNL conducted tests to determine whether the individual short-circuit current contributions of a battery and a battery charger are independent of each other in a typical NPP DC system configuration. This information is necessary to ensure understanding of the fault characteristics of batteries and chargers individually and in parallel as described in the Institute of Electrical and Electronic Engineers (IEEE) Standard (Std.) 946-2004, “IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations.” The results conducted at BNL provide the empirical data to support improvements to industry standards and to the NRC’s oversight of DC distribution systems.

BNL used three sets of Class 1E vented lead acid batteries from three different vendors and two battery chargers: one a Silicon Controlled Rectifier (SCR)-type and one a Controlled Ferroresonant (CF) transformer design. A fault condition was applied to each battery and charger individually and to combinations of each battery in parallel with a battery charger to determine the overall fault responses in these configurations.

This report discusses the potential implications on how protective coordination is approached in NPP DC distribution systems and how a fault on the DC distribution system can impact plant operation. The testing demonstrated that the contribution to a fault from a battery charger and the impedance of the DC system circuit should be considered when establishing the settings for the DC distribution system protective devices. Incorrect settings of these protective devices can lead to undesirable system responses.

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The testing performed at the BNL Battery Test Facility used three Class 1E battery strings and two battery chargers: (1) a Silicon Controlled Rectifier (SCR) type and (2) a Controlled Ferroresonant (CF) transformer type. The three nuclear-qualified batteries from three different vendors are representative of the battery models used in more than 75% of the current NPPs in the United States. The SCR and CF battery chargers represent about 90% of the battery charger designs used in the current U.S. NPPs.

The primary objective of this testing was to determine whether the individual short-circuit current contributions to the downstream fault by the battery charger and the battery are independent of each other or whether they are influenced when the battery and the battery charger are connected in parallel. This is important to know so that the fault current can be properly calculated, and DC system fault protection circuits can be designed such that a fault on the DC system can be isolated as close to the location of the fault as possible, thereby minimizing the impact on plant operations and safety.

A series of short-circuit tests were conducted on each of the battery strings and each of the battery chargers individually to determine their response to a fault. Tests were then conducted with each of the battery strings connected in parallel to each one of the battery chargers. These tests provided new information about how this equipment would respond to a fault when connected in the configuration commonly used in NPPs.

Prior to conducting this testing, BNL completed a detailed review of the literature associated with DC system faults and its effects, including industry standards that provide guidance on how to manage and minimize the effects of these faults. As documented in a BNL Technical Report [1], some of the guidance is conflicting and little of it is based on published empirical data. As a result, the lack of a standard method for approaching the short-circuit protection and coordination of DC distribution system protective devices could lead to different settings for protective devices and different plant responses to a fault on the DC distribution system. The results from this testing program provide the empirical data to minimize the impact of a DC system fault on plant operations and safety, as well as support improvements to industry standards and to the NRC's oversight of DC distribution system protective coordination.

The key observations of the test report are:

1. The measured short-circuit current contributions from the battery compared favorably to the calculated short-circuit current of the batteries using the methodology contained in IEEE Standard 946-2004. The magnitude of the battery currents obtained in this testing were much less than the rule-of-thumb values that estimate the current contribution from a short that occurs at the battery terminals illustrating the importance of including the DC circuit impedance when performing fault calculations for protection system coordination.

2. The battery chargers were able to sustain a 2-second (2000 milliseconds) fault without tripping when tested individually or when connected in parallel to a battery. The 100A-rated SCR charger produced a short-circuit current of 930A and the 100A-rated CF charger produced a short-circuit current of 1246A when tested without a connected battery. The maximum short-circuit contribution from the SCR charger decreased to approximately 700A when connected to each of the three battery strings while the CF charger's maximum short-circuit contribution decreased to about 1150A when connected to a battery. This response is different than what is provided in IEEE 946-2004, which states that when a battery charger is connected in parallel with a battery, the battery capacitance will limit the maximum current from the charger to the current limit value of the charger (110A for the chargers used in the tests).

3. The series of short-circuit tests on each of the three battery strings with each of the two types of battery chargers illustrated that the total short-circuit current in the first 100 milliseconds is impacted by the contribution from the charger, more significantly with the SCR type than the CF type. The main reason for the difference is that the CF charger current limit was achieved within 30 milliseconds, well before the battery reached its maximum short-circuit current. The SCR charger required about 300 milliseconds to achieve its current limit. Therefore, the SCR charger contributes more to the total short-circuit current during the first 100 milliseconds following a fault event.

4. When the short circuit was applied to a battery, either individually or in parallel with the battery charger, the output voltage decreased and remained low for as long as the short circuit was applied. The individual cell voltage decreased from about 2.2 volts to 1.0 volt or less for all three battery strings. For a typical 60-cell string operating at 130 volts in a NPP, this would mean a reduction in the voltage on the DC bus to less than 50 volts during the fault, low enough to potentially cause other DC power supplies or inverters to trip due to their under-voltage protection. If that were to occur, a disruption to important instrumentation and controls is likely. Following the removal of the fault, the battery voltage will recover if the battery charger is available to carry the DC load and recharge the battery. If the battery charger trips during the fault (which occurred at Palisades but not during the testing at BNL), the operator needs to recognize that the DC bus voltage will be lower than it was prior to the fault event. Follow-on testing was performed to examine the battery voltage response with shorter fault durations that are representative of typical circuit breaker clearing times. The test demonstrated that the battery voltage decreased to approximately the same value as the 2-second faults, but the post-fault battery voltage was higher for the short duration tests. (See Figures 2-5 and 2-6.)

5. No apparent damage to the battery or the battery chargers was detected because of the short-circuit testing. The recharge of the battery following a 2-second short-circuit was accomplished in less than one hour. This indicates that following a fault, the battery will still have sufficient charge to perform its design function.

The empirical data obtained from this testing will be useful to the revision of IEEE Standards that provide guidance on the short circuit response of batteries and battery chargers in DC distribution systems. IEEE Standard 946-2004 and IEEE Standard 1375-1998 contain statements which have assumptions that are not supported by this testing. These standards are used by the nuclear industry but have not been endorsed by the NRC. The data obtained from this testing will assist the NRC staff during the development and issuance of a Regulatory Guide endorsing these standards with appropriate NRC staff condition/limitations (or exceptions) as needed.

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ACRONYMS

AC	Alternating Current
BNL	Brookhaven National Laboratory
CF	Controlled Ferroresonant Type Battery Charger
CT	Current Transformer
DC	Direct Current
IEEE	Institute of Electrical and Electronic Engineers
NFPA	National Fire Protection Association
NPP	Nuclear Power Plants
NRC	U.S. Nuclear Regulatory Commission
SCR	Silicon Controlled Rectifier Type Battery Charger
SIT	Special Inspection Team

1 INTRODUCTION

On September 25, 2011, at the Palisades Nuclear Plant, both the battery and the battery charger tripped on overcurrent on one Class 1E Division, when a fault occurred in a downstream DC panel (see Information Notice 2013-17). The fault induced an electrical transient that resulted in the failure of the in-service battery charger and the inverters that it supplied. This significant plant transient prompted a Special Inspection Team (SIT). The complete details of this event are provided in the SIT Report (ADAMS Accession No. ML113330802).

The IEEE Standard 946-2004, Paragraph 7.9.2, states: "When the battery charger is connected in parallel with the battery, the battery capacitance will prevent the battery charger contribution from rising instantaneously. Therefore, the maximum current that a charger will deliver on short circuit will not typically exceed 150% of the charger full load ampere rating. Instantaneous battery charger current rise should only become a concern during periods when the battery is disconnected."

During the Palisades Nuclear Plant event, the battery charger tripped when a downstream fault occurred. Due to this operating event, the U.S. Nuclear Regulatory Commission (NRC) staff identified the need to confirm whether the charger contribution to the short-circuit current would not exceed 150% of the charger full load current while the battery was also connected in parallel. In essence, the NRC staff needed to evaluate the synergistic contribution of both the battery and battery charger to the short-circuit current.

To further analyze the problem and determine whether the individual short-circuit current contributions of a battery and a battery charger are independent of each other in a typical nuclear power plant (NPP) DC system configuration, testing was performed at the Brookhaven National Laboratory (BNL) Battery Test Facility using three 12-cell battery strings and two different types of battery chargers. This report describes the approach taken for the testing, the results achieved, and the implications of the results.

1.1 Objectives

The primary objective of this project was to evaluate the short-circuit current contributions of the battery charger and the battery to a fault on the DC distribution system. This information was needed to confirm that the battery and battery charger contributions to the fault current on the DC distribution circuit are being correctly applied in the design of protective coordination to limit the impacts of a fault event on the non-faulted parts of the DC distribution system.

1.1.1 Background Information (Literature Review)

The response to a fault on the DC distribution system at a NPP can have a significant impact as seen by the event that occurred at the Palisades Plant in September 2011. The approach that NPPs take to minimize the impact of such a fault is derived from industry consensus documents, such as IEEE Standard 946-2004, "IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations." It is important that these recommended practices be based on a strong foundation of analyses, testing, and experience.

BNL performed a detailed literature review of technical papers, Industry Standards, and previous test reports related to the fault current produced by battery chargers and batteries in an industrial setting. The results of this review were published as BNL Technical Report BNL-107800-2015-IR (ML 16190A093). The observations made in this report include:

1. Many papers published in the 1990s that are referenced in the technical report and even one published as recently as 2013 indicate that there is not a standard method of approaching the short-circuit protection and coordination of critical DC distribution system protection devices. One of the reasons for this is that there has been very little empirical data made available to quantify the short-circuit currents that a battery and a battery charger will contribute in combination. Therefore, it appears that the assumptions of the supplied fault current from batteries and chargers could be different. This could lead to different settings for protective devices and different plant responses to a fault on the DC distribution system.

2. Testing has been performed individually on two vented lead-acid batteries from different manufacturers (C&D and AT&T) and one battery charger type (SCR type). These tests revealed that the measured short-circuit currents are less than the calculated values, sometimes by a factor of 2, due to circuit impedances and battery voltage response.

3. There are several different types and sizes of battery chargers being used at NPPs. How each is protected to withstand a fault condition and how each would contribute to such a fault may be different.

4. A battery's theoretical short-circuit contribution is attainable from the battery vendor's specification sheets. However, this same information is not readily available from the battery charger vendors. This could be due to the prevalent wisdom that the battery contribution to a DC distribution system fault will dominate that from the charger even though limited testing conducted prior to this project indicates that a charger can provide a fault current contribution that is similar in magnitude to the battery for a short time.

5. The DC distribution circuit can influence the magnitude, characteristics, and potential consequences of the fault current produced by the battery and the charger. The rate of rise, for instance, of the fault current could impact the speed at which protective devices react and, therefore, the time that conductors and connectors are exposed to these high currents. The rate of rise and associated time constant will differ due to the DC circuit inductance.

6. Assuming greater values than the actual fault currents that will occur could result in higher ("conservative") settings for protective devices that may have unintended consequences during a fault. The literature indicates that a lower fault current can increase the response time of the protective device enough to cause a fire if the setting of the protective device is too high. Using "rules of thumb" for the battery short-circuit contribution as described in several standards rather than more realistic values may not be appropriate for NPP applications where high reliability and availability of safety-related components is essential.

1.1.2 Batteries and Battery Chargers Tested

BNL has three sets of nuclear-qualified batteries from a previous test setup. The three battery types are:

- Enersys-type 2GN-23 cells with an 8-hour rating of 1800 Amp-hours at 225 Amperes (A),
- Exide GNB-type NCN-21 cells with an 8-hour rating of 1496 Amp-hours at 187A, and
- C&D Technologies-type LCR-33 cells with an 8-hour rating of 2320 Amp-hours at 290A.

Each battery string consists of 12 cells. The production and control of the cells meet 10 CFR 50 Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants,” criteria and other requirements that apply to batteries that are installed as Class 1E at nuclear stations. The battery test setup is consistent with a typical nuclear power station’s Class 1E battery design except for seismic supports.

Two battery chargers were procured that are representative of the battery chargers used in NPPs. The types and models obtained are:

- Controlled ferroresonant (CF)-type charger, single-phase 208 VAC, 24A input; 24V and 100A DC output. CF-type chargers comprise about 15% of the charger population at NPPs. The CF charger has a 125A DC output circuit breaker and no internal fuses.
- SCR-type, 3-phase 480 VAC, 6A input; 24V and 100A DC output. SCR-type chargers comprise about 75% of the charger population at NPPs. The SCR charger has a 150A DC output breaker and a 200A DC output fuse, but no internal fuses on the firing circuit.

The three nuclear-qualified vented lead acid battery strings are representative of the battery models used in more than 75% of the current NPPs. The CF and SCR-type battery chargers represent about 90% of the battery charger designs used in the current U.S. NPPs. The two battery chargers that were procured for this testing were not qualified to IEEE 650-2006.

1.2 Test Approach

This project involves short-circuit testing of batteries and battery chargers that are representative of those typically used in commercial NPPs in the U.S. They are installed in a configuration similar to that used in typical U.S. NPPs and were subjected to a series of short-circuit tests to simulate fault conditions on a DC distribution system in a NPP. Initially, 12 short-circuit tests were conducted: one on each of the two battery chargers (total of 2), one on each of the three battery strings (total of 3), and one on each of the combined battery string and each charger types arranged in parallel (total of 6). Because of the NRC’s interest in validating if the battery voltage would respond with shorter duration faults that are more representative of NPP circuit breaker clearing times, 15 additional short-circuit tests were conducted (5 on each battery string) with fault duration times ranging from 80mS to 700mS.

This testing was designed to determine the short-circuit characteristics and performance of the charger designs that are most often used in NPPs. This included an SCR type and a CF type. A high-power shorting switch was used to initiate and interrupt the fault. High-capacity calibrated shunts were used to measure the current produced by the battery and the charger. A high-speed data logger was used to collect and store the data.

The instantaneous and steady-state response and output characteristics of the equipment under short circuit (fault) were evaluated under the following conditions:

- Battery charger(s) operating as a battery eliminator (no battery in parallel) at a nominal load (~ 20 amps) prior to being subjected to a short circuit (fault). The current limit setting for the chargers was set at 110% of its 100A rating (110A).
- Each of the three 12-cell battery strings subjected to a 2-second short circuit (fault).
- Battery charger(s) operating in parallel with a battery string (battery charger supplying the float current to the battery) prior to being subjected to a short circuit (fault).

1.3 Assumptions and Measures of Uncertainty

In conducting the testing to assess the battery and battery charger response to a fault (short-circuit), certain assumptions were made that could contribute to slight uncertainties in the final test outcome:

a. The testing was performed using three 12-cell battery strings that have an output voltage of approximately 27 volts DC as compared to 60-cell battery strings that have an output voltage of approximately 130 volts DC in a NPP. It is assumed that the short-circuit current achieved is basically the same regardless of the number of the cells in the string.

b. Three battery models from three different battery manufacturers were used in this test program. It is assumed that other models and types of vented lead acid batteries used in NPPs would perform similarly to the batteries tested.

c. Only two battery chargers from two different vendors (non-class 1E) were tested: one an SCR type and the other a CF type. It is likely that other suppliers of each of these types of chargers have some design variations (different size output filter capacitors, for example) that could yield somewhat different responses to an applied short circuit.

d. The magnitude of the short-circuit current achieved is dependent on the resistance and inductance of the DC distribution circuit. The test setup used at BNL is not nearly as complex as the DC distribution system at a NPP so the absolute values could differ although the relationship between the battery and the charger should be similar.

e. The battery chargers are new and may not respond the same as an aged charger.

1.4 Test Facility

1.4.1 BNL Battery Test Facility

BNL established a controlled area for this testing that had been previously used for two sets of battery tests sponsored by the NRC (see NUREG/CR-7148 and NUREG/CR-7188). The BNL Battery Test Facility contains area temperature and humidity control and monitoring, electrolyte spill control measures, and adequate ventilation to prevent hydrogen accumulation. Suitable AC input power was provided to each of the two new battery chargers. Data acquisition equipment was installed to acquire and store the measured parameters during testing. The installation is shown in Figure 1-1.

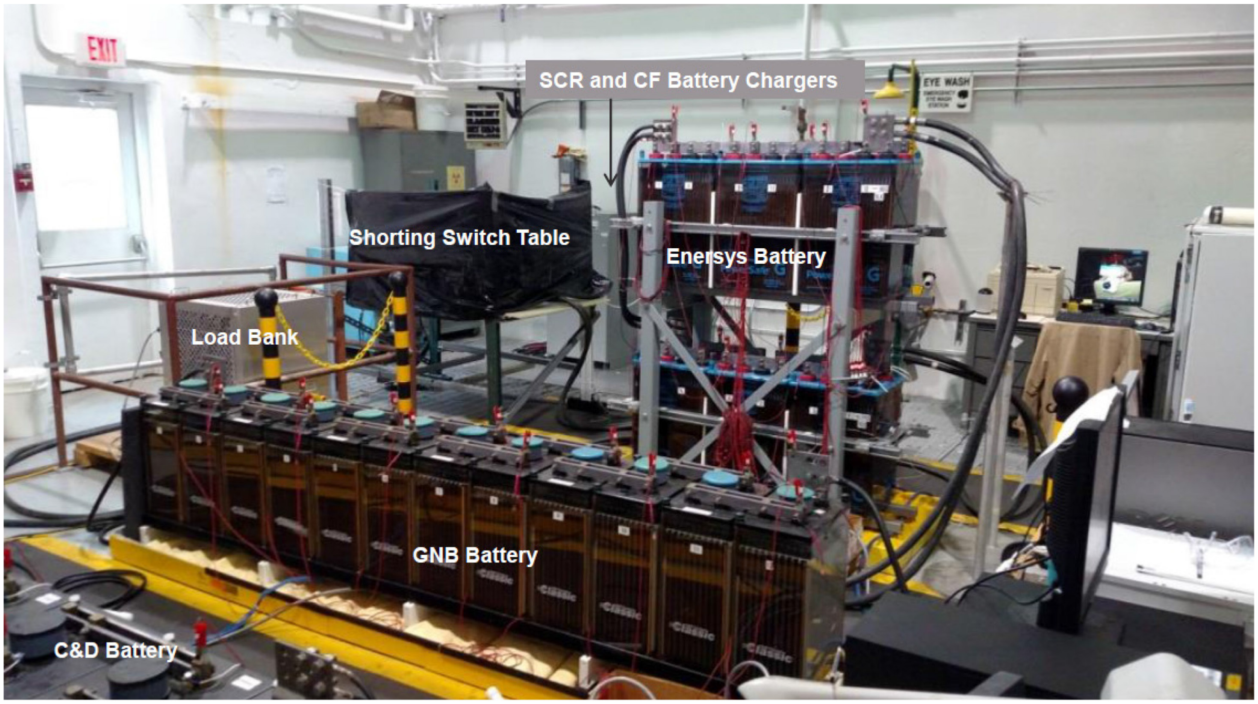


Figure 1-1 BNL Battery Test Facility

1.4.2 Test Setup

A general schematic of the combined charger and battery test configuration is illustrated in Figures 1-2 and 1-3. Note the location of the 10,000 A current shunt in series with the 12.5 kA shorting switch (contactor) to measure the overall short-circuit current, a 1000 A current shunt to measure the output of the battery charger, the current transformers (CTs) used to measure one phase of the AC input to the SCR-type charger, and the other inputs to the high-speed data logger.

1.4.3 Data Acquisition Equipment

The test program employed an automated capacity test set, manufactured by the Alber Corporation, to control the initial load on the battery charger prior to initiating the fault. A 600A load bank was used in conjunction with the Alber BCT-128 capacity test set to provide the resistive load used to control the initial current from the battery charger.

In addition to test equipment that acquires a continuous stream of data during testing, manual specific gravity readings using a digital hydrometer (Model SBS-2500 with an accuracy of .0001g/cm^3) were taken in accordance with the battery vendor recommendations to assess battery condition. Float current and individual cell voltages were monitored to verify the state of charge of the battery prior to and following each fault current test on the batteries. The battery charger performance was checked following each test to determine if any damage had occurred.

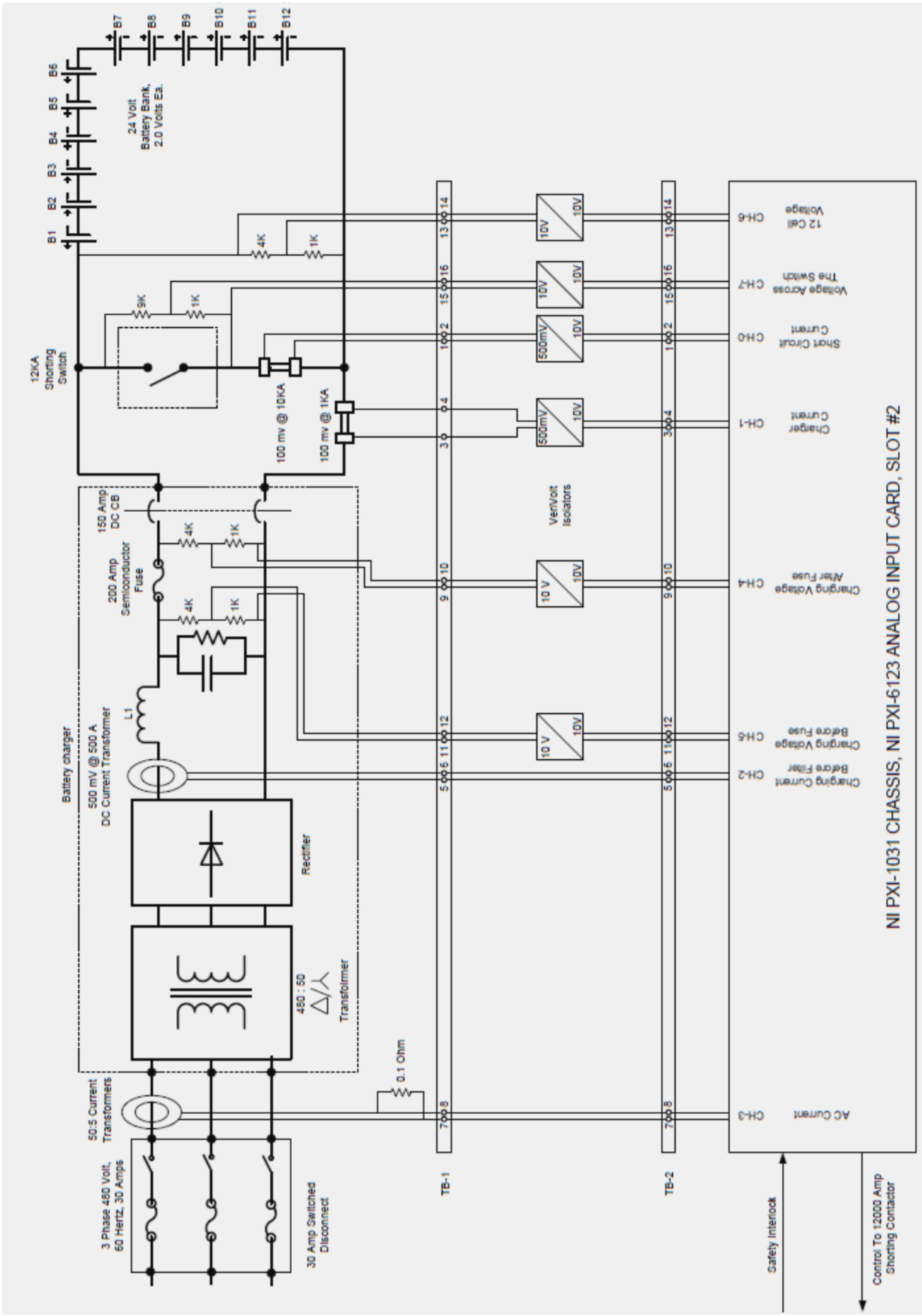


Figure 1-2 Schematic for SCR Battery Charger-Battery Short-Circuit Test

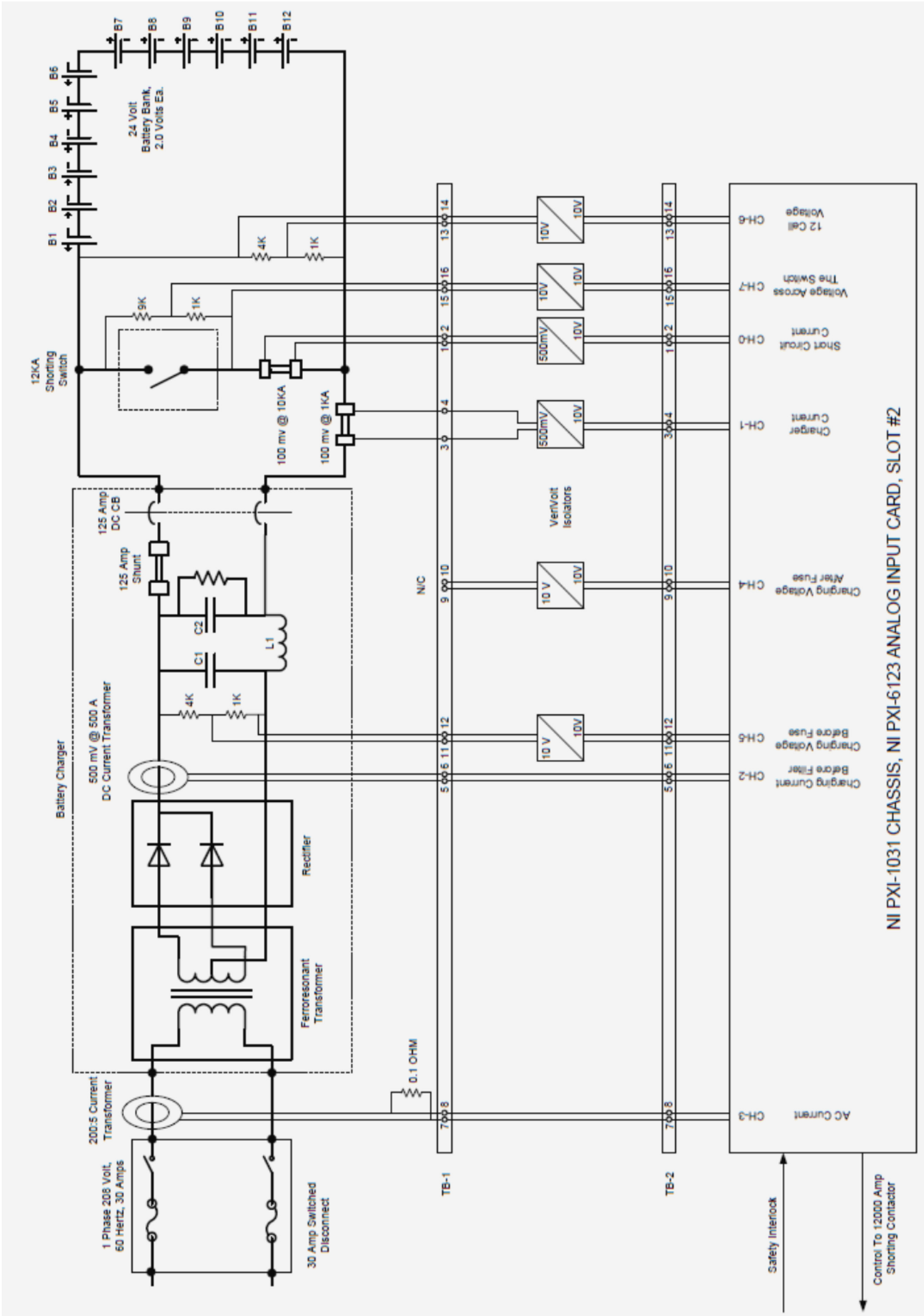


Figure 1-3 Schematic for CF-Type Battery Charger-Battery Short-Circuit Test

Details of the equipment and instrumentation used for this testing are as follows:

High-Speed Data Logger: The 16-channel high-speed data logger has a sampling rate of 100K samples/sec per channel. This logger is programmed using LabView Real Time graphical programming software and uses analog to digital converter hardware from National Instruments (see Figure 1-4).

High-Voltage Isolators: These isolator modules manufactured by VeriVolt Inc. provide fast response and isolation between channel-to-channel and channel-to-ground in excess of 10,000V. They have programmable gain to maintain the output voltage within +/- 10V range for the data logger.

High-Power Shorting Switch: A contactor with a 65 kA interrupting current rating was used to initiate the short circuit remotely. The unit selected to perform this critical aspect of the test is a pneumatically operated 12.5 kA shorting switch assembly custom manufactured by Watteredge for the BNL tests.

Current Transformers (CTs): The AC inputs to the battery chargers had CTs installed to monitor for any transient effects on the AC distribution system from the DC fault.

Shunts - 10000A, 100mV and 1000A, 100mV: The voltage signal across these shunts will be used to capture the short-circuit current contributions from the battery and the battery charger.

Thermal Imaging Camera: This equipment was used to monitor the temperature response of the battery connections and the battery charger during the short-circuit test.

Load Bank: A programmable resistive load bank was used to place an initial load on the battery chargers prior to the fault initiation. The initial load on the charger insured that output capacitors were charged prior to fault initiation.

Figure 1-4 High-Speed Data Logger

The following parameters were measured and logged using the high-speed data logger:

- I_{TOTAL}: Voltage across 10,000A shunt that measures the total fault current.
- I_{BC}: Voltage across 1000A shunt that measures the fault current contribution from the battery charger.
- I_{AC}: AC input current on the AC supply cable(s) to the chargers as measured by the current transformer(s).
- V_1: Overall Voltage of the battery string under test.
- V_{cell}: Voltage of Cell #1 in each battery string.
- V_2: Output voltage of the battery charger under test.
- CB_2 status: SCR and CF Battery Charger DC output circuit breaker status (open/close).
- F_1 status: SCR Battery Charger DC output fuse status (open/close).
- SW_1: open/close status of the 12.5kA shorting switch.

In addition, an Omega data acquisition system acquired cell temperature data and provided backup battery string and cell voltage measurements. It was also used to monitor float current during the recharge of the battery string following each short-circuit test.

Captured data was logged and synchronized with the closing of the contactor used to initiate the fault from the control console.

1.5 Quality Plan

Existing BNL quality control procedures were used to ensure that results are reproducible and accurate. Instruments were calibrated traceable to a national standard.

1.6 Test Plan

In previous testing (documented in NUREG/CR-7148 and NUREG/CR-7188), the batteries have been subjected to approximately 30 deep-cycle performance and/or service tests. In this testing program, these same batteries were subjected to a series of short-circuit tests individually and in conjunction with the two battery chargers. Each of the two battery chargers' tests subjected the charger to a short circuit while it was supplying a resistive load.

- A pneumatically operated, 12.5 kA shorting-switch assembly was used to initiate and interrupt the fault. The switch has a momentary interrupting rating of 65 kA and is pneumatically operated using a solenoid-operated valve that was remotely operated from the control console. The shorting-switch, along with the shunts for measuring the currents and associated control wiring, were mounted on a test table shown in Figure 1-5.

- In the initial testing, the short circuit (fault) applied in each of the tests was maintained for about two seconds, allowing the current limit circuitry to achieve a steady-state output. This test duration was chosen to determine if the battery charger would self-regulate its output and achieve a steady-state response under a prolonged fault condition. The pneumatic switch timing was controlled by the high-speed data logger which energized and de-energized the solenoid valve that supplied compressed air to the shorting switch.

- Fifty thousand (50,000) samples were acquired over a 5-second timeframe for each of the tests; one sample every 100 µS. These data were saved as an Excel file so that graphical depictions could be provided. The horizontal axis, therefore, is displayed in 100 µS (or 0.1 millisecond) time intervals.

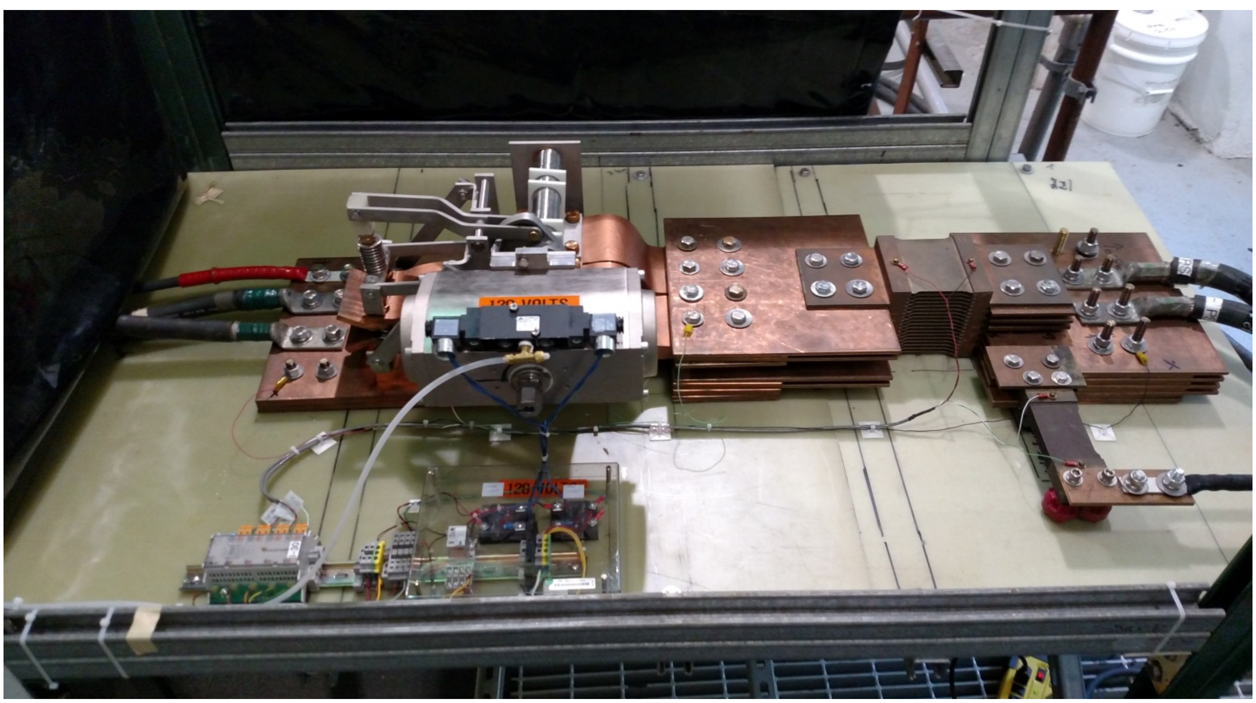


Figure 1-5 12.5 kA Shorting-Switch Assembly with Current Shunts

The Test Plan was augmented by an Experimental Safety Review coordinated by the BNL Nuclear Science and Technology Safety and Health professionals. Safety precautions were taken to ensure that personnel were protected from the arc at the shorting switch produced by creating and interrupting the short circuit. In addition, checklists were used to assist BNL staff in ensuring that power sources were isolated when connecting and disconnecting the cables from the batteries and the chargers to the shorting switch.

2 TEST RESULTS AND DATA ANALYSIS

This section presents the significant amount of data that were acquired during each of the test sequences. The test data presented include:

- The magnitude of the battery output current and voltage under fault conditions,
- The magnitude and duration of the battery charger output current and voltage under fault conditions with and without the battery connected to it,
- The assessment of the differences in battery charger response to the fault conditions with and without the battery connected in parallel,
- The battery charger AC input voltage, current, and frequency under fault conditions, and
- The effect of shorter duration faults on the battery voltage response.

Section 2.1 focuses on the battery short-circuit response, Section 2.2 on the battery charger short-circuit response, and Section 2.3 on the short-circuit responses when the battery charger and battery were connected in parallel (the normal NPP configuration). Section 2.4 contains testing results for follow-on testing that was performed with shorter fault times. This was done to assess the battery voltage responses to the shorter, more realistic, fault clearing times. Section 2.5 discusses the temperature changes that occurred during the fault and Section 2.6 describes how software was used to determine the fault current from the batteries as the external circuit impedance is changed.

2.1 Battery Short-Circuit Response (Battery Only)

The test circuit for shorting each of the 12-cell battery strings used the same cable lengths, shorting-switch assembly and current shunt. Two 535-MCM cables were run in parallel from the positive end of the battery to the shorting switch (30’ lengths of stranded cable) and from the negative terminal of the battery string to the 10,000A current shunt used to measure the total short-circuit current (50’ length of stranded cable). This arrangement was used to minimize the potential for overheating of the cables during the test. Figure 2-1 shows the cable connections to the Enersys battery. The measured resistance of the positive cable was 0.3035 milliohms; the resistance of the negative cable was 0.4701 milliohms. The test setup is depicted in Figure 2-2.

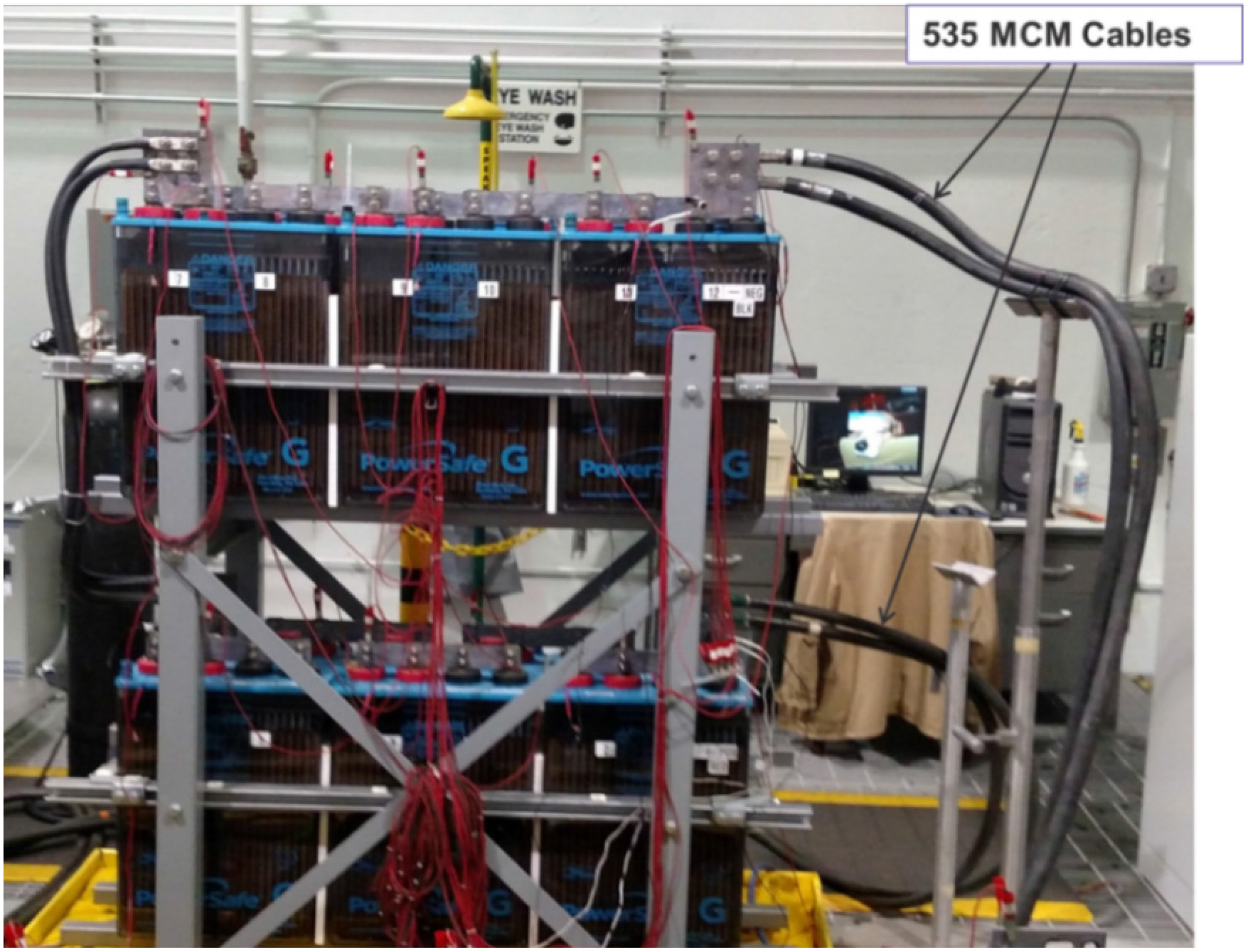


Figure 2-1 535-MCM Cables in Parallel Used for Battery Short-Circuit Tests

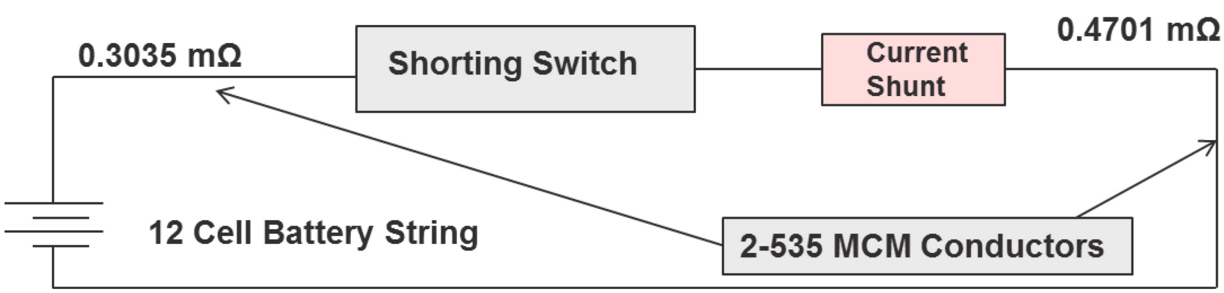


Figure 2-2 Schematic of Battery Short-Circuit Test Arrangement

Because the battery chargers were expected to contribute a lower fault current, a single 2/0 cable was used to carry current from the output of the charger. As might be expected, the magnitude of the short-circuit responses of the battery strings were in proportion to their ampere hour rating. Table 2-1 summarizes the battery information along with the maximum short-circuit current obtained and the current at 100 milliseconds following the initiation of the short circuit.

Table 2-1 Battery Short-Circuit Response (Battery Only)

Battery Type	A-H Rating	Maximum Current (I_{MAX})	Current at 100 mS
C&D LCR-33	2320 A-H at 290A	13,520A	13,320A
Enersys 2GN-23	1800 A-H at 225A	12,700A	12,560A
GNB NCN-21	1496 A-H at 187A	10,900A	10,781A

The battery response can be seen in the following figures (Figures 2-3 and 2-4) that represent the short-circuit response over the 2-second applied short circuit and the first 100 milliseconds following initiation of the short circuit, respectively. Figure 2-3 illustrates the relatively constant current that is supplied by the battery during the time of the applied short circuit, reducing gradually over time as the resistance of the circuit increases slightly due to the temperature effect on the conductors and connectors. Figure 2-4 focuses on the battery responses during the first 100 milliseconds of the applied fault. It is interesting to note the nearly identical current responses of the three different battery strings over the 2 seconds of the short circuit.

The overall battery string voltage was monitored on the high-speed data logger during each of the short-circuit tests along with Cell #1 from each battery string. The temperature of the cells (using surface-mounted thermocouples) was monitored using the Omega data acquisition system. The Alber battery capacity test set monitored each of the cell voltages and the overall battery string voltage for approximately 10 minutes. The Omega and Alber data were acquired at a sampling rate of about one sample every 0.1 seconds as opposed to the high-speed data logger which was acquiring data every 0.1 milliseconds (1000x faster).

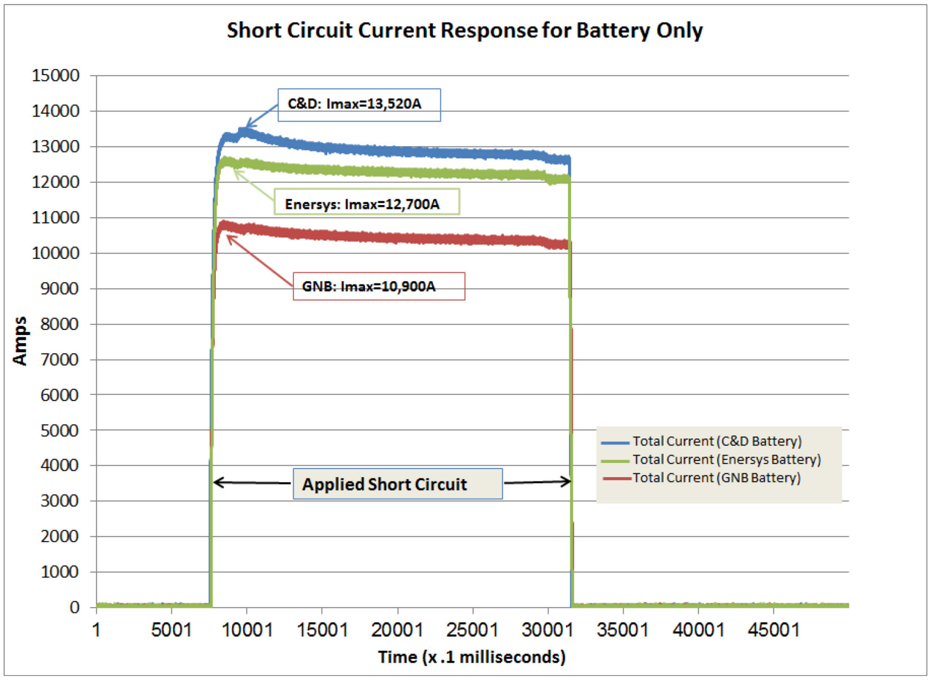


Figure 2-3 Short-Circuit Response of Each of the Battery Strings

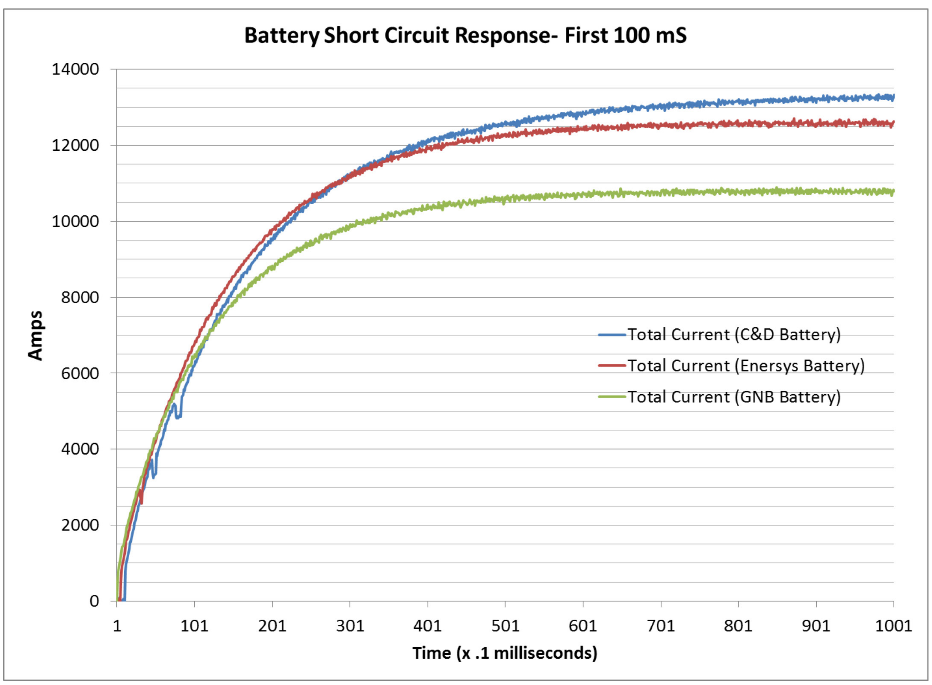


Figure 2-4 Short-Circuit Response of Each of the Battery Strings – 1st 100 mS

Figures 2-5 and 2-6 illustrate the overall battery string voltage and individual cell response to the short circuit, respectively, for the three battery types tested. For the 12-cell configuration used in this testing, the overall battery string voltage decreased from about 27 volts to about 10 volts. For the typical 60-cell, 125-volt DC distribution system illustrated in Figure 2-7, the equivalent change

would be from 125 V to 60 V or less during the fault and a lower overall voltage of approximately 120 V once the fault is cleared. The significance to the plant of the overall battery voltage decreasing by this much during the short circuit is that DC power supplies and/or inverters powered by the battery could trip depending on the setting of their protective devices, resulting in the loss of important instrumentation and controls.

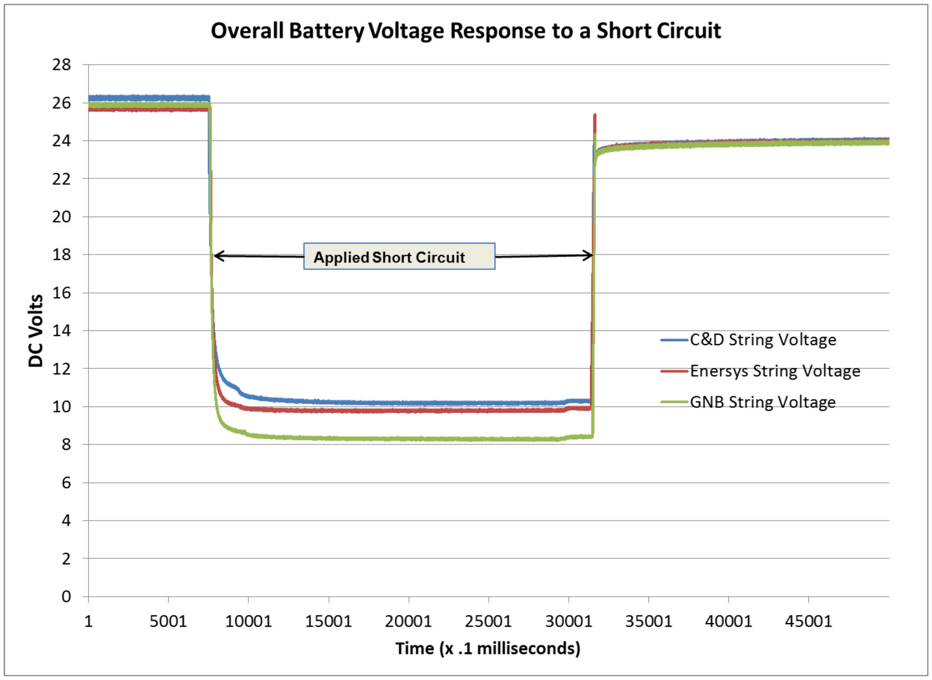


Figure 2-5 Battery Output Voltage Response to a Short Circuit

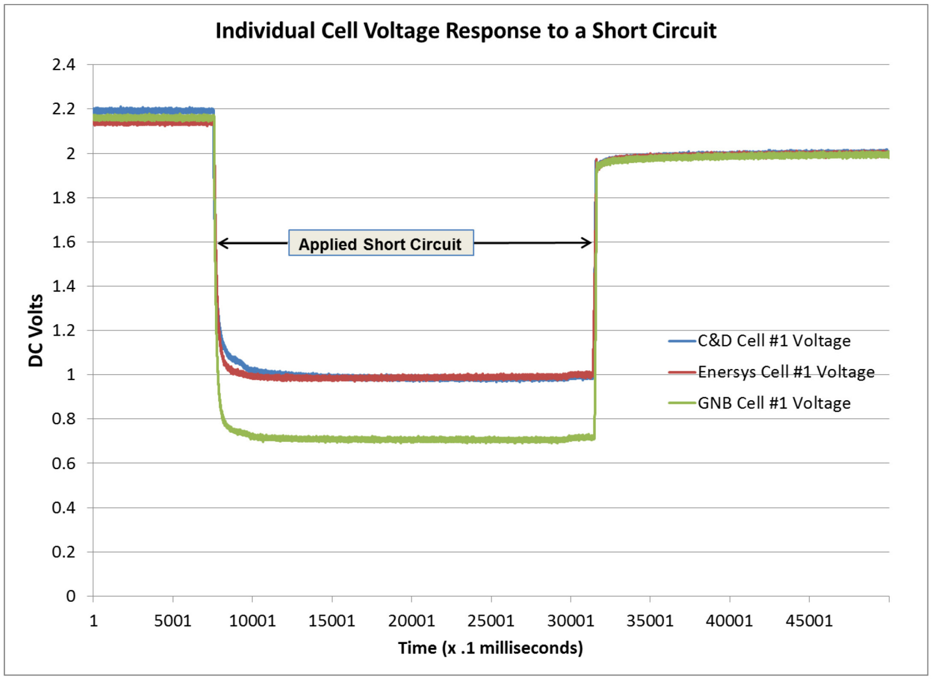


Figure 2-6 Cell #1 Output Voltage Response to a Short Circuit

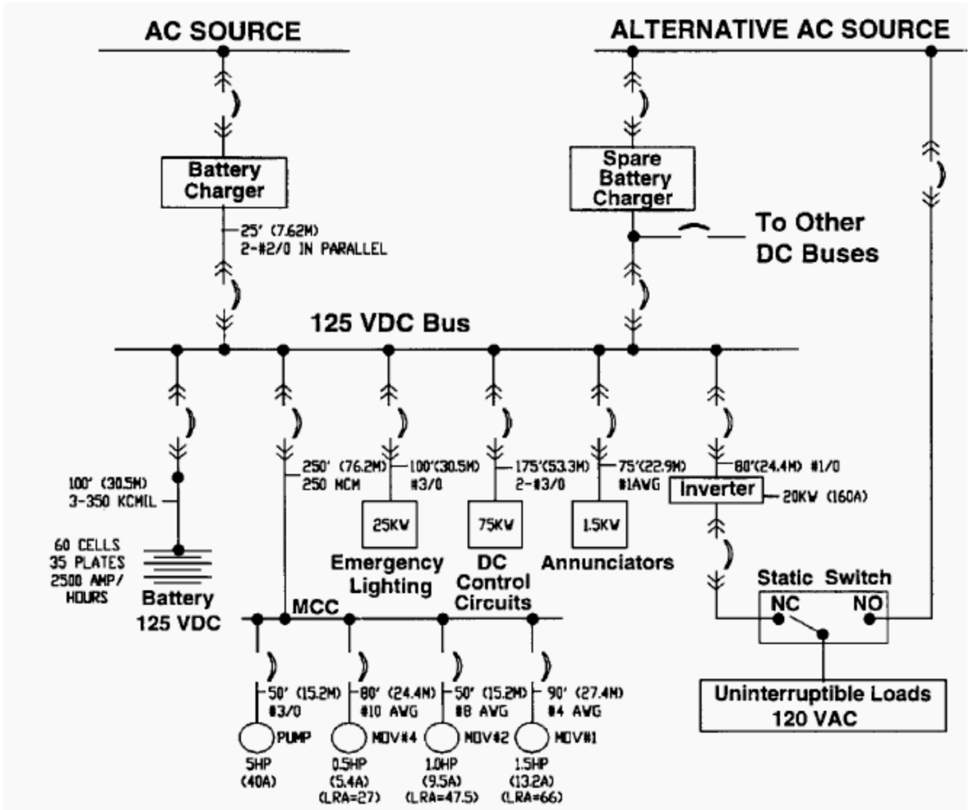


Figure 2-7 One-Line Diagram of DC Distribution System (IEEE 399-1997)

As illustrated in Figure 2-6, the output voltage for Cell #1 was seen to decrease from about 2.2 volts to 1.0 volt for the C&D and Enersys batteries and to ~ 0.7 volts for each of the cells in the GNB battery string. During routine performance testing of a battery, observation of a cell voltage less than 1.0 volts would be cause for concern. A phenomenon known as cell reversal[1] can permanently damage a cell and steps are taken during testing to avoid this by taking the cell out of service if this were to occur (EPRI, TR-100248, Rev. 2, Chapter 14). However, in the case of a short circuit, it was observed that each of the 12 cells in the string responded similarly, thereby reducing the risk of any one cell being the recipient of current from the other cells. Following the termination of the short circuit, the battery voltage immediately increased, but not to the level that it was prior to the applied short circuit. The resulting overall voltage of 2 volts per cell would yield a system voltage of 120 V for a typical 130 V, 60-cell battery string. Note that the additional short-circuit tests that were conducted with shorter duration faults are described in Section 2.4.

Post-Test Evaluation of the Batteries: Following the short-circuit tests on each of the battery strings, midpoint-specific gravity readings were taken on each cell. Specific gravity readings provide an indication of the batteries state of charge. The battery vendors recommend taking the reading at the mid-level or midpoint position for an overall/average value. Actions were then promptly taken to recharge the batteries while monitoring the recharge/float current. Recharge of the batteries was accomplished using a 200A battery charger that was not part of the fault testing.

[1] Cell reversal is a condition where the positive and negative terminals switch polarity due to a discharged cell being subjected to continued discharge.

As previously determined (NUREG/CR-7148), when a steady-state float current is obtained, the battery is recharged and is capable of meeting its design requirements. In all cases following the applied 2-second short circuit, the battery reached a steady-state float current within an hour or less when recharged at a float voltage of 27 volts (2.25V/cell). Figure 2-8 illustrates the recharge of the Enersys battery that reached a steady-state float current after about 35 minutes.

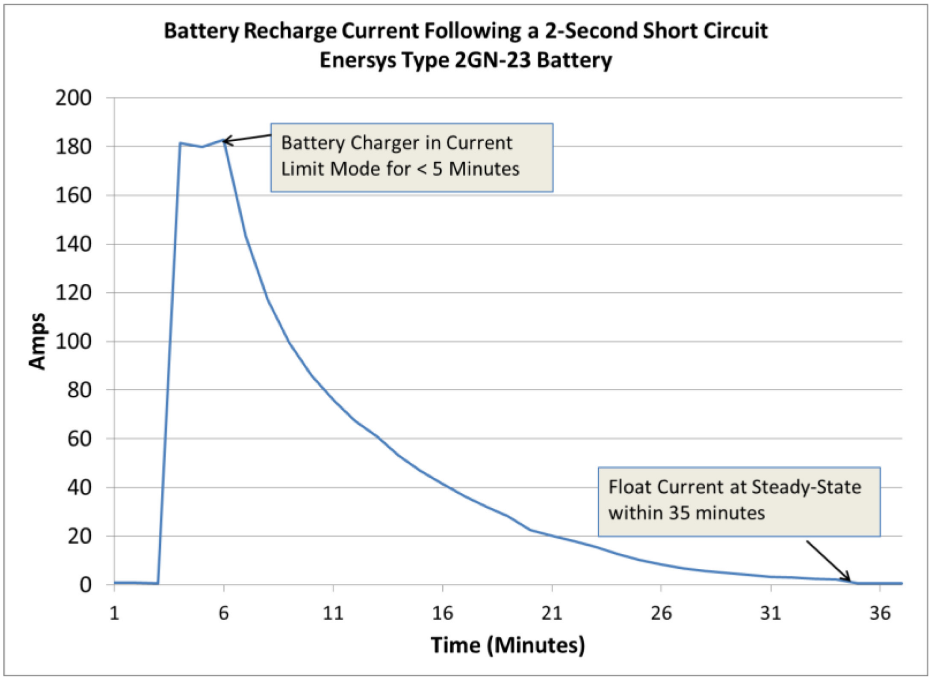


Figure 2-8 Recharge Plot of the Enersys Battery Following a 2-Second Fault

This is consistent with the realization that the total ampere-hours removed from this 1800 A-h rated battery was only 7 A-h (12,700 A x 2 seconds x 1/3600 hours). Therefore, replacing the expended ampere-hours from the 200A charger with a current limit of 180A is accomplished relatively quickly.

In addition, as shown in Table 2-2, there was virtually no change in the specific gravity readings taken prior to and following the short-circuit test. Note that a check of the hydrometer was conducted after each series of readings using distilled water (shown as “cal. check”). This further lends support to the observation that a DC distribution fault would not detrimentally impact the performance of the station battery or challenge the battery’s ability to perform its design function following the fault.

Table 2-2 Battery-Specific Gravity Readings Prior to and Following a 2-Second Fault

C&D Battery-9-3-15			GNB Battery-9-9-15			Enersys Battery-9-10-15		
Cell #	Pre-SC	Post-SC	Cell #	Pre-SC	Post-SC	Cell #	Pre-SC	Post-SC
1	1.228	1.227	1	1.215	1.216	1	1.226	1.224
2	1.228	1.228	2	1.221	1.222	2	1.224	1.224
3	1.228	1.228	3	1.218	1.218	3	1.227	1.227
4	1.228	1.228	4	1.219	1.219	4	1.227	1.227
5	1.232	1.232	5	1.217	1.217	5	1.227	1.227
6	1.226	1.226	6	1.218	1.218	6	1.225	1.225
7	1.228	1.228	7	1.218	1.218	7	1.230	1.230
8	1.235	1.235	8	1.215	1.216	8	1.233	1.232
9	1.230	1.231	9	1.218	1.218	9	1.231	1.231
10	1.229	1.229	10	1.220	1.220	10	1.230	1.230
11	1.228	1.228	11	1.218	1.218	11	1.229	1.231
12	1.231	1.231	12	1.218	1.218	12	1.230	1.230
Cal. Check	1.001	1.000	Cal. Check	1.003	1.004	Cal. Check	1.004	1.004

2.2 Battery Charger Short-Circuit Response (No Battery)

Two battery chargers were procured for the short-circuit testing: a 100A SCR-type charger with a 24VDC output and a 480VAC 3-phase input and a 100A CF-type charger with a 24VDC output and a 208V 1-phase input. The intent of testing the two types of battery chargers is to understand the short-circuit responses from both types that are used in safety-related applications at NPPs. As previously noted, the size of chargers used in the Class 1E DC systems in a NPP are larger (e.g., 200A-400A at 130VDC output); however, many of the circuit elements are similar to the smaller units used in this testing. While the response will be similar, the higher the rating of the charger, the higher the magnitude of the short-circuit current.

The same general test procedure was followed for both chargers. That is, a small load (20A) was initially placed on the charger using a resistive load bank that could be programmed and monitored from the Alber battery capacity test set. The purpose of the initial load was to ensure that the charger internal circuitry, especially the filter capacitors, was in a configuration that it would typically be in during normal power operation at a NPP. The results of the tests for the two chargers follow.

2.2.1 SCR-Type Charger Short-Circuit Response

The overall response of the SCR-type charger to a 2-second short circuit is illustrated in Figure 2-9. This figure covers a 5-second time span with the first second and last two seconds showing the charger supplying the 20A resistive load. The charger was able to withstand the maximum short-circuit current of 930A without tripping. Depending on the magnitude and duration of the short circuit and the circuit breaker or fuses used, a charger may not always be able to withstand a fault without tripping. In this test, the current limit circuit effectively reduced the charger's short-circuit current contribution to 110A after 460 milliseconds.

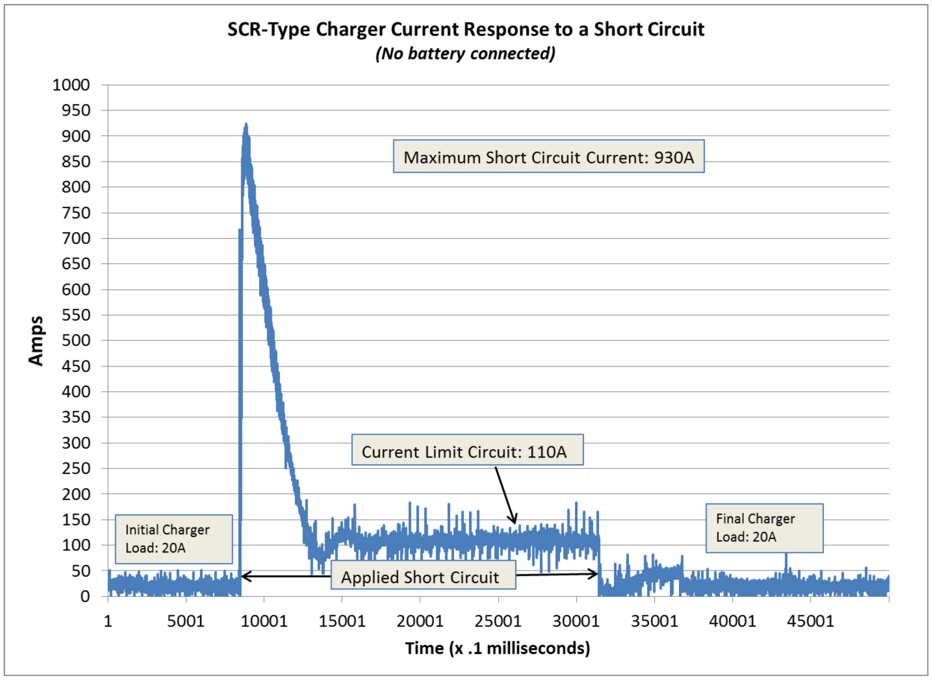


Figure 2-9 SCR-Type Charger Response to a Short Circuit

One of the objectives of this test was to determine how long it took the current limit circuit to achieve its design function. The data illustrated in Figure 2-9 were expanded in Figure 2-10 to focus on the time from initiation of the short circuit to the time that the current output from the charger reached 110A. As illustrated in Figure 2-10, this time was approximately 460 milliseconds, significantly higher than the 32 milliseconds described in IEEE 946-2004. For instance, IEEE 946-2004 states in Annex E that "In current-limited chargers, the current-limiting circuits will typically act to reduce the current after the first zero crossing (four-half cycles, 32 mS, or less) …" and "It is therefore conservative to assume that the maximum sustained fault current after 32 mS is the current-limiting value…" As seen by the SCR response, the contribution to a fault goes well beyond 32 mS so this assumption would not be conservative for the testing conducted on this SCR charger.

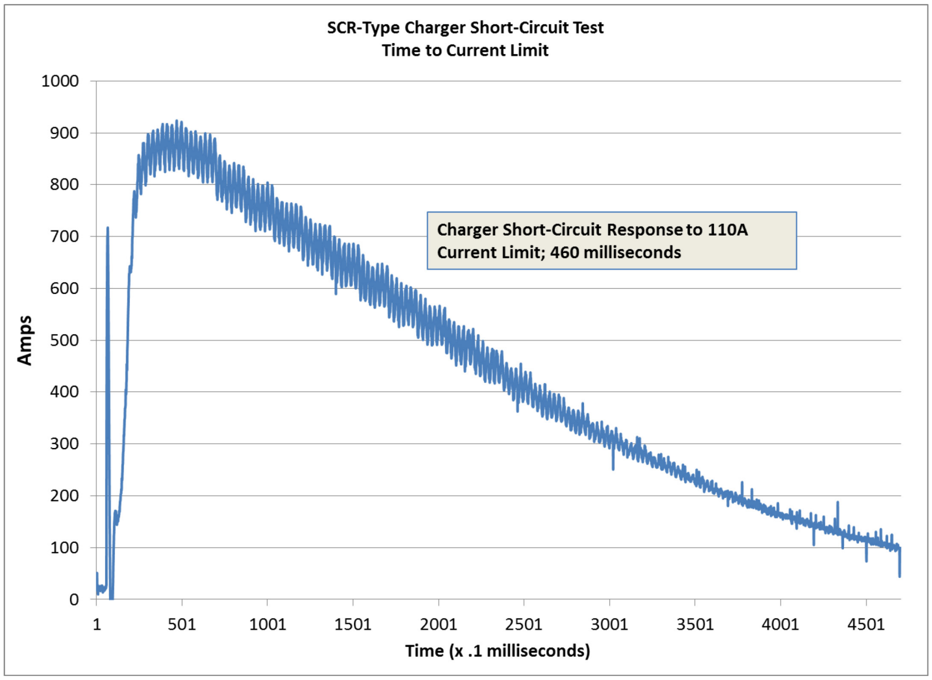


Figure 2-10 SCR-Type Charger Current Limit Circuit Response

A second objective of this test was to delineate the response of the charger during the first 100 milliseconds following initiation of the short circuit. Generally speaking, the protective devices used in a NPP should isolate a large fault on the DC distribution system within about 100 to 200 milliseconds.

As illustrated in Figure 2-11, the peak current was reached in about 30mS following initiation of the short circuit. The charger output slowly decreased but continued to supply > 700 amps to the fault at and beyond 100 mS after the short circuit was initiated.

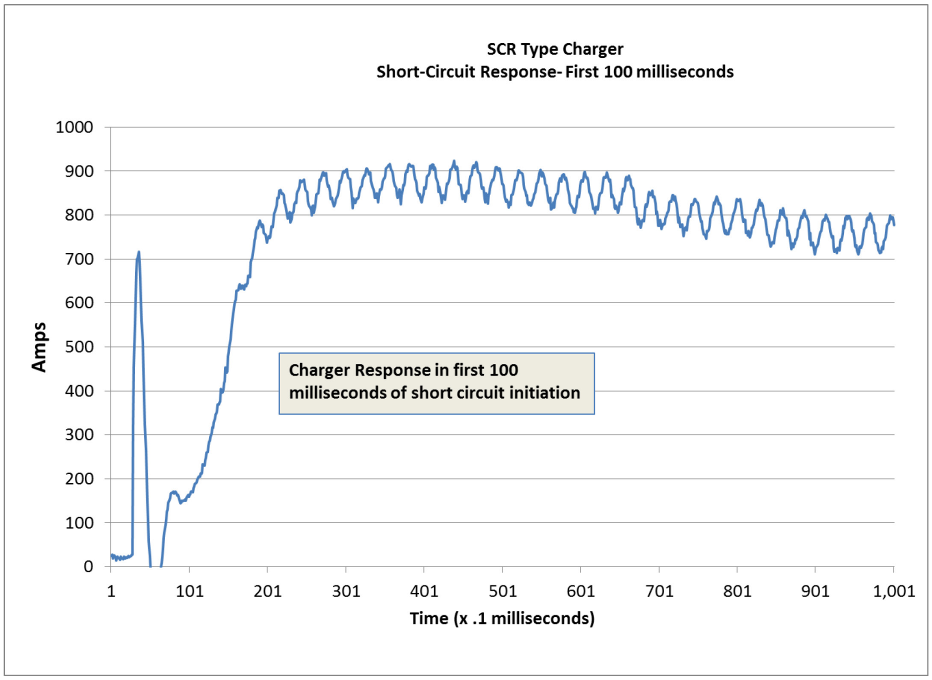


Figure 2-11 SCR Charger Short-Circuit Response in the First 100 mS

While the SCR charger was able to withstand the applied fault and continue to operate, it should be noted that its output voltage during the short circuit was about 1V. This response is depicted in Figure 2-12. Once the fault was terminated, the SCR charger required about 0.8 seconds to provide a stable output voltage to the load.

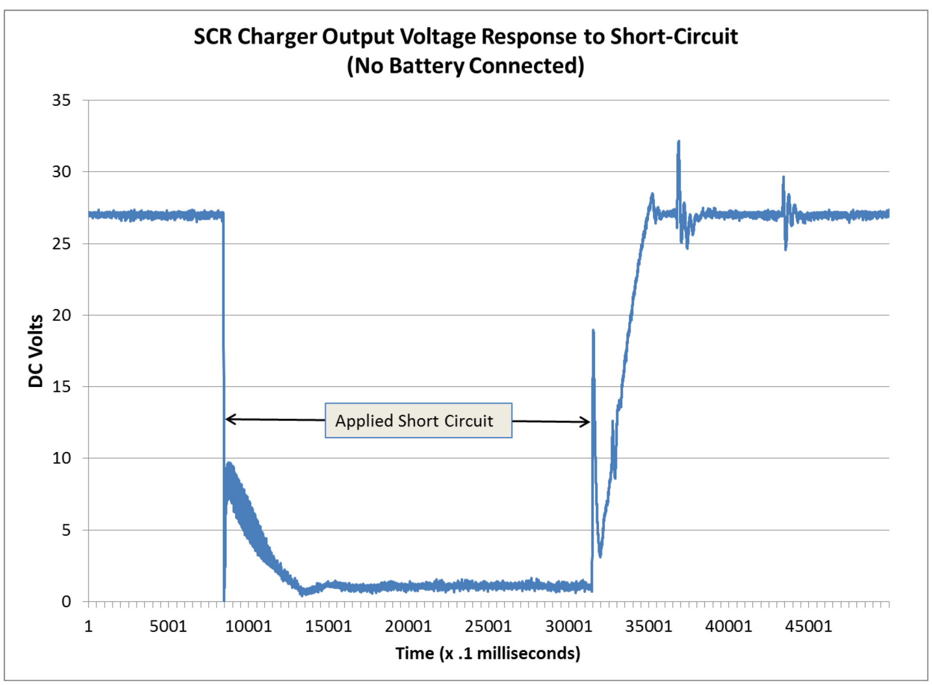


Figure 2-12 SCR Charger Output Voltage Response to a Short Circuit

A third objective of the battery charger short-circuit test was to evaluate the impact of the DC short circuit on the AC supply to the charger. The potential for a DC fault to cause a disturbance on the AC Class 1E distribution system was a concern that could be examined during this test. The AC current to the charger increased during the fault but was not in any other way detrimentally impacted by the fault applied to the output of the charger.

Figure 2-13 shows the AC input to the charger as measured by a current transformer mounted on one of the three input phases to the charger. There is a 6A AC breaker on the input to the charger, but the maximum current input obtained during the applied fault was 5.6A so the breaker did not trip. The AC input current was found to be roughly proportional to the DC load being carried by the charger. At the maximum short-circuit current of 930A, the AC input approached 6 amps peak to peak (p-p). At the current limit of 110A, the AC input was about 0.8A p-p, and at the 20A DC load, the AC input was 0.2A p-p. For larger battery chargers that are typically used in NPPs, the AC current to the charger during a fault event will be larger and should be factored into the AC breaker ratings and setpoints.

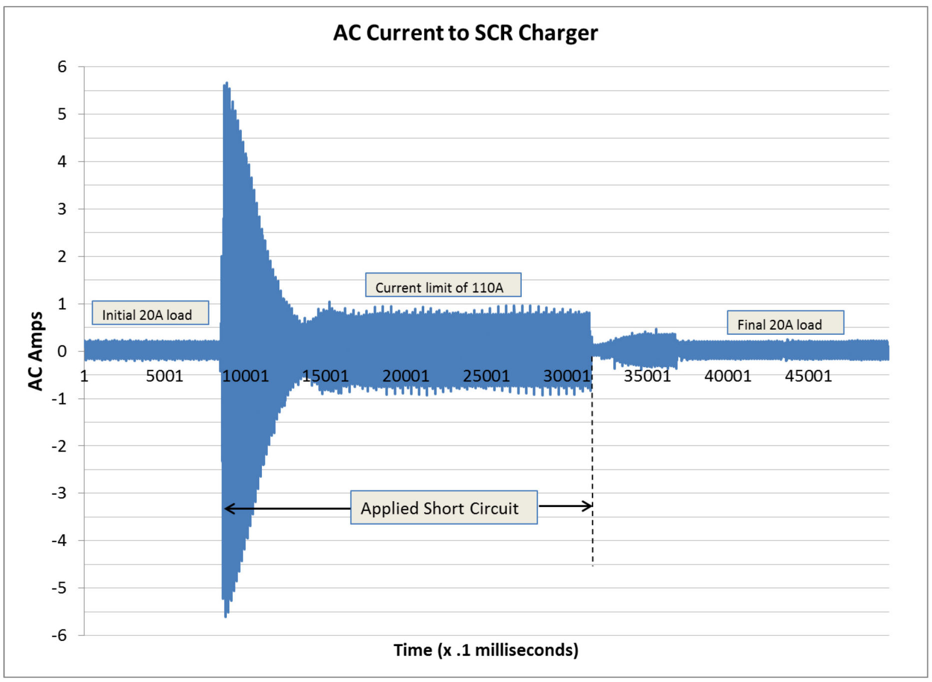


Figure 2-13 AC Current Input Response to a Fault on the SCR Charger

Figure 2-14 shows the AC input voltage response during the first 100 mS of the applied short circuit. Even with the high-speed data acquisition system, no voltage disturbance was observed at the initiation point or when the fault was cleared. The conclusion from this test is that the potential for transients from a DC fault to cause a disturbance of the AC distribution system is small for SCR-type chargers. Note that this same observation was made when the SCR charger was connected in parallel to a battery. Those data are presented in Section 2.3.

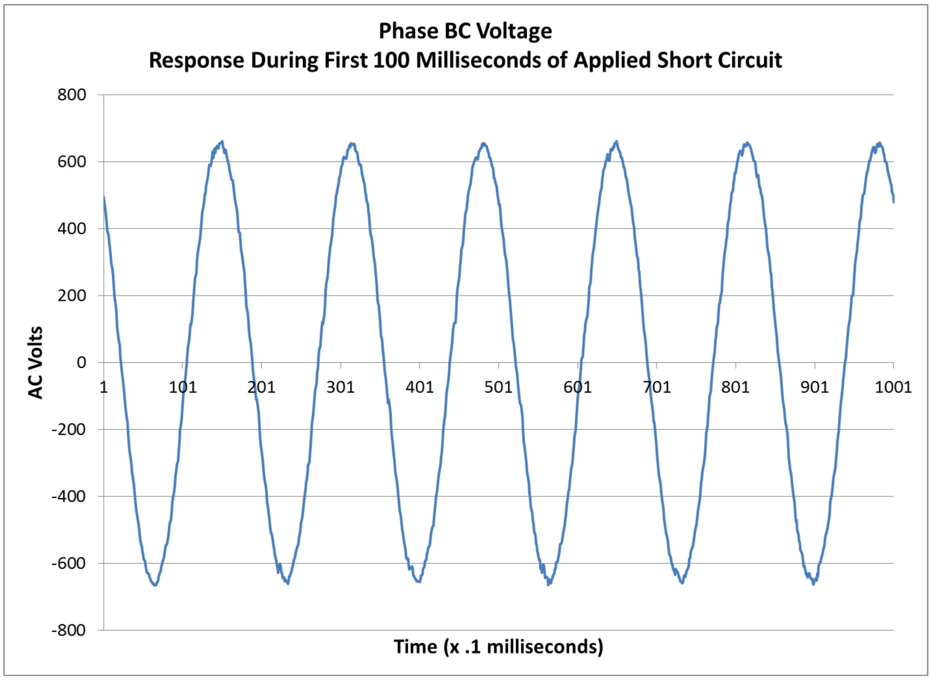


Figure 2-14 AC Voltage Input Response to a Fault on the SCR Charger

2.2.2 Controlled Ferroresonant (CF)-Type Charger Short-Circuit Response

The overall response of the CF-type charger to a 2-second short circuit is illustrated in Figure 2-15. This figure covers a 5-second time span with the first second and last two seconds showing the charger supplying the 20A resistive load. The charger produced a maximum short circuit current of 1246A and was able to continue to operate and supply the DC load during the fault condition. Its current limit circuit effectively reduced the charger's contribution to the short circuit to 110A very quickly.

The CF-type battery charger exhibited a very fast acting current limit response of about 20 mS as compared to 460mS for the SCR-type charger. The two peaks that are seen in Figure 2-16 represent the discharge of the charger's output filter capacitor to the fault followed by the charger response.

Figure 2-17 summarizes the CF charger output voltage response over the 5-second test sequence in which a 20A load was placed on the charger and a 2-second short circuit was then applied. The charger voltage decreased to about 0.5V during the short circuit but after a brief transient when the short circuit was removed, recovered to its pre-short circuit output voltage of 26.2VDC.

The AC current input to the CF charger was also monitored to determine if the applied short circuit would create a current surge on the AC distribution system that supplies power to the charger. Figure 2-18 shows a step increase in the current when the short is applied and the charger increases its DC supply from 20A to 110A (its current limit), and another momentary step increase (somewhat higher) as the fault is cleared and the DC output voltage returns to normal. This somewhat unexpected pulse is largely due to the magnetic forces in play. The cables physically move when the fault is applied and terminated creating an induced current that is reflected back through the charger.

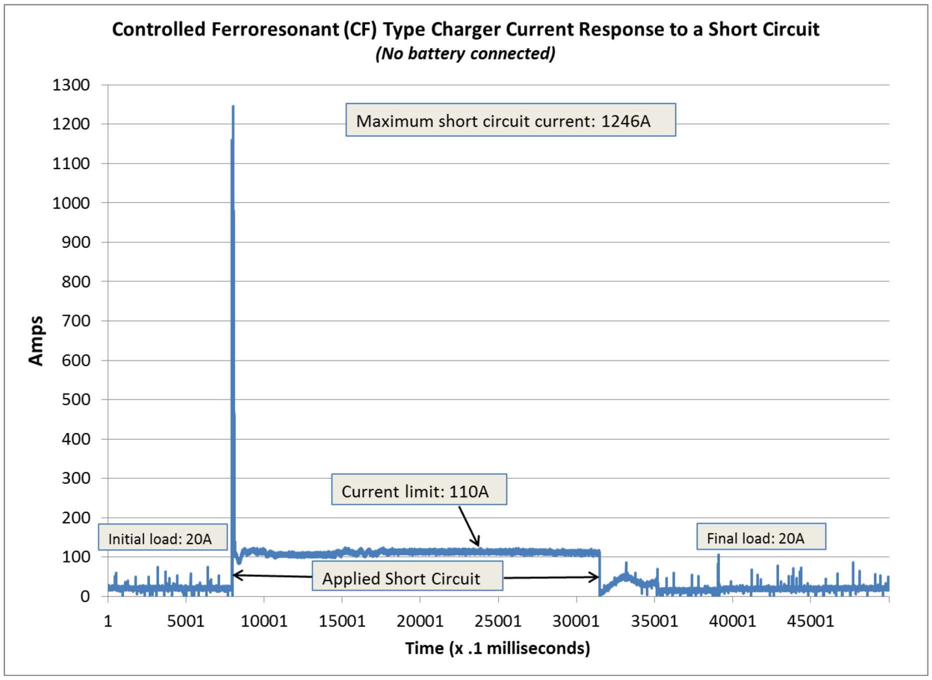


Figure 2-15 CF-Type Charger Response to a Short Circuit

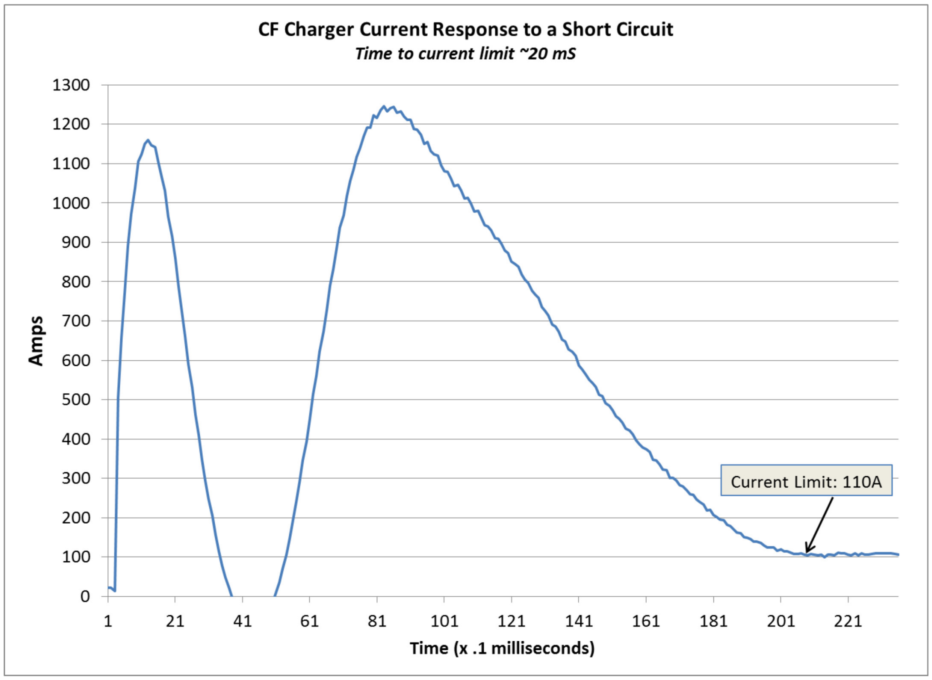


Figure 2-16 CF-Type Charger Current Limiting Response to a Short Circuit

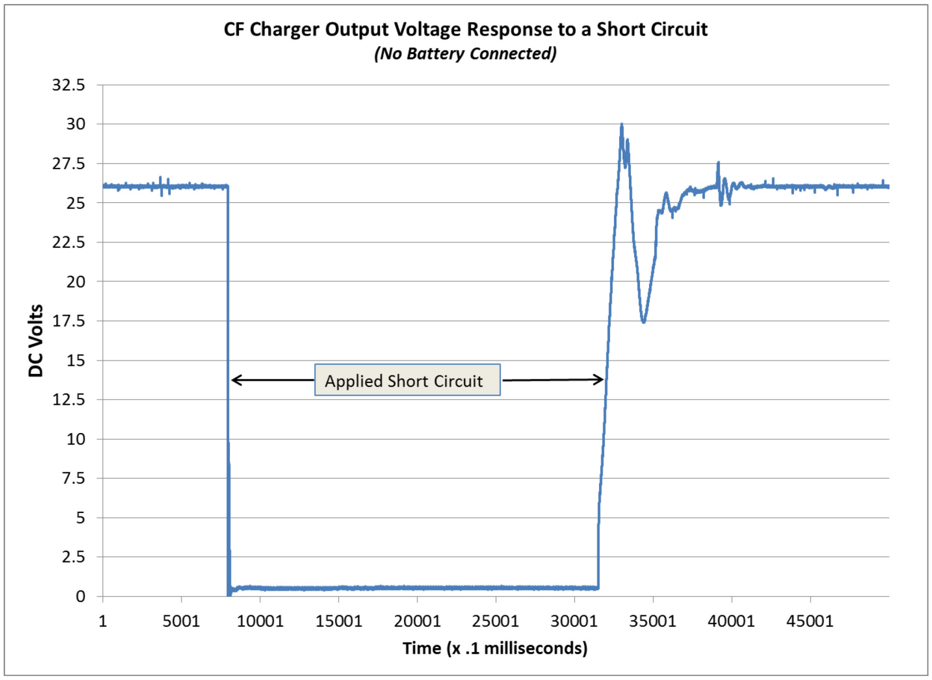


Figure 2-17 CF-Type Charger Output Voltage Response to a Short Circuit

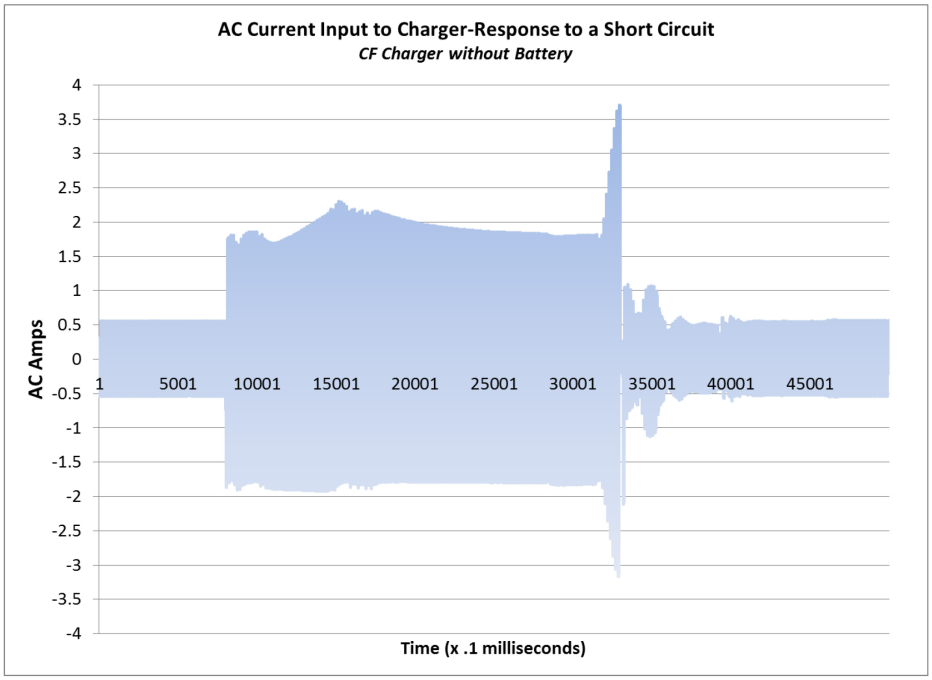


Figure 2-18 AC Supply Current Response to a Short Circuit on the CF-Type Charger

Figures 2-19 and 2-20 depict the AC response in more detail during the initiation of the short circuit and the termination of the applied short circuit, respectively. Note that no significant transient is seen at the initiation of the short circuit even though the charger DC output increases from 20A to 1246A but for only a few milliseconds. Once the fault is cleared, however, the input current to the charger increases over about 100 milliseconds as the output voltage of the charger increases from 0.5V to 26.2V and the charger's filter capacitors are recharged.

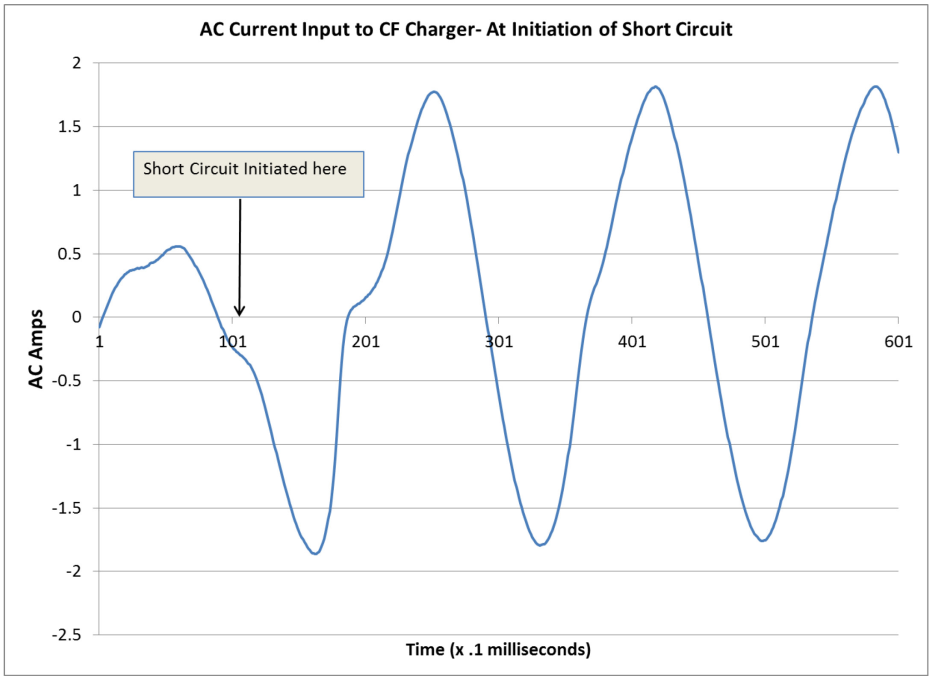


Figure 2-19 Response of the AC Input to the CF Charger at Short Circuit Initiation

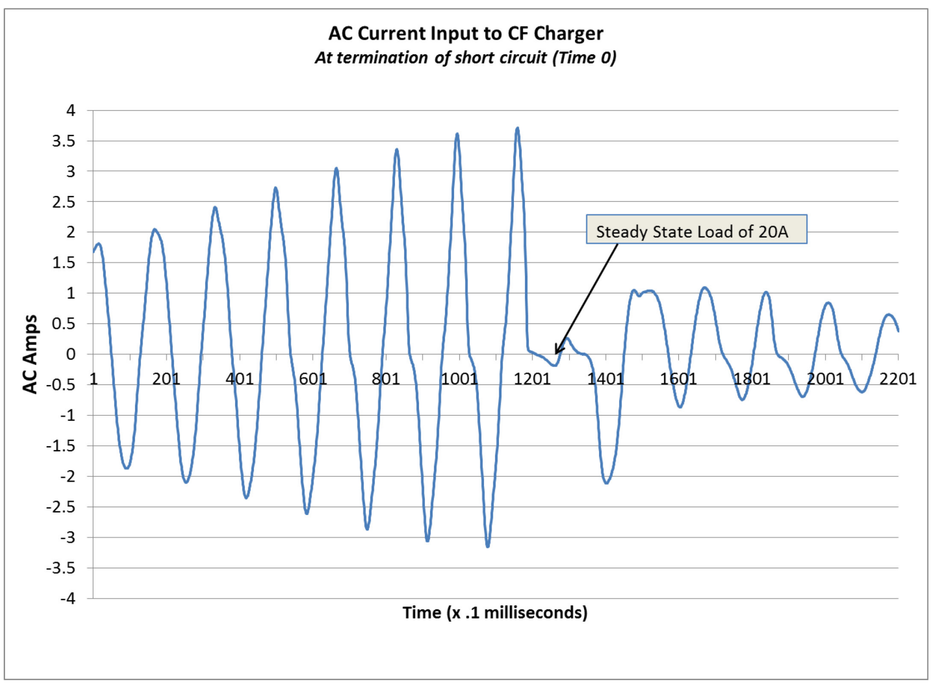


Figure 2-20 Response of the AC Input to the CF Charger at Fault Clearing

No voltage disturbance was seen on the AC supply to the CF charger over the course of the 5-second test cycle. Figure 2-21 illustrates the voltage response on the AC supply when the short circuit was initiated. No voltage transient was detected on the AC supply to the charger when the fault was applied or when it was cleared.

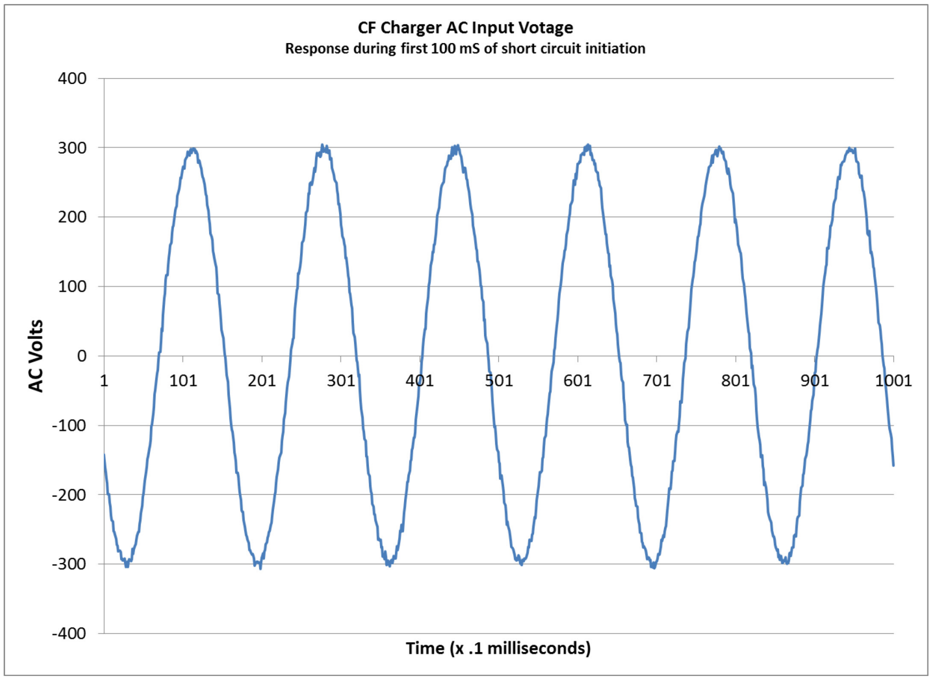


Figure 2-21 AC Input Voltage to the CF Charger at Short-Circuit Initiation

2.3 Combined Battery and Battery Charger Short-Circuit Response

A series of seven 2-second short-circuit tests were performed that combined a battery charger and a battery in parallel. These included three tests using the SCR-type charger—one test with each of the three battery strings—and four tests using the CF-type charger—two with the C&D battery and one each with the GNB and Enersys batteries. The results of these short-circuit tests are delineated in this section for each of the two charger types.

2.3.1 SCR-Type Charger in Parallel with a Battery

Three tests were conducted using the SCR charger in parallel with a battery. Table 2-3 summarizes the short-circuit currents obtained with the SCR charger by itself and the three tests where it experienced the short circuit in combination with one of the battery strings.

Table 2-3 Summary of SCR Short Circuit Test Results

Equipment Tested	Total Maximum Current (Amps)	Maximum Charger Current (Amps)	Time to Current Limit (milliseconds)
SCR Charger (No battery)	**930A**	**930A**	**460mS**
SCR Charger-C&D Battery	**13,970A**	**630A**	**320mS**
SCR Charger-GNB Battery	**11,517A**	**700A**	**318mS**
SCR Charger-Enersys Battery	**13,315A**	**704A**	**300mS**

When the SCR-type charger was connected in parallel with a battery bank, the charger's short-circuit current contribution decreased by about 25% (930A to 700A). The rating of the batteries made little difference on the amount current contributed to the short by the SCR battery charger.

When the battery charger was connected in parallel with a battery bank, the time to achieve its current limit target of 110A decreased by about 30% compared to when the short circuit was applied to the charger only. Part of this time reduction can be attributed to the fact that the magnitude of the peak current from the charger decreased by 25%, and, therefore, the current limit circuit could respond more quickly.

Figure 2-22 illustrates the total short-circuit current contributions from the SCR charger and battery when the charger was connected in parallel with each of the battery strings. Also shown on this graph is the SCR charger response when it was connected in parallel with the C&D battery. The charger's response with the other two battery strings was very similar as depicted in Figure 2-23.

In addition to the magnitude of the charger contribution to a short circuit, the timing of the short-circuit response is of interest as well. As noted in Figure 2-24, the time to reach the current limit target (110A in this case) decreases when the SCR battery charger is connected in parallel with a battery. This outcome can be attributed in part to the lower peak current that the current limit circuit is responding to (note the similarity in the shape of the curves for all the responses).

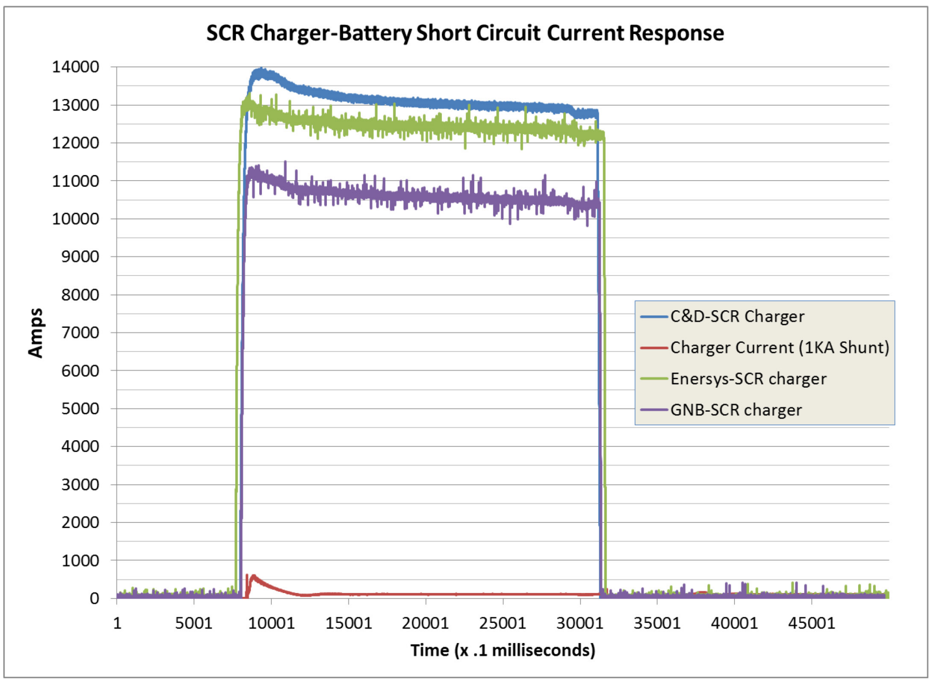


Figure 2-22 SCR Charger Short-Circuit Response in Parallel with Batteries

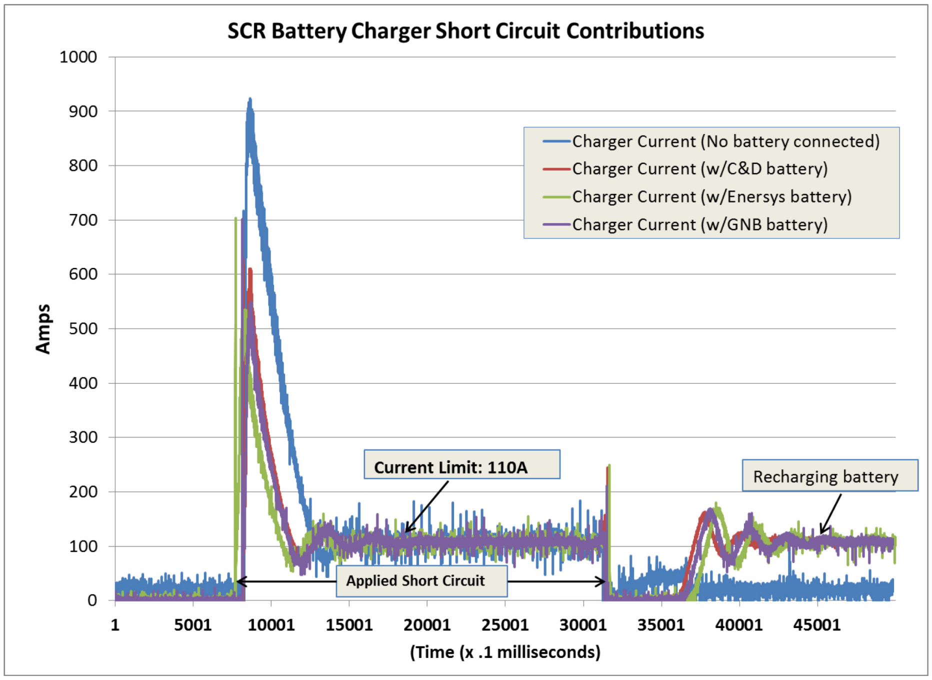


Figure 2-23 SCR Short-Circuit Contribution With and Without Battery Connected

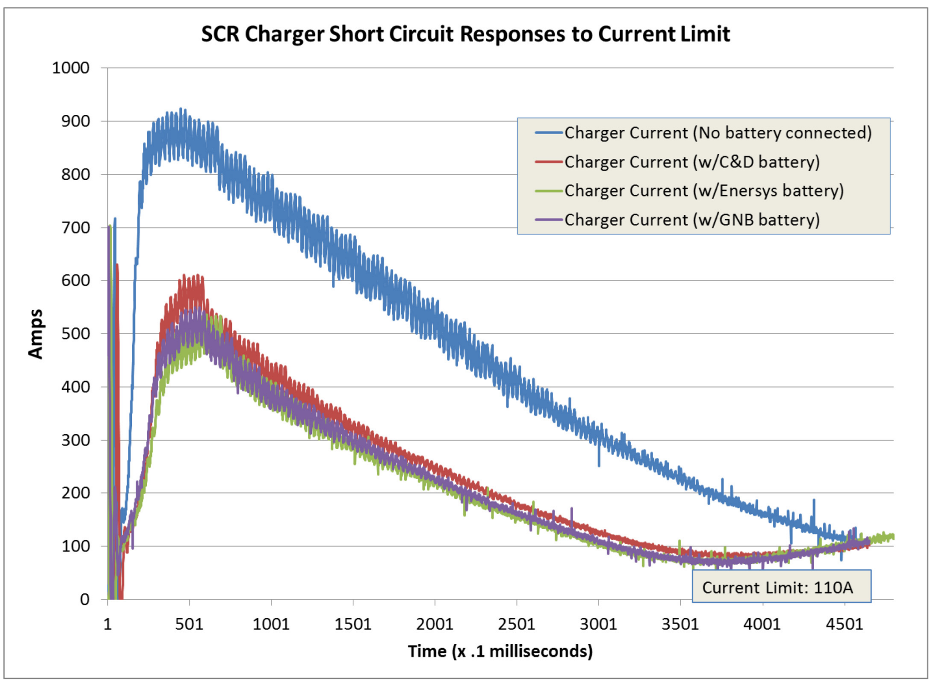


Figure 2-24 SCR Charger Current Limit Response With and Without a Connected Battery

Figure 2-25 focuses on this same response during the first 100 milliseconds following the initiation of the short circuit. The SCR charger current response when the short circuit was applied was nearly identical for each of the three size battery strings.

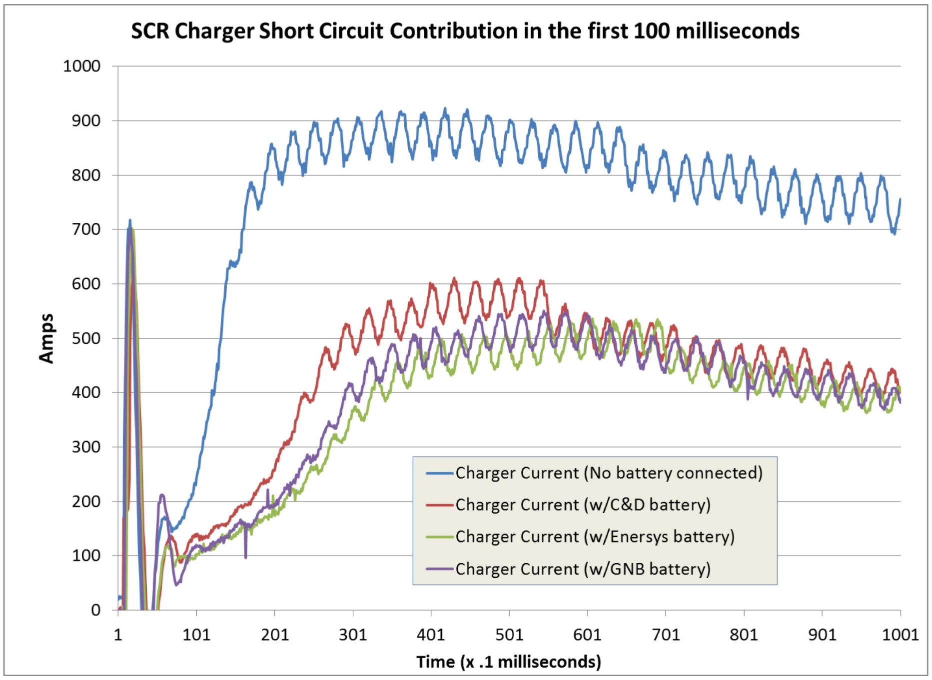


Figure 2-25 SCR Charger Short-Circuit Contribution During the First 100 Milliseconds

As illustrated in Figure 2-26, the voltage response of the SCR charger is noticeably different when the short circuit is applied to the charger without a battery connected as compared to when it is connected in parallel with a battery. The battery and the cables provide a reactive component that yields a sizable voltage spike when the short circuit is terminated. The SCR charger under test was not supplied with a high-voltage shutdown relay, but it is an option that may be chosen. Chargers provided with this protective circuit may trip when a short circuit occurs not because of the high current caused by the short circuit, but rather due to the voltage spike that occurs when the fault is cleared.

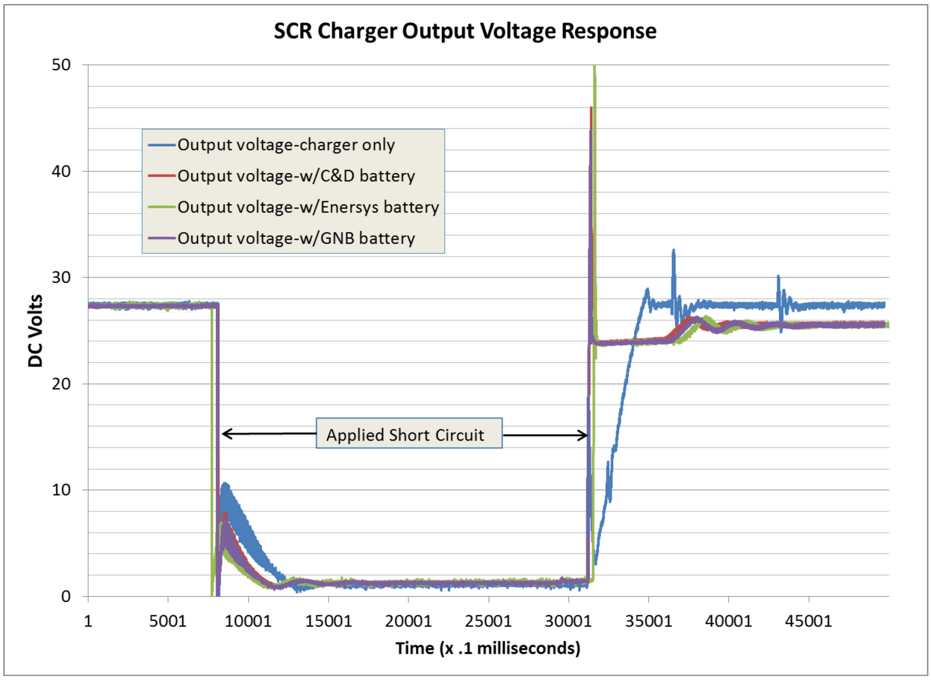


Figure 2-26 SCR Charger Output Voltage Response to a Short Circuit

2.3.2 Controlled Ferroresonant Charger in Parallel with a Battery

Four tests were conducted using the CF charger in parallel with a battery string. A second test of the CF charger with the C&D battery was conducted because following the first test, the charger input breaker was found tripped. The assumption was that the input breaker tripped when the output breaker was manually opened as part of the test restoration activities. On the second test, the charger did not trip during the application of the short circuit.

Table 2-4 summarizes the short-circuit currents obtained for the CF charger and the time for the current limit circuit to limit the current contribution to the fault.

Table 2-4 Summary of CF Charger Short-Circuit Test Results

Equipment Tested	Maximum Total Current (Amps)	Maximum Charger Current (Amps)	Time to Current Limit (milliseconds)
CF Charger (No battery)	1246A	1246A	20mS
CF Charger-C&D Battery (#1)	13,781A	1162A	37mS
CF Charger- C&D Battery (#2)	13,747A	1099A	38mS
CF Charger-GNB Battery	11,038A	1182A	35mS
CF Charger-Enersys Battery	12,881A	1143A	35mS

Figure 2-27 illustrates the short-circuit response on the DC test system over a 5-second time frame when the CF charger was tested. Without any battery connected, the charger contributed over 1200A to the applied fault and over 1100A when the charger was connected in parallel with a battery string. In all cases, the CF charger's current limit circuit very quickly reduced the current to

110A until the short circuit was terminated. At that point, a current spike was observed on the tests where the charger and the battery were connected in parallel. As indicated earlier, this spike results from the magnetic forces in the cables produced by the large fault currents.

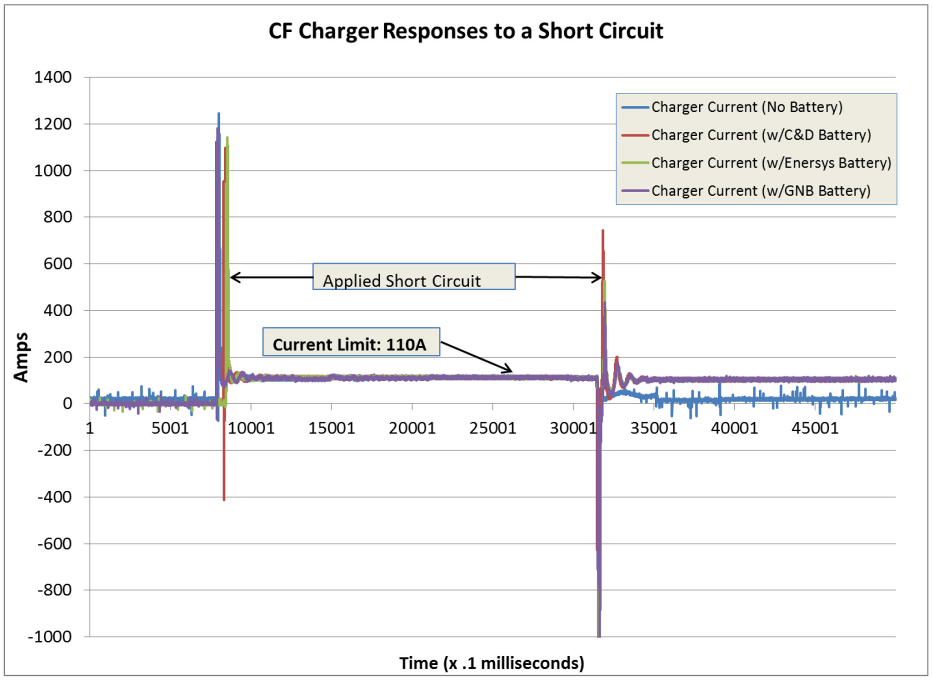


Figure 2-27 CF Charger Responses to a Short Circuit

As stated previously and shown in Table 2-4, the time for the current limit circuit to clamp the short-circuit current contribution to the fault was much faster than the SCR-type charger. This response is illustrated in Figure 2-28.

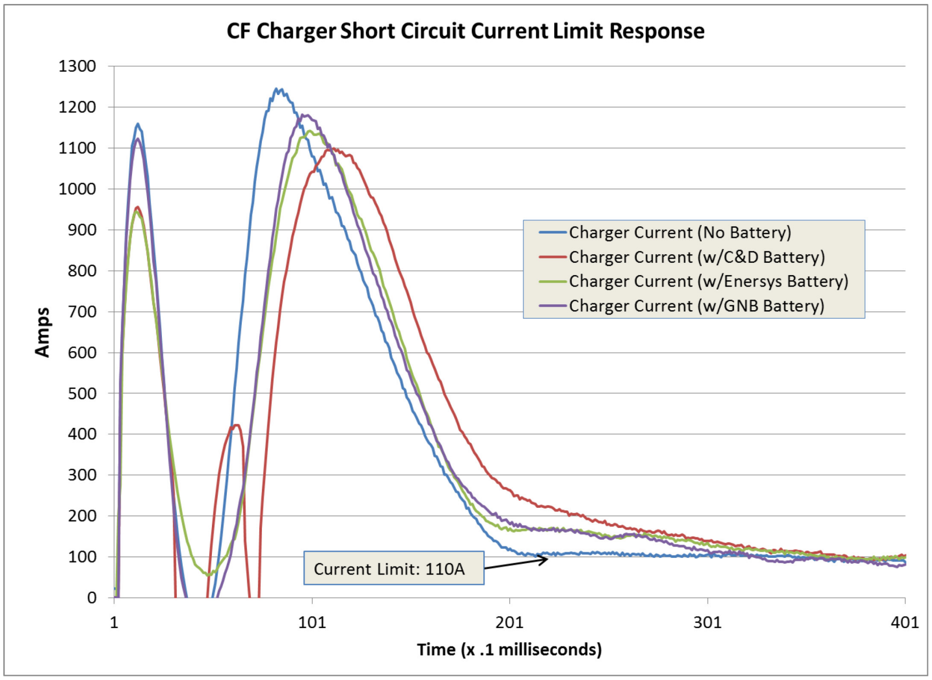


Figure 2-28 CF Charger Current Limit Response (<40 mS)

Figure 2-29 expands the data to illustrate the CF charger's current limit response over the first 100 milliseconds following the short circuit. This is the time frame of general interest since it represents the likely fault clearing time of the protective devices used to isolate a fault in the DC distribution system at a NPP.

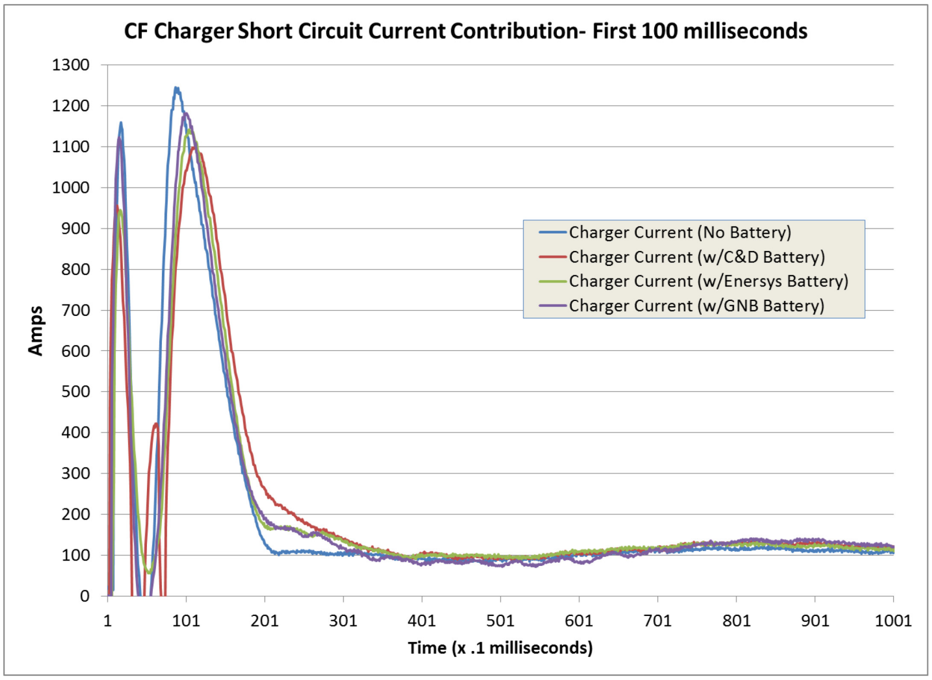


Figure 2-29 CF Charger Response During the First 100 Milliseconds Following the Short Circuit

Figure 2-30 illustrates the output voltage response of the CF charger over the 5-second test period. The voltage decreases to less than one volt during the applied short circuit. Without a battery connected in parallel, its voltage output increases and oscillates for about 0.5 seconds before steadying out at 27 volts. With a battery connected, the output voltage spikes to between 40 and 50 volts when the short circuit is terminated before quickly returning to 27 volts.

The CF charger that was tested has a DC high-voltage shut off set at 30 volts but with a 1-second time delay. So even though the 30V was exceeded, it was for only for about 20 milliseconds.

2.3.3 Summary of Responses in the First 100 Milliseconds

Figures 2-31, 2-32, and 2-33 illustrate the composite responses for the three battery strings by themselves and in combination with the SCR- and CF-type chargers. The shapes of the curves are very similar indicating that the circuit time constants are very similar as well. While the battery charger short-circuit values are low when compared to the battery contribution, they are measurable and, in the case of the SCR charger, contribute to the short circuit for more than 100 milliseconds.

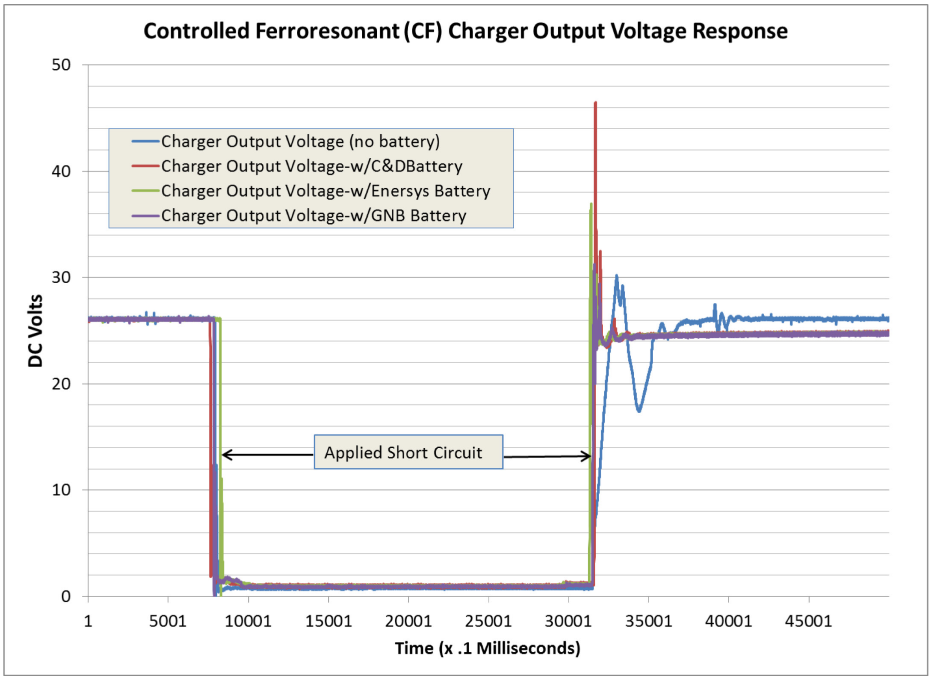


Figure 2-30 CF Charger Output Voltage Response over the Test Period

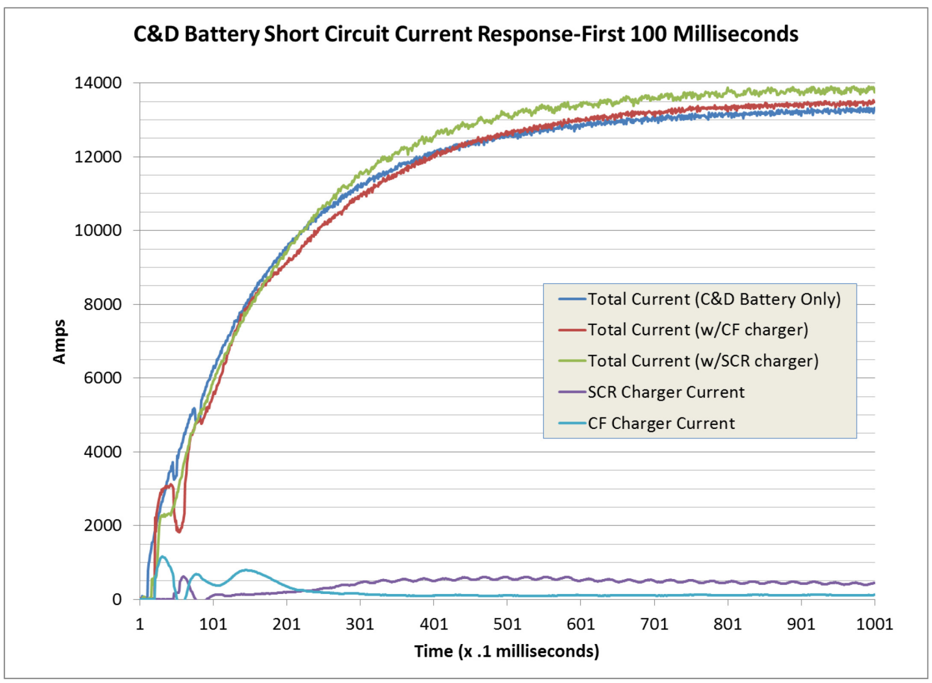


Figure 2-31 C&D Battery Short-Circuit Current Response — First 100 Milliseconds

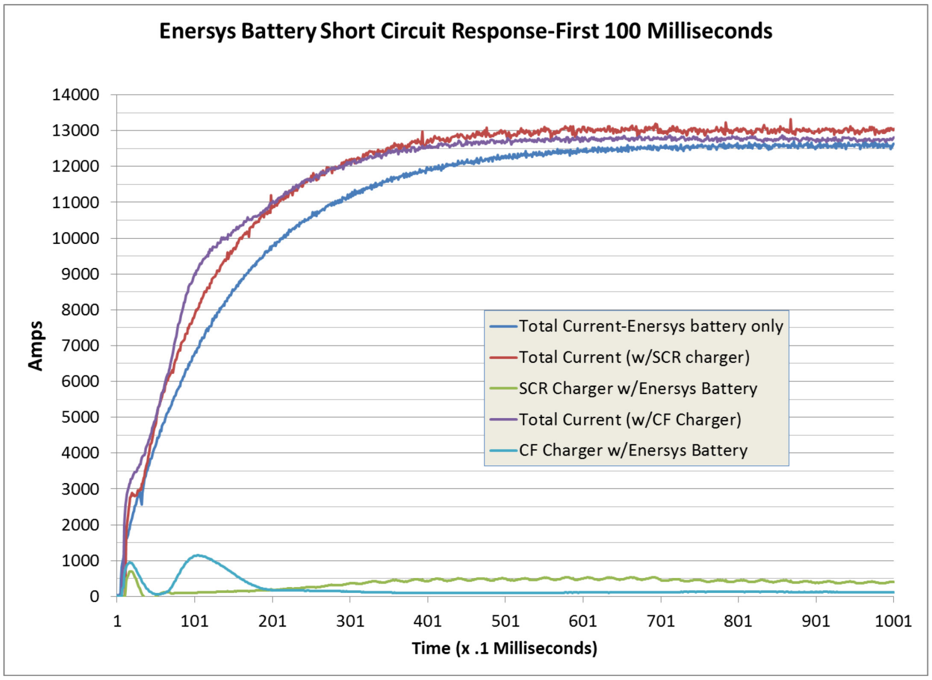


Figure 2-32 Enersys Battery Short-Circuit Current Response — First 100 Milliseconds

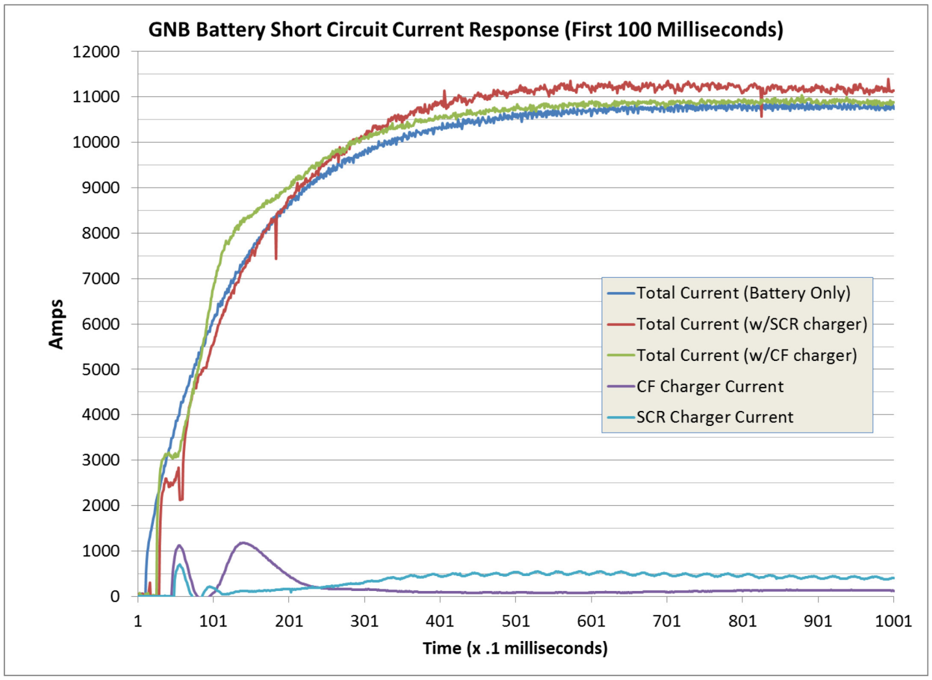


Figure 2-33 GNB Battery Short-Circuit Current Response — First 100 Milliseconds

2.4 Short Duration Fault Testing Results

A series of shorter duration faults were applied to each of the battery strings in order to determine the impact on the battery voltage, both the magnitude of the decrease in battery string voltage and the post fault battery voltage level. These shorter duration tests were achieved by modifying the software to the shorting switch. The mechanical aspects of the pneumatically operated switch precluded us from getting the exact switch closure time for each battery string; however, we were able to achieve five data points that allowed us to understand the impact of the fault duration on the battery voltage over the range of interest. Table 2-5 summarizes the voltage response for the C&D battery. Both the overall string voltage and the Cell #1 response are shown for each of the tests. The original 2-second (2000 mS) test results are also shown as a reference.

Table 2-5 C&D Battery Summary for Short Duration Fault Response

Contact Closure Time	Overall Battery Voltage Pre-Test Post-Test		Cell #1 Voltage Pre-Test Post-Test		Voltage Change per Cell	Resulting Voltage for 60-cell string (nominally 130V)
100 mS	26.33V	25.0V	2.2V	2.12V	0.08V	123.4V
200 mS	26.8V	25.0V	2.25V	2.10V	0.15V	121.0V
400 mS	26.3V	24.4V	2.2V	2.04V	0.16V	120.4V
500 mS	26.9V	24.2V	2.25V	2.025V	0.225V	116.5V
700 mS	26.4V	24.0V	2.20V	2.00V	0.20V	118.0V
2000 mS	26.4V	23.9V	2.20V	2.00V	0.20V	117.5V

For the 100 mS duration fault, the voltage drop per cell was observed to be only 0.8V, and for the 12-cell string, a voltage decrease of 1.33V. Extrapolating this response to a 60-cell string most commonly found in a NPP results in an expected voltage change on the DC bus of 6.65V, reducing its nominal voltage level to about 123.4V. This is not of immediate safety significance since the DC bus is typically considered operable down to about 105V (minimum voltage per cell is 1.75 V).

Figure 2-34 illustrates the voltage response for each of the five short duration tests performed on the C&D battery string. Regardless of the duration of the fault, the overall battery string voltage decreased to less than 12 volts. Once the fault is removed, the battery voltage recovery occurs within 10-20 mS but not quite to what the voltage level was prior to the fault.

This same response can be seen on the single cell response shown in Figure 2-35. Even if the fault was sustained for 0.5 seconds (500 mS), the resulting 60-cell voltage level would be 122.4V (60 x 2.04V) well within a plant's acceptable operating range.

A similar response was obtained for the Enersys battery string as well. The overall battery string response for the five shorter duration tests conducted on the Enersys battery is shown in Figure 2-36. Figure 2-37 has the response on a per cell basis.

Finally, the GNB battery response to the five shorter duration faults is illustrated in Figures 2-38 and 2-39. Except for the observation that the magnitude of the voltage during the fault for the GNB battery was less than that for the other two vendors, the general response was the same. Note that the GNB battery is the lowest capacity battery of the three tested and has the highest internal resistance per cell. The higher voltage decrease is, therefore, to be expected.

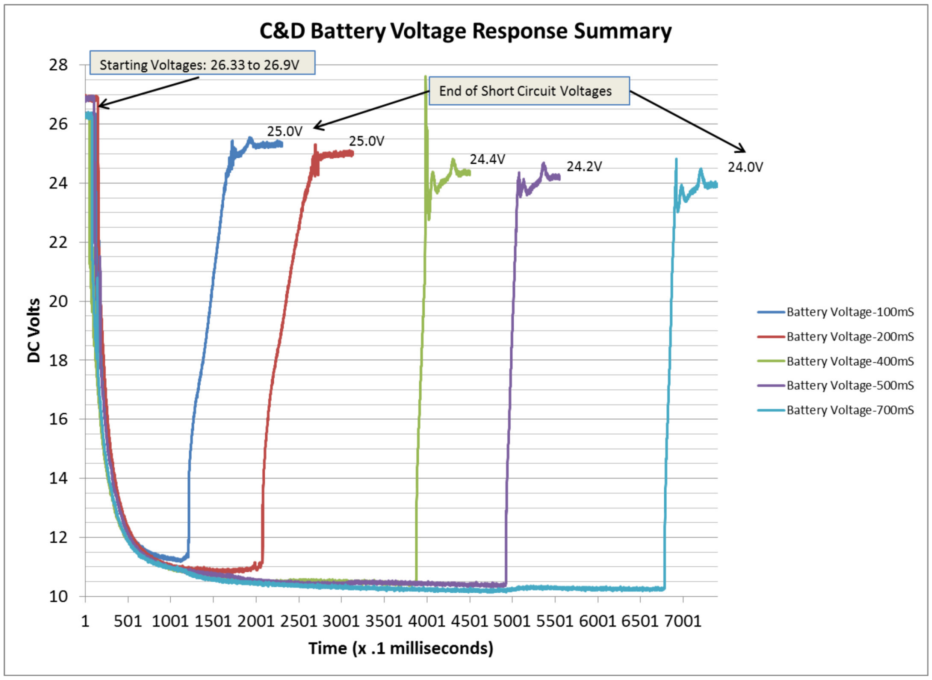


Figure 2-34 C&D Battery Voltage Response Summary

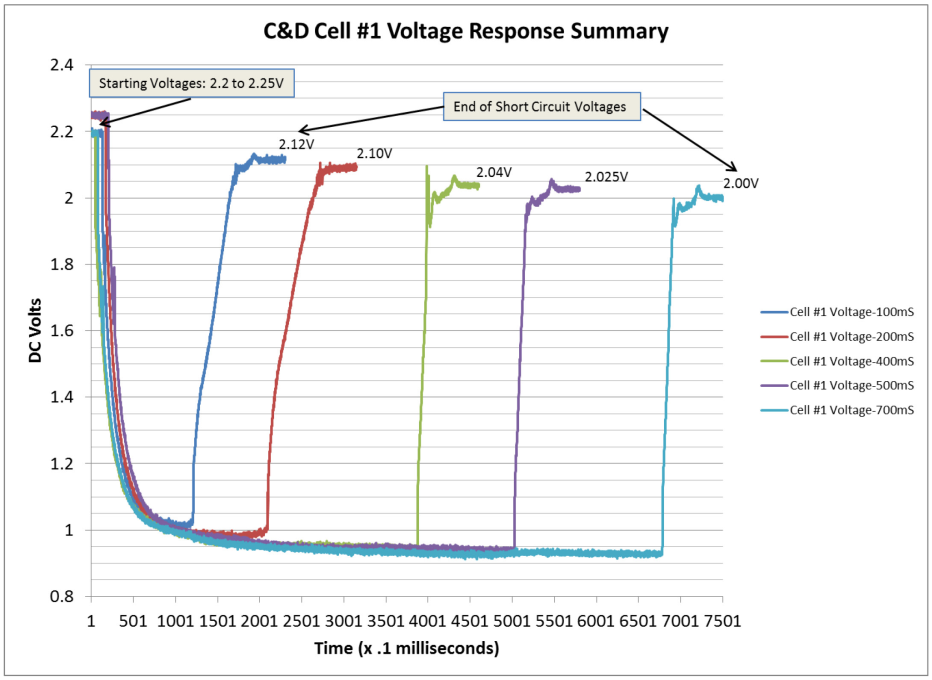


Figure 2-35 C&D Cell #1 Voltage Response Summary

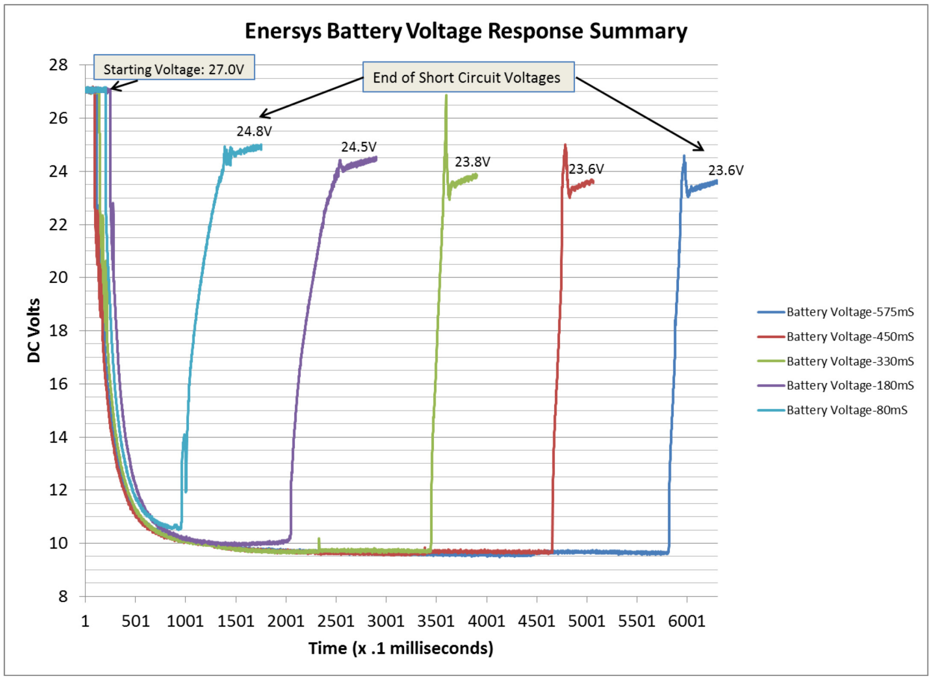


Figure 2-36 Enersys Battery Voltage Response Summary

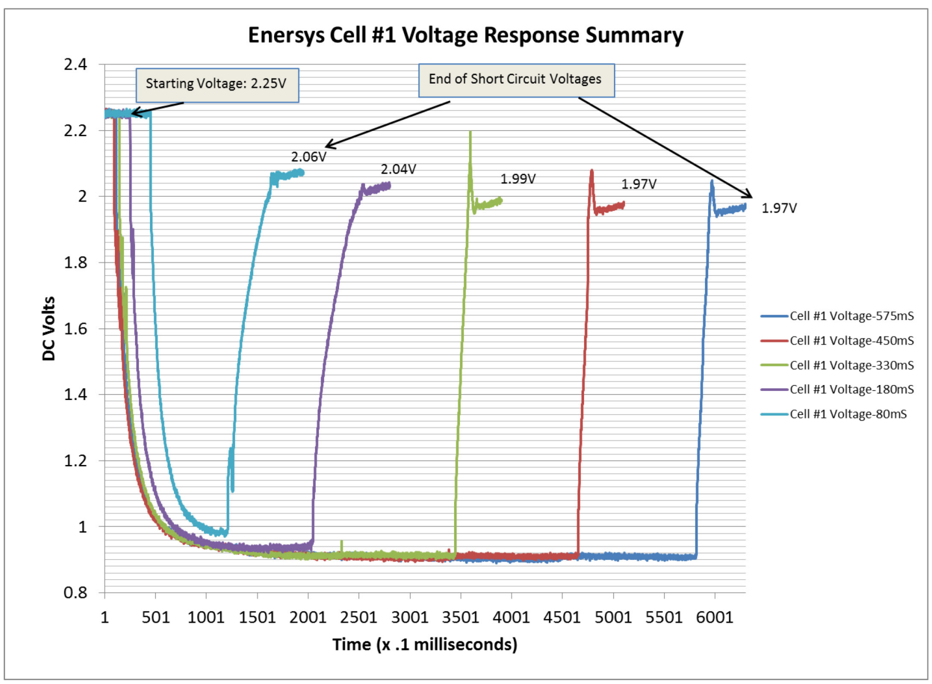


Figure 2-37 Enersys Cell #1 Voltage Response Summary

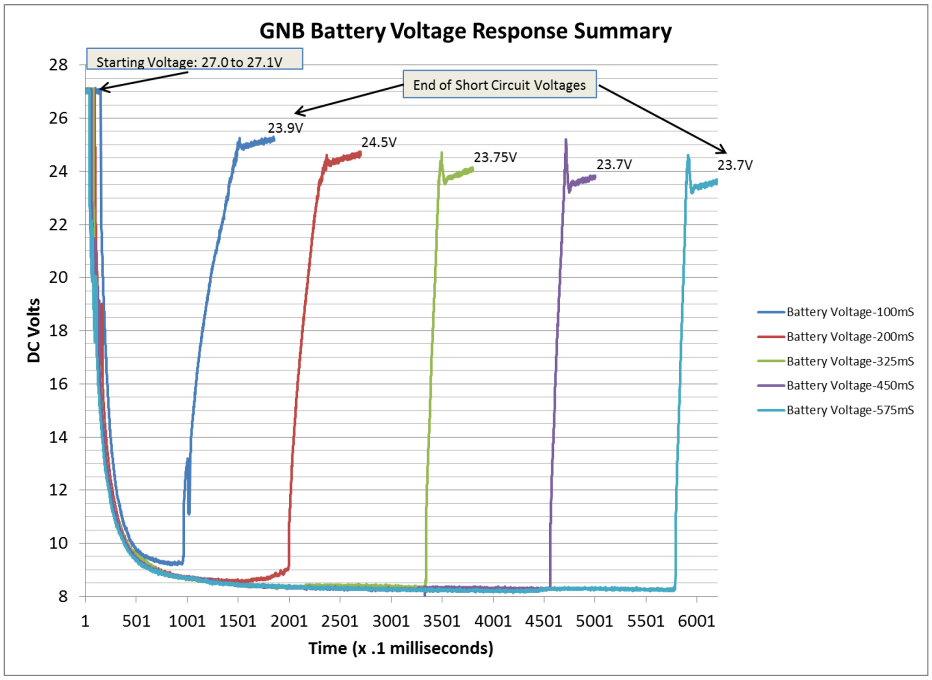


Figure 2-38 GNB Battery Voltage Response Summary

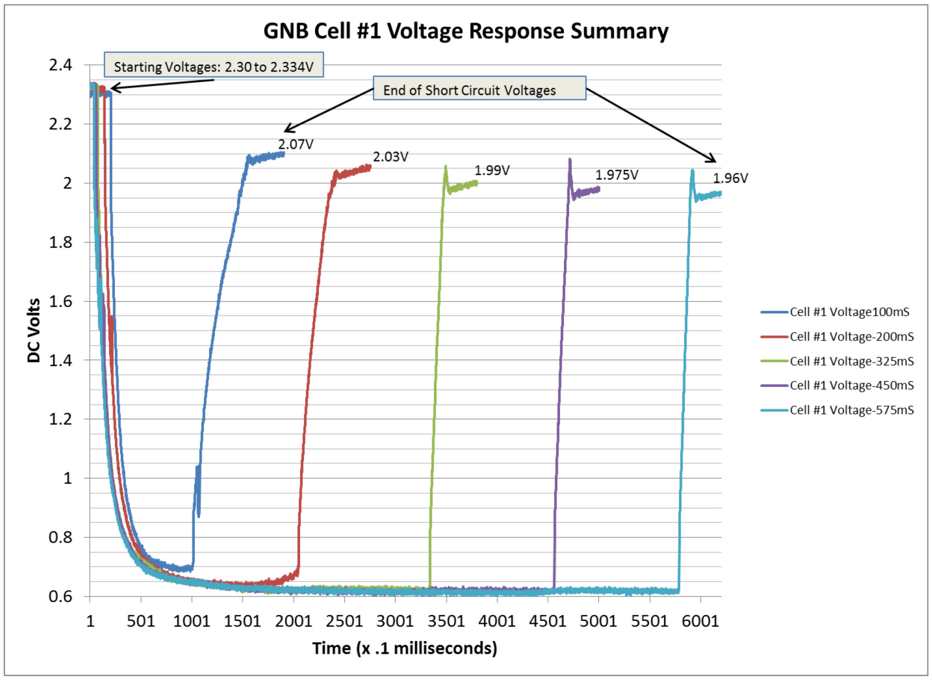


Figure 2-39 GNB Cell #1 Voltage Response Summary

One other way to graphically represent the end voltage response relationship with the fault duration is illustrated in Figure 2-40 for the Enersys battery. This figure shows the Cell #1 end voltage plotted as a function of the fault duration for the five short duration tests as well as the original 2-second (2000 mS) test that was performed. As might be expected, the shorter the duration of the fault, the less the impact on the battery voltage. However, at about 500 milliseconds, this effect stabilizes out to the 2000 mS fault duration. That can be explained by the fact that regardless of the short-circuit duration (up to 2 seconds), very little capacity is taken from the cell. This fact is demonstrated by the very short time it takes to return the battery string to its pre-faulted state of charge (less than ½ hour for the 2-second fault). The change in voltage to ~1.97V/cell is similar to the voltage change that occurs during a 4-hour performance test on the battery. As soon as a load is placed on the battery, its voltage decreases to this value before slowing decreasing towards 1.75V/cell as the battery is fully discharged.

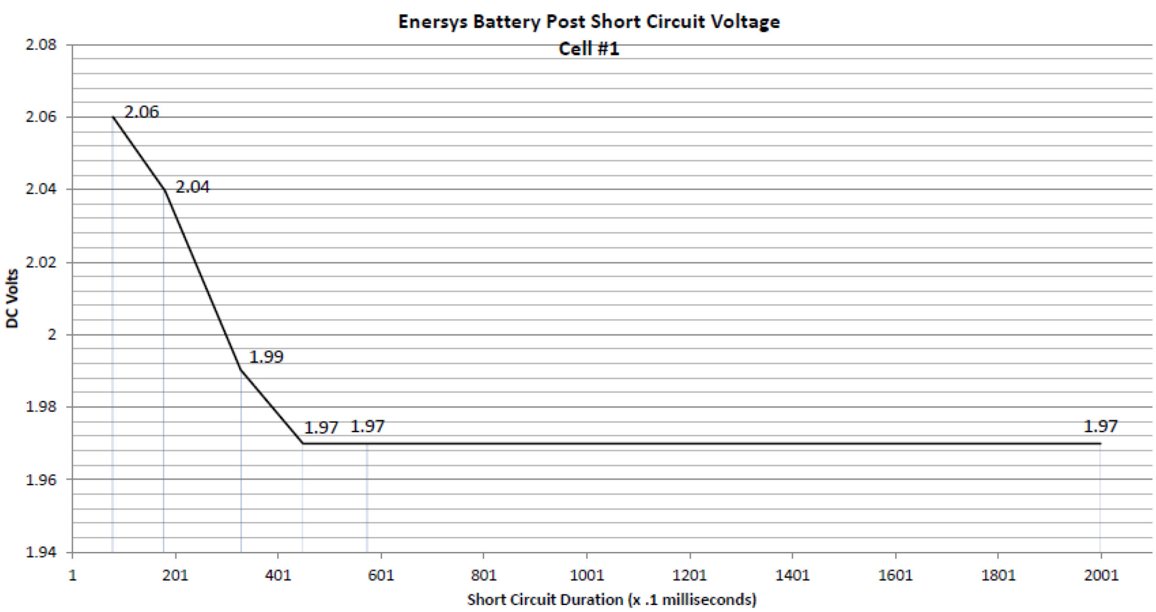


Figure 2-40 Battery End Voltage Response to Fault Duration Times

The impact, however, of the decrease in voltage during the fault is not as innocuous. Other research and experience has shown that inverters, DC power supplies, and digital controllers are susceptible to voltage sags and are often protected with devices to trip the equipment. While some equipment may automatically recover once the fault is cleared, there is sufficient evidence to indicate that at least some of the equipment must be manually reset following a fault where the DC voltage decreases to roughly 60 volts (1V/cell). Further plant-specific research is required to fully understand the plant's impact to a fault on the DC bus. As shown by the event at Palisades, a significant operational disturbance can occur that requires aggressive operator action to restore the plant to a safe condition.

2.5 Thermography Results

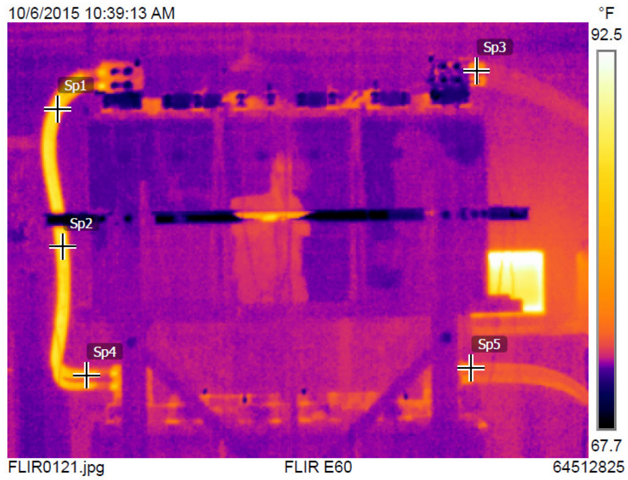
During the testing, an infrared camera was used to monitor the temperature of the batteries, the battery charger, the cables, and the connectors. The purpose of this effort was to determine if any equipment was reaching dangerously high temperatures that could result in equipment damage or a fire, and to ascertain if there were any high resistance points that could have impacted the magnitude of the fault current that was achieved. The sensitivity of the camera allowed small

temperature changes (<5ºF) to be detected and recorded. The data obtained showed that the 2-second applied fault did not create any unusually hot spots indicating that there were no unusually high resistances at any of the battery or cable connections.

Figure 2-41 depicts the inter-tier cables on the Enersys battery during the 2-second applied fault. These inter-tier cables carry the entire short-circuit current. The colors produced by the infrared camera indicated a temperature rise of approximately 13ºF, not enough to significantly change the resistance of the circuit over that time interval.

Measurements	°F
Sp1	85.4
Sp2	85.6
Sp3	75.5
Sp4	80.0
Sp5	74.6

Parameters	
Emissivity	0.95
Refl. temp.	68 °F
Distance	3.3 ft
Atmospheric temp.	68 °F
Ext. optics temp.	68 °F
Ext. optics trans.	1
Relative humidity	50 %



Battery

Point SP2 show cable temperature increase of about 13F.

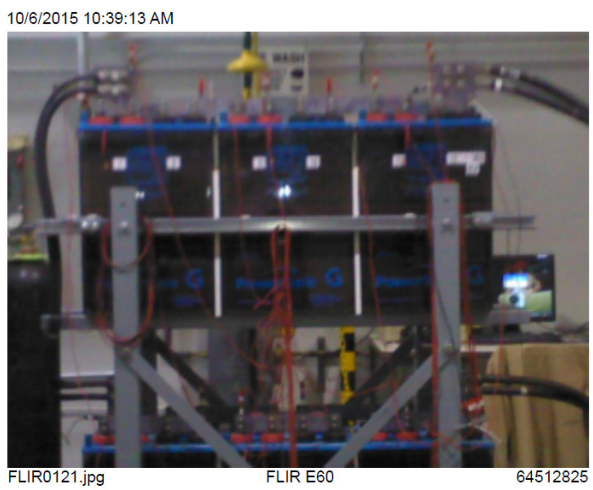


Figure 2-41 Enersys Inter-tier Cable Temperature Change During Short-Circuit Test

Figure 2-42 captures the response of the C&D battery string during the fault. As illustrated here, the intercell connectors carrying the current did increase in temperature but only by approximately 8ºF.

The use of the infrared camera was useful in demonstrating that no hot spots existed and that the fault currents were not creating any safety issues for the equipment or the personnel.

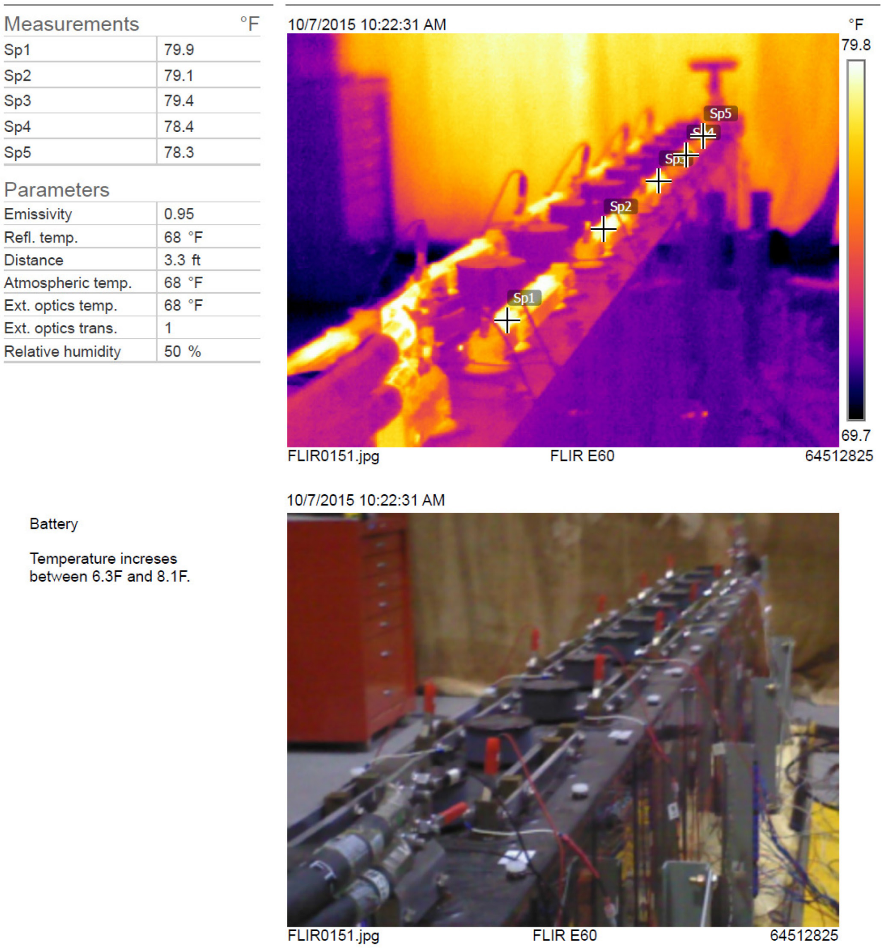


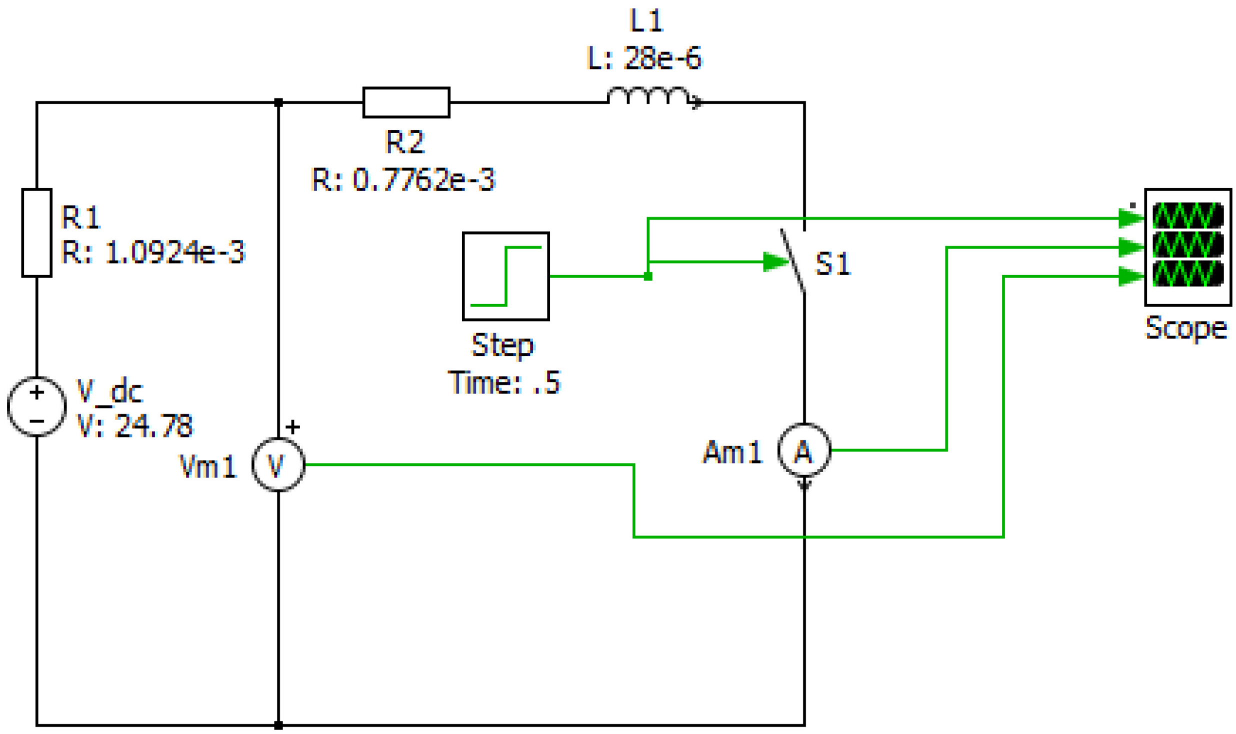
Figure 2-42 C&D Battery Temperature During Applied 2-Second Fault

2.6 Parametric Analyses

Following the testing, presentations of the preliminary data were given to the NRC staff and the IEEE Stationary Battery Working Group. A recommendation from both groups was that it would be useful to evaluate how different cable lengths and sizes would impact the resulting short circuit responses. BNL procured a software package that allowed different circuit configurations to be evaluated—namely, PLECS, Simulation Software for Power Electronics, by Plexim Electrical Engineering Software. Conducting these parametric analyses showed that: (1) the electrical test circuit could be accurately modeled; (2) changes in the circuit impedance impacts the fault current contribution significantly and in a somewhat proportional manner, and (3) the results obtained from this testing should be applicable to any DC circuit arrangement as long as the circuit impedance is known.

2.6.1 Tested Circuit

The first parametric study that was conducted was to replicate the measured parameters. Figure 2-43 illustrates the modeled test circuit and the parameters that represent the measured values in the test circuit.



Simulated Circuit
R1= Battery internal resistance
R2=Cable and other external circuit resistance
L1= Cable and other external circuit inductance
Vdc=Nominal battery voltage for 12 cell in series.

Figure 2-43 Model of Tested Circuit

The maximum short circuit current obtained using the modeled circuit is depicted in Figure 2-44.

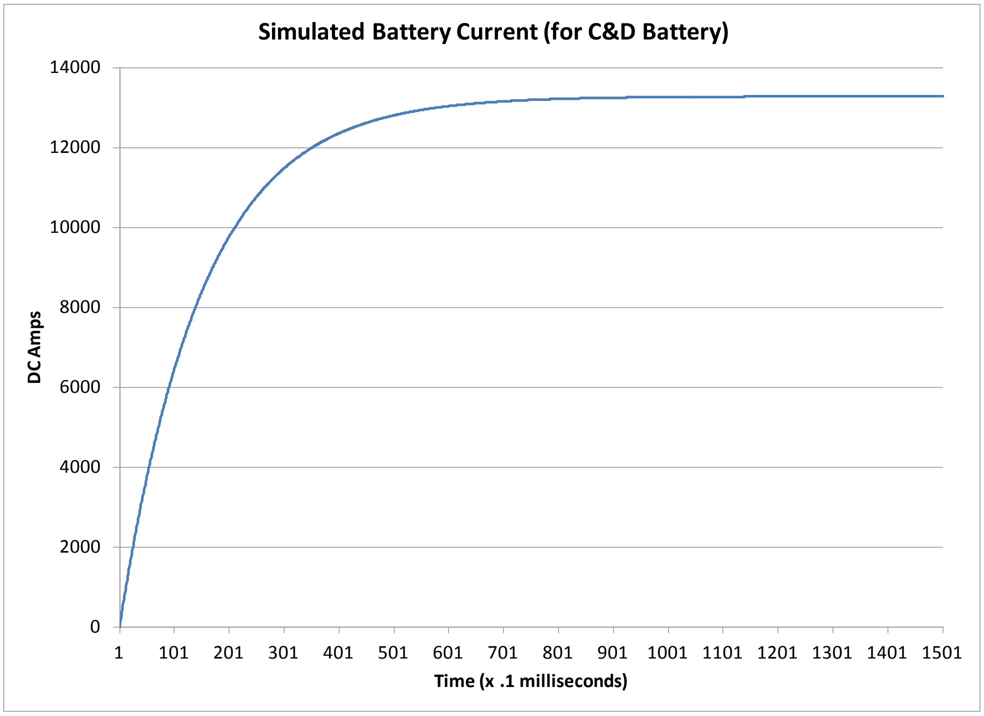


Figure 2-44 Simulated Current for the C&D Battery

Figure 2-45 illustrates the actual tested current for the C&D Battery. Note that the response and the magnitude of the current match very well to the simulation.

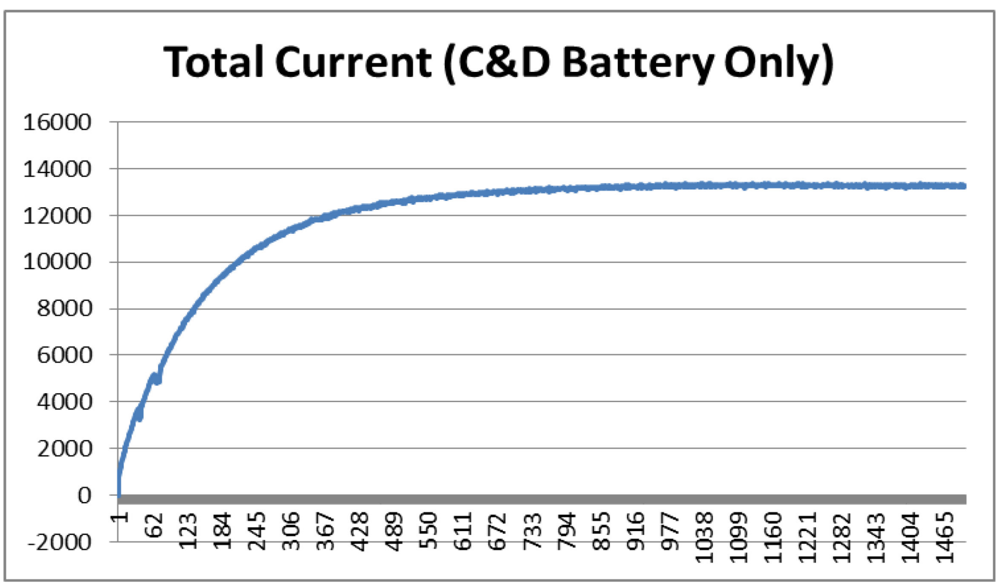


Figure 2-45 Tested Response of the C&D Battery

2.6.2 Simulated Circuits

To determine the changes in the magnitude of the fault current due to changes in the cable size and length, two simulations were run. For a simulation that has half the resistance and inductance (represented by four 500 MCM cables in parallel), the magnitude of the short-circuit current

increases accordingly. The model used in the software is illustrated in Figure 2-46; the responding battery short circuit current and voltage response is shown in Figures 2-47 and 2-48.

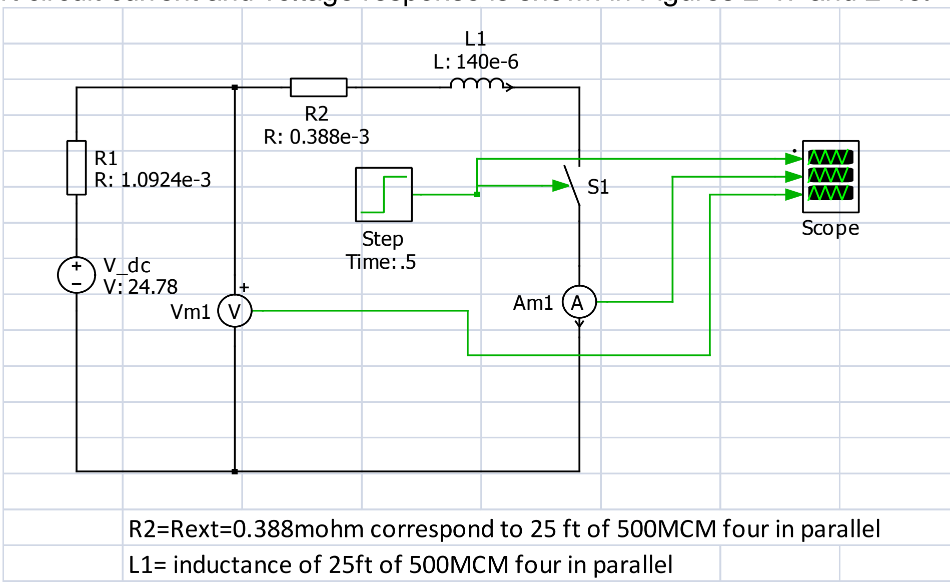


Figure 2-46 Model of Circuit with Four 500 MCM Cables Connected in Parallel

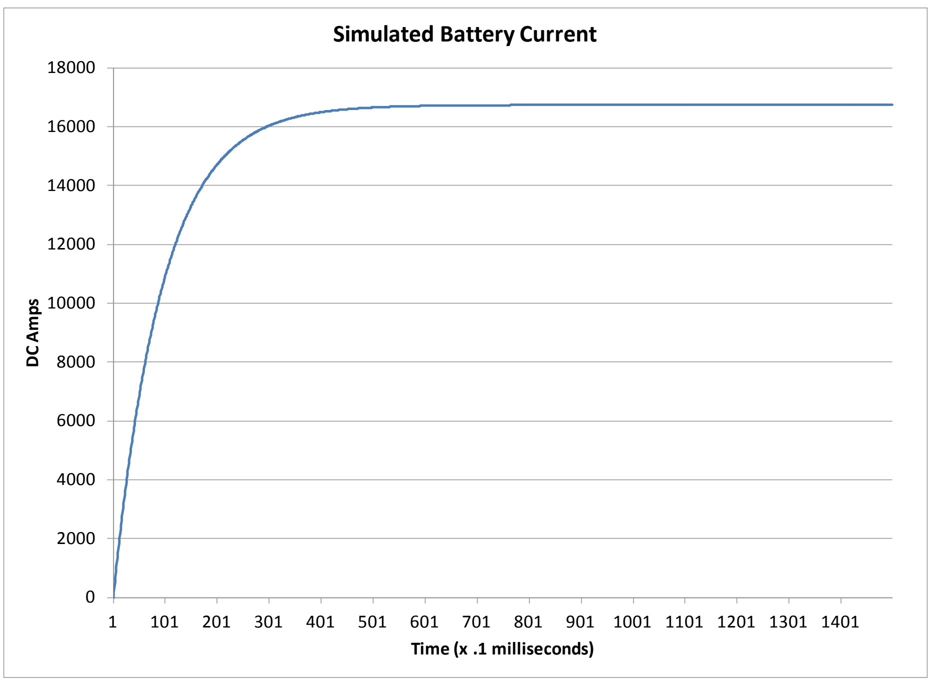


Figure 2-47 Short-Circuit Current Response to Simulated Circuit

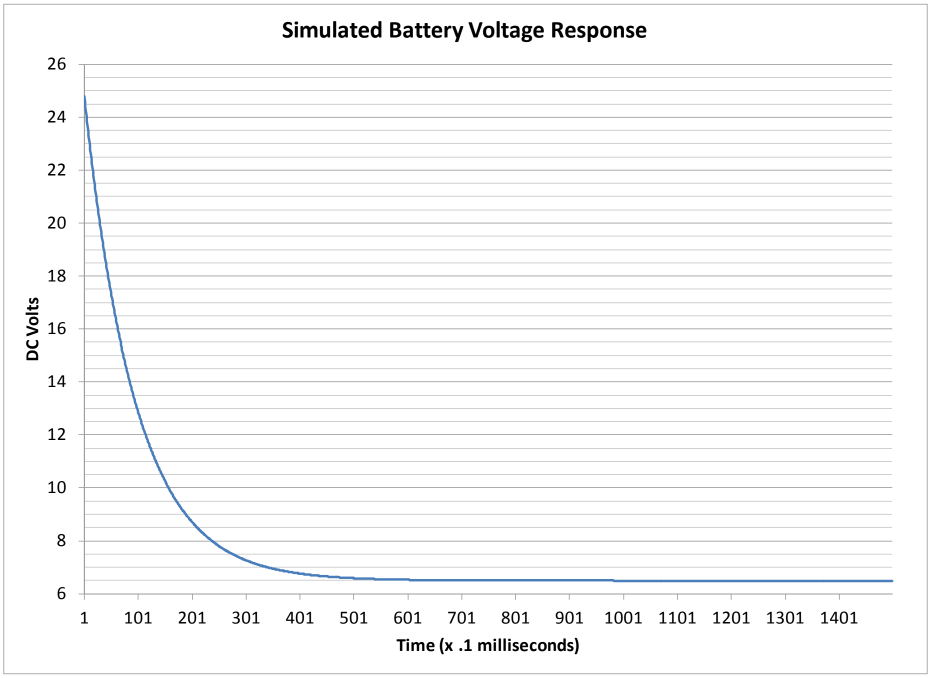


Figure 2-48 Battery Voltage Response to Simulation Circuit with ½ Test Resistances

In the simulation shown in Figure 2-49, the effect of increasing the impedance of the circuit is illustrated. As expected, the magnitude of the short-circuit current is significantly decreased as is the impact on the battery voltage. These effects are illustrated in Figures 2-50 and 2-51.

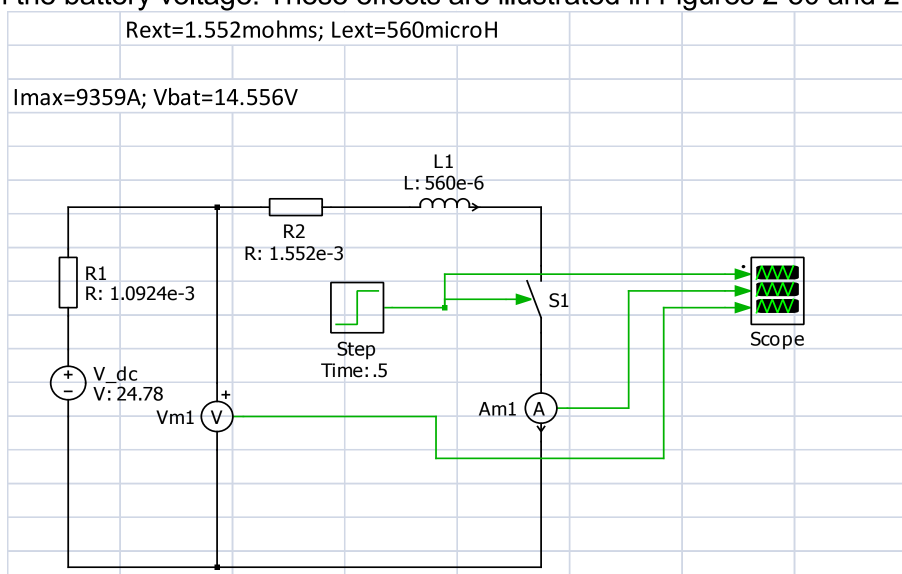


Figure 2-49 Simulation of Test Circuit with Twice the Resistance and Inductance

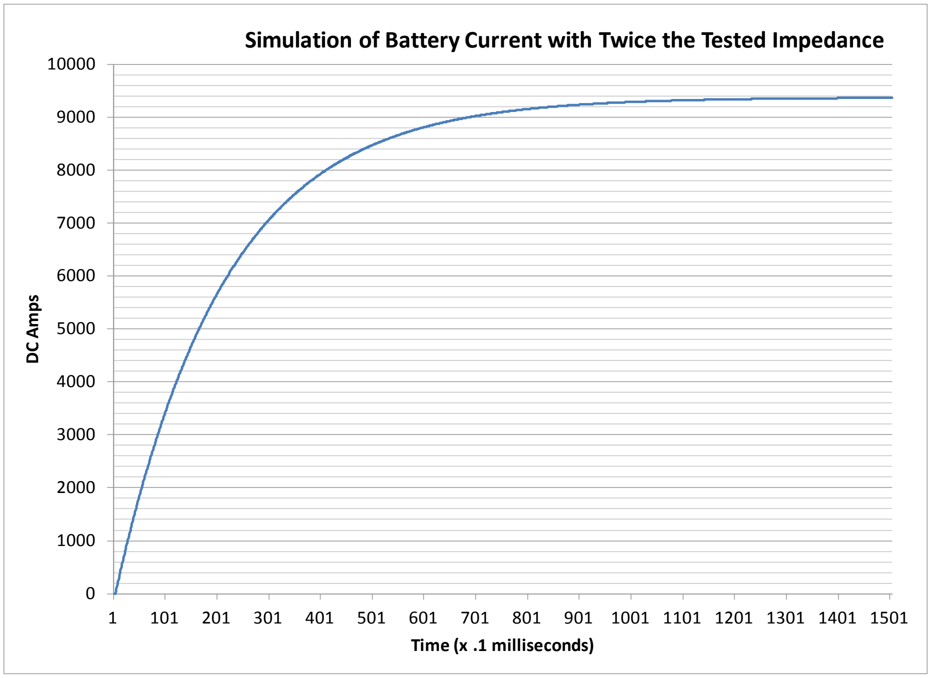


Figure 2-50 Simulation of Battery Short-Circuit Current with Twice the Circuit Impedance

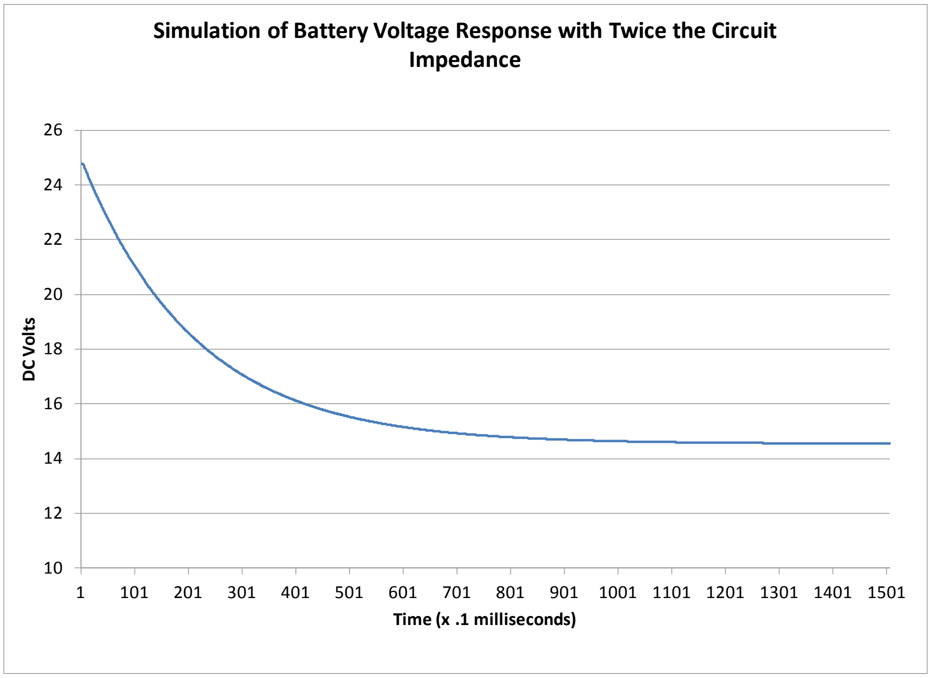


Figure 2-51 Battery Voltage Response to Higher Circuit Impedance

3 CONCLUSIONS AND RECOMMENDATIONS

Short-circuit testing has been completed on three sets of Class 1E vented lead-acid batteries and two types of battery chargers that are used in safety-related NPP DC distribution systems. The objective of the tests was to determine the short-circuit contributions from these batteries and battery chargers when the fault was applied individually or in parallel.

The key observations and recommendations described in this test report are:

1. The measured short-circuit current contributions from the battery compared favorably to the calculated short-circuit current of the batteries using the methodology contained in IEEE Standard 946-2004. The magnitude of the battery currents obtained in this testing were much less than the rule-of-thumb values that estimate the current contribution from a short that occurs at the battery terminals illustrating the importance of including the DC circuit impedance when performing fault calculations for protection system coordination.

2. The magnitude of the short-circuit current from an SCR battery charger is about 9 times its rated output; the magnitude of the short circuit from a CF charger is about 12 times its rated output. The maximum short-circuit contribution from a battery charger is reduced by ~25% when it is connected in parallel with a battery. Note that IEEE Standard 946-2004 indicates that the charger contribution will be limited to its current limit setting (usually 110% of its rating) when connected in parallel with a battery.

3. The short-circuit current contribution from a battery charger to the overall fault current depends on the response time of its current limit circuit. In the testing conducted, the SCR-type charger contributed more to the overall fault than the CF charger due to the longer response time of its current limit circuit. The assumption made in IEEE Standard 946 2004 that the current limit circuit will operate within 2 cycles (32 mS) may be accurate for CF chargers but not for all SCR chargers. The additional current contribution from the SCR chargers can impact protective coordination calculations important to minimize the impact of a fault on the plant safety systems. Further evaluation by the NRC staff of the adequacy of the short circuit calculations for a fault on safety related DC systems at NPPs through the NRC Inspection Program (e.g., Electrical Distribution System Functional Inspection-EDSFI) may be warranted.

4. The battery charger current limit function operates differently in a short-circuit scenario when the charger is connected to a battery than when the fault is applied to the charger only. While this does not have a dramatic effect on the overall DC system response, the designer should be aware that the circuit impedance will affect the charger response to a fault condition.

5. The testing demonstrated the substantial voltage drop (>50V) that occurs on the DC system during a fault may disrupt or disable other safety related power supplies due to actuation of their low voltage protection. The loss of inverters or DC power supplies could result in the inoperability of important instrumentation and controls. The operator's response to a fault should be identified in NPP standard operating procedures and operator training to ensure that challenges to plant safety systems are minimized as a result of a postulated fault on the DC system.

6. The battery voltage drop is approximately the same for fault times varying from 2 seconds to 100mS; however, the battery voltage immediately after the fault is cleared tends to be higher when the fault time is shorter, demonstrating that faults should be cleared as quickly as possible to minimize the long-term operational effects of a fault on the DC system.

7. No apparent damage to the battery or the battery chargers was detected because of the short-circuit testing. In fact, the recharge of the battery following a 2-second short circuit was accomplished in less than 1 hour as compared to nearly 24 hours following a standard 4-hour performance test. This indicates that the battery state of charge will still be sufficient to carry out its design function after a fault event.

8. The empirical data obtained from this testing will be useful input to updating several IEEE Standards (e.g., IEEE 946-2004 and 1375-1998) that provide guidance on the short-circuit response of batteries and battery chargers in DC distribution systems. The testing revealed the significance of the overall circuit impedance on the fault current contributions from the battery and battery chargers. Using an accurate value for the circuit impedance when calculating fault currents is essential for achieving the desired coordination of the associated protect devices to minimize the impact of a fault on safety system operability. In addition, certain assumptions made in these standards are not applicable to all battery charger designs.

9. The NRC staff should consider endorsing IEEE Standards 946-2004 and 1375-1998 once they are revised since they are widely used in the nuclear industry. Further information dissemination of the technical information identified in this report should also be considered by the NRC staff, such as a new or revised Information Notice, Information Bulletin, Regulatory Guide, or Inspection Procedure, to ensure that NPPs have correctly analyzed the potential current contributions from a battery and battery charger to a fault on the safety related DC distribution system.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT (200 words or less)

On September 25, 2011, at the Palisades Nuclear Plant, both the battery and the battery charger on one Direct Current (DC) Class 1E power division tripped on overcurrent when a fault occurred in a downstream DC panel (see NRC Information Notice 2013-17). The response to a fault on the DC distribution system at a nuclear power plant can have a significant impact as seen by this event. Therefore, proper DC fault calculations are necessary to design effective DC system fault protection with coordination that would minimize the safety system impacts of a fault event. As a result of the significance, the U.S. Nuclear Regulatory Commission (NRC) contracted with Brookhaven National Laboratory (BNL) to investigate the interactions between a battery and a battery charger under fault conditions. BNL conducted tests to determine whether the individual short-circuit current contributions of a battery and a battery charger are independent of each other in a typical nuclear power plant (NPP) DC system. Tests conducted at BNL provide the empirical data to support improvements to industry standards and to the NRC's oversight of DC distribution systems. Results demonstrate that the contribution to a fault from a battery charger and the impedance should be considered when establishing the settings for the DC distribution system protective devices to avoid undesirable system responses.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

protective coordination, battery, battery charger, direct current (DC), DC auxiliary power systems, fault condition, DC system fault protection, fault characteristics, protective devices, DC system circuit, silicon controlled rectifier (SCR)-type charger design, controlled ferroresonant (CF) transformer charger design, Palisades Nuclear Plant, short circuit, current contributions and DC distribution systems.

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