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

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Introduction

Testing was performed at Brookhaven National Laboratory for the U.S. Nuclear Regulatory Commission to determine whether the individual short circuit current contributions to a fault by a battery charger and battery are independent of each other or are influenced when the battery and the battery charger are connected in parallel. The need for this testing was prompted by a fault that occurred on the DC distribution system at a nuclear power plant that had an unexpected system response.

A series of short-circuit tests were conducted on three vented lead-acid battery strings of 12 cells (24 Volt nominal systems) and each of two 24 Volt battery chargers (a controlled ferroresonant and an SCR design) 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 information about how this equipment would respond to a fault when connected in the configuration most commonly used in safety related DC power distribution systems at U.S. nuclear power plants.

The results from this testing program that are presented in this paper may provide the empirical data to support improvements to the industry standards that provide guidance on DC system short circuit characteristics and electrical protection design and to the NRC's oversight of DC distribution system protective coordination.

Objective

The primary objective of this project was to conduct testing to evaluate the short circuit current contributions of the battery charger and the battery to a fault on the DC distribution system. This information is needed to confirm that the battery and battery charger contributions to the fault current on the DC distribution circuit are being correctly applied to the dc system over-current protective device selection and coordination to limit the impacts of a fault event on the non-faulted distribution and connected loads on the DC system. A secondary objective is to support an update to industry standards that the NRC could endorse via a Regulatory Guide.

Overview

The testing performed at BNL used three Class 1E qualified battery strings that were previously employed on two projects sponsored by the NRC (see NUREG/CR-7148 and NUREG/CR-7188). Two new battery chargers were procured; one a Silicon Controlled Rectifier (SCR) type and one a Controlled Ferroresonant (CF) transformer design. The three nuclear-qualified batteries are representative of the battery vendors used for more than 75% of the current nuclear power plants. The battery chargers, while not Class 1E qualified, represent about 90% of the battery charger design technology used in the current U.S. nuclear power plants.

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 seven combined charger and battery tests provided new information about how this equipment would respond to a fault when connected in the configuration most commonly used in nuclear power plants and other standby power systems.

Industry standards provide guidance on how a battery and battery charger should respond to a short-circuit condition. As documented in a BNL Technical Report [Ref. 1], some of the guidance is conflicting and little of it is based on empirical data. The lack of a standard method for approaching the short-circuit protection and coordination of critical DC distribution system protective devices could lead to different settings for protective devices and potentially less than optimal plant responses to a fault on the DC distribution system.

The key observations that are described further in this paper are:

1. The magnitude of the currents obtained in this testing were much less than the vendor provided or rule-of-thumb values that estimate the current contribution from a short that occurs at the battery terminals. Calculations of the short circuit current performed without the external resistance of the test circuit compare favorably to the vendor provided values.
2. The measured short circuit current contributions from the battery compared favorably to the calculated short circuit current of the batteries using the battery manufacturer's published internal resistance of the cells, the measured resistance of the external test circuit and the cell open circuit potential.
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.
4. The maximum short-circuit contribution from a battery charger is not significantly reduced when it is connected in parallel with a battery, however, its current limit function behaves differently when the charger is connected to a battery than when the fault is applied to the charger only.
5. A substantial battery voltage drop occurs when a short-circuit is applied and can result in a subsequent plant upset condition if the low voltage protective devices on DC power supplies and/or inverters actuate.
6. No apparent damage to the battery or the battery chargers was detected as a result of the short-circuit testing. The recharge of the battery following a two second short-circuit was accomplished in less than one hour.
7. The empirical data obtained from this testing may be useful in IEEE Standards that provide guidance on the short circuit response of batteries and battery chargers in DC distribution systems (see Table 2).

Preliminary Testing Results

Battery Current Contribution to a Fault

The test circuit for simulating a fault on 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 (2-30' 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 (2-50' lengths of stranded cable). The overall measured resistance of the cables and connectors external to the battery string was ~ 0.8 milliohms. The test setup is depicted in Figure 1.

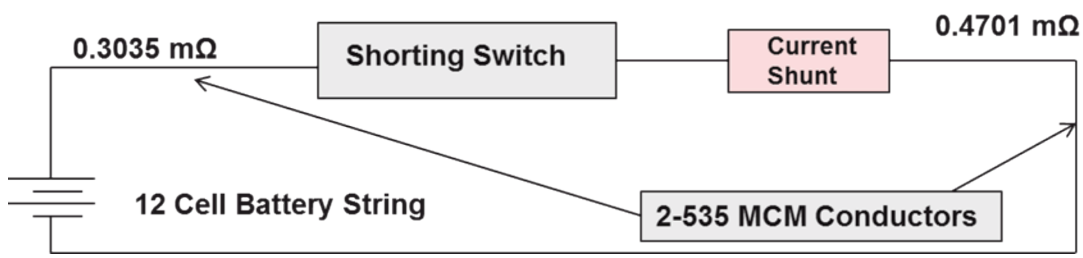

Figure 1. Schematic of Battery Short Circuit Test Arrangement

As illustrated in Figure 2, the maximum short-circuit current obtained during testing for the C&D battery was 13,520A; the maximum short-circuit current obtained during the short-circuit test of the Enersys battery produced 12,700A; and the GNB battery maximum short-circuit current was 10,900A. These results are summarized in Table 1, along with an estimate of the short circuit current based on 10X the one minute rating of the cell, and the battery vendor supplied short circuit values that are based on the internal resistance of the cell. Both of these estimates are based on a short-circuit that is applied across the terminals of the battery.

It is interesting that including the external circuit resistance of. ~0.8 mΩ to the C&D LCR-33 battery short circuit tests yields an expected short circuit current of approximately 13,282 A, within 2% of the 13,520 A measured during the test.

This was determined by using the published internal resistance of 0.000091 Ω for one (1) – LCR-33 cell that includes 1 inter-cell connector. The battery string consisted of 12 cells so the overall battery internal resistance including the inter-cell connectors yields 12 x 0.000091 Ω = 1.092 mΩ.

Using the open circuit potential for the LCR-33 battery of 2.065 VPC x 12 cells = 24.78 V and a total resistance of $R_{battery} + R_{external\ circuit}$ = 1.092 mΩ + 0.7736 mΩ= 1.8656 mΩ = R_T, the expected or calculated short circuit current would be: $I_{SC} = V_{battery\ open\ circuit} / R_T$ or 24.78 V/1.8656 mΩ = 13,282 A. Note that this calculation uses the methodology recommended in IEEE Std. 946 for determining available short circuit current where the battery open circuit potential is used (2.065 VPC).

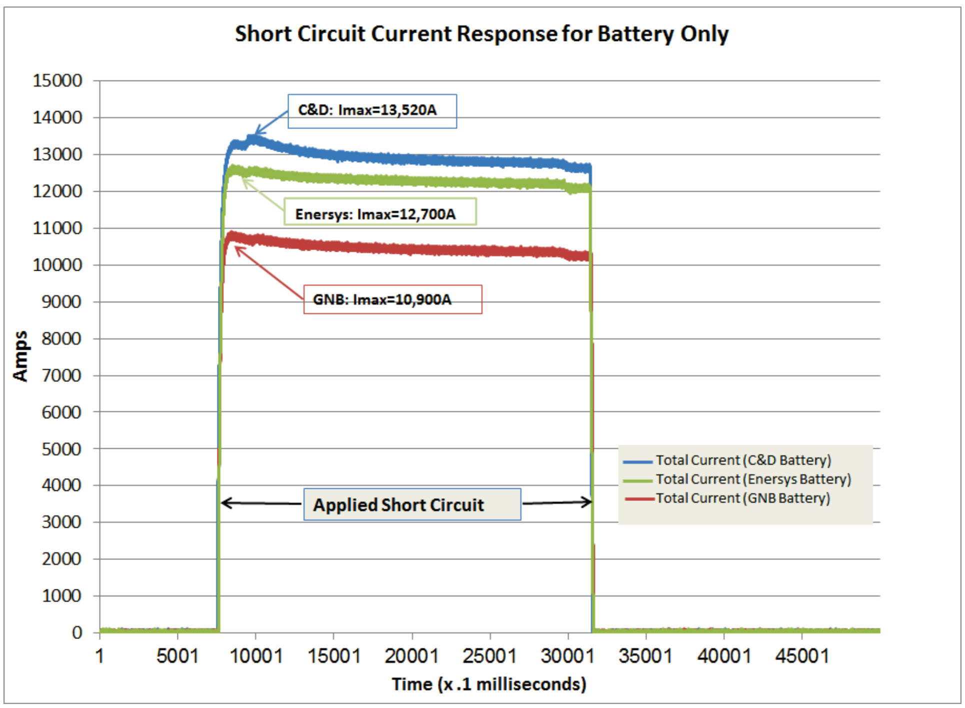

Figure 2. Short Circuit Response of Each of the Battery Strings

Table 1. Comparison of Test Data to Estimates of Battery Short Circuit Current

Battery	Max. Current - **Test**	1-minute rating	10x the 1-minute rating	Vendor I_{SC}
C&D LCR-33	**13,520A**	**2350A**	**23,500A**	**21,834A**
Enersys 2GN-23	**12,700A**	**2100A**	**21,000A**	**18,690A**
GNB NCN-21	**10,900A**	**1400A**	**14,000A**	**12,393A**

Battery Charger Current Contributions to a Fault

The battery chargers were able to sustain the 2 second 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. The lower short-circuit contribution from the chargers when connected to a battery is expected due to the additional circuit electrical impedance associated with the batteries and the cables. Of importance, however, is that the charger contribution is measurable and more significant than what is currently described in documents such as IEEE Standard 946-2004 which states that when the battery charger is connected in parallel with the battery, the battery capacitance will prevent the battery charger contribution from rising instantaneously. The short-circuit current contributions from the SCR and CF chargers with and without a battery connected in parallel are illustrated in figures 3 and 4.

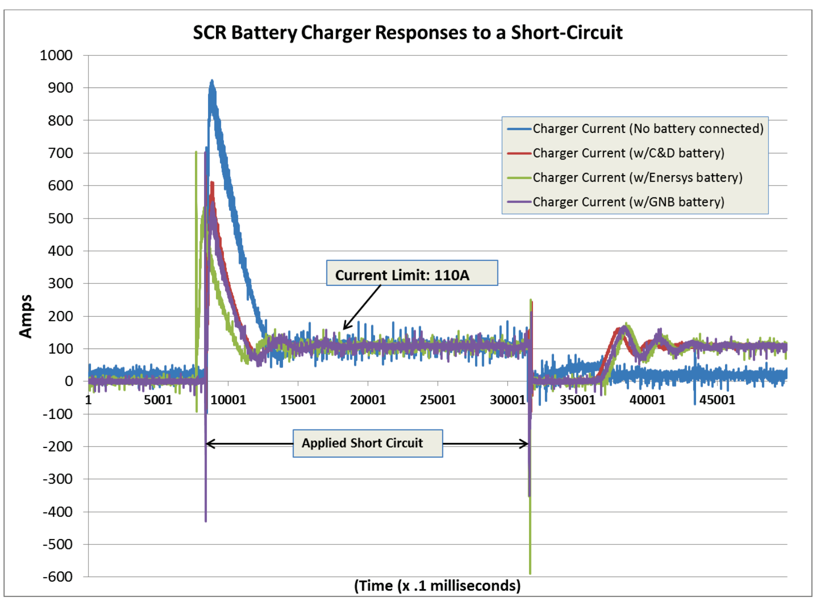

Figure 3. SCR-Type Battery Charger Response to a Short Circuit

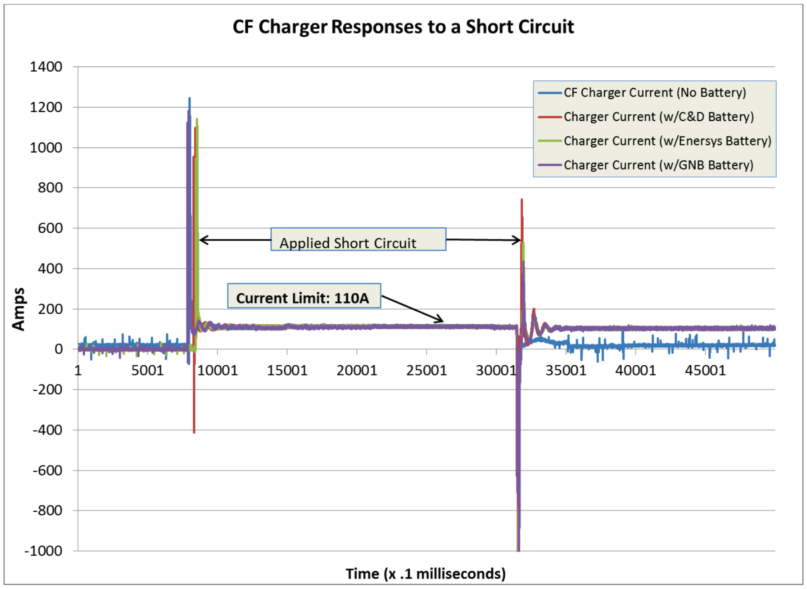

Figure 4. Controlled Ferroresonant (CF) Responses to a Short Circuit

Combined Battery and Battery Charger Response in the First 100 Milliseconds

The initial series of tests performed at BNL used a 2 second short circuit to allow adequate time for the batteries and chargers to respond to the fault condition. Subsequent tests were performed with shorter fault times primarily to examine the battery voltage response.

The time period of most interest is based on the operating times of the protective devices that would actuate if such a fault condition was to occur. This time period is generally 100-200 milliseconds or less. 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 value of 110A. It therefore contributed more to the total short circuit current during the first 100 milliseconds following such an event. This is illustrated for the C&D battery string in figure 5. Overall we concluded that the internal circuitry of the battery charger can vary and the design of the current limit circuit can impact the charger's contribution to the overall fault current from the battery and the battery charger operating in parallel.

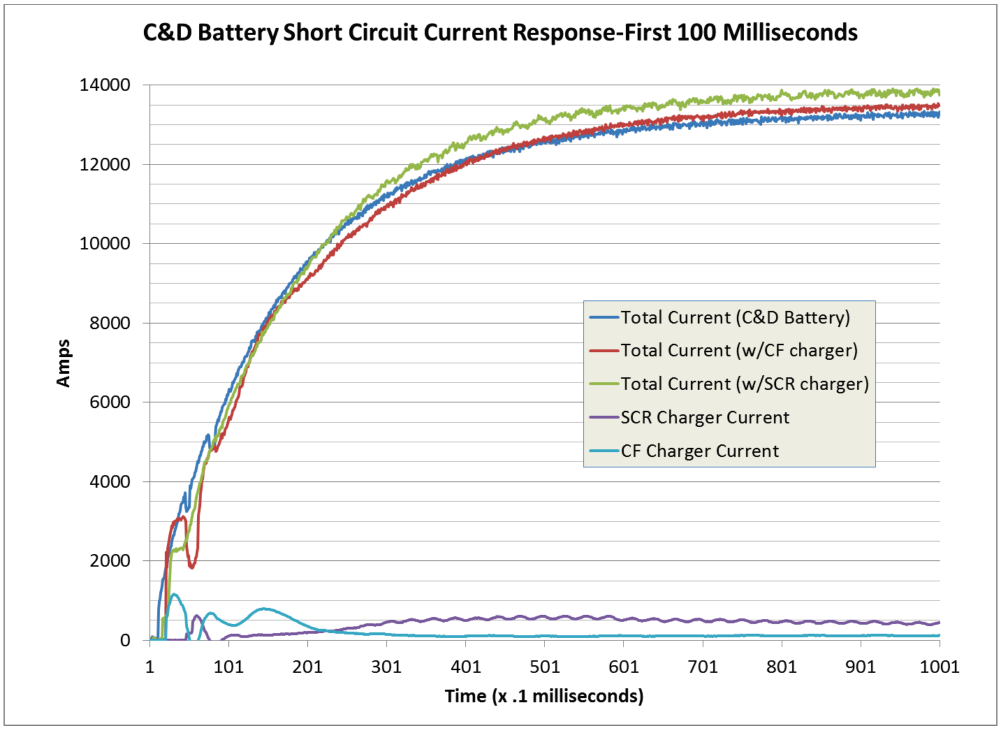

Figure 5. C&D Battery Short-Circuit Response-First 100 Milliseconds

Battery Voltage Response During a Fault

The battery output voltage decreases when the short circuit is applied to a battery, either individually or in parallel with the battery charger, and remains low as long as the short circuit persists. For the 12-cell configuration used in this testing, the overall battery string voltage decreased from about 27 volts to about 10 volts. Cell #1 was also monitored in each battery string during the applied fault. The output voltage was seen to decrease from about 2.2 volts to 1.0 volt or less. As illustrated in Figure 6, the GNB cell voltage decreased to approximately 0.8 volts during the applied short circuit and then returned to a voltage level slightly less than its starting point (about 2.0 V/cell). For a typical 60 cell string operating at 130 volts in a nuclear power plant, 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 from their under-voltage protection (depending on the timing of their protective devices). 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 as long as the battery charger is available to carry the DC load and recharge the battery. If the battery charger trips during the fault (which did not occur during the testing at BNL), the operator needs to recognize that the battery string voltage will be lower than it was prior to the fault event.

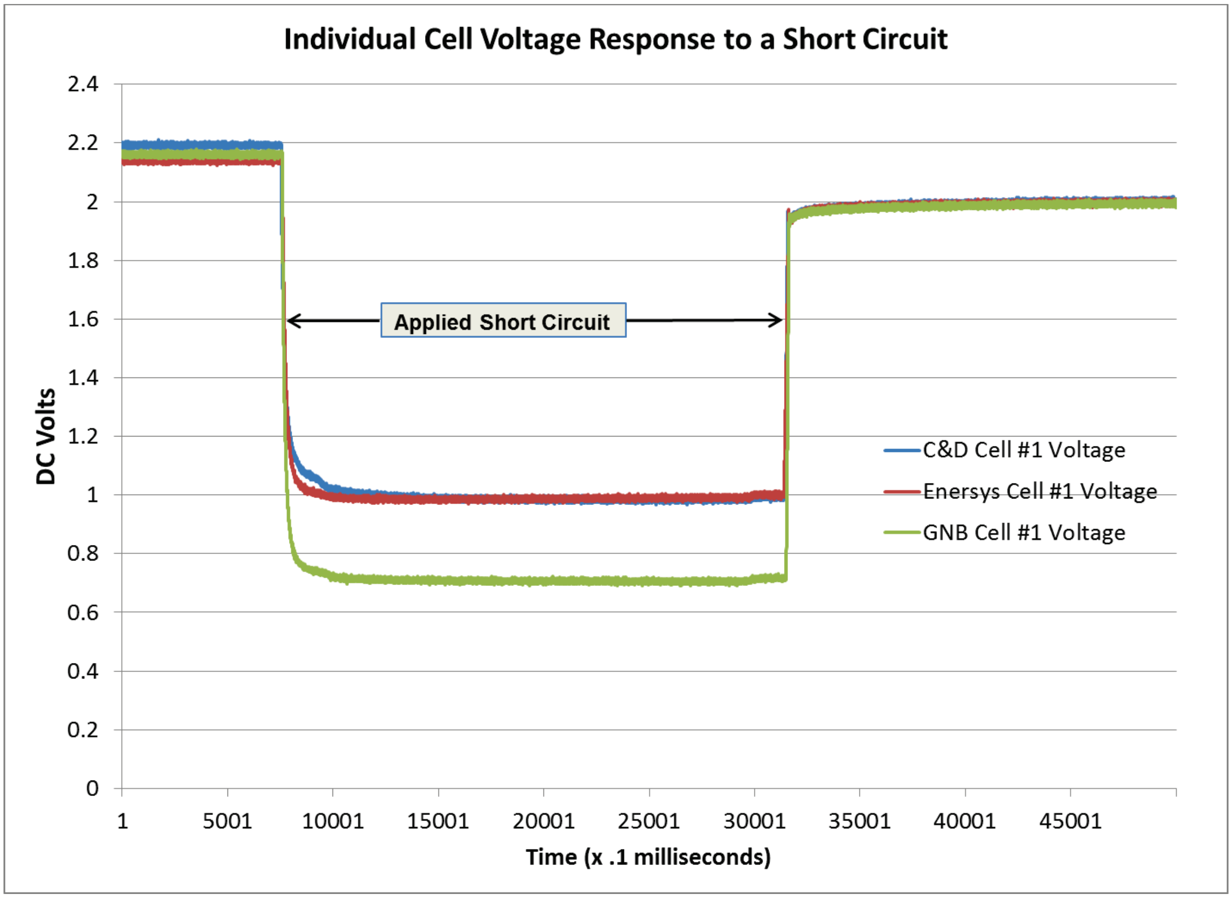

Figure 6. Individual Cell Voltage Responses to a Short Circuit

Potential Contribution to Relevant Industry Standards

Prior to conducting this test program, BNL examined many documents to evaluate the body of knowledge related to the effects of a fault on batteries and battery chargers in a DC distribution system. The results of this review are documented in a BNL technical report (Ref. 1).

We found that many papers published in the 1990s 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 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.

There are several different types and sizes of battery chargers being used at nuclear power plants. How each is protected to withstand a fault condition and how each would contribute to such a fault may be different. One of the important industry standards that discuss battery and battery charger short circuit response is IEEE Std. 946-2004, IEEE Recommended Practice for the Design of DC Auxiliary Systems for Generating Stations. This Standard is currently under revision. The test results described in this paper were shared with the Working Group responsible for this latest revision so that they could evaluate the potential impact of test data on the Standard.

Several excerpts taken from the Standard directly associated with the short-circuit testing that was performed by BNL for the NRC are:

a. Section 7.9, Available short-circuit current:

Batteries

The Standard states that a conservative approach in determining the short-circuit current that the battery will deliver at 25 °C is to assume that the maximum available short-circuit current is 10 times the 1 minute ampere rating (to 1.75 V per cell at 25 °C and specific gravity of 1.215) of the battery. When a more accurate value is required, the short-circuit current for the specific application should be calculated (provided in Annex C of the Standard) or actual test data should be obtained from the battery manufacturer. The testing described in this paper revealed much lower short-circuit values for the batteries due to the test circuit resistance. Using the higher 10x value to determine the setting of the protective devices may not be conservative if the protective devices take longer to operate due to the lower magnitude of the short circuit current.

Battery Chargers

The Standard states that the battery charger current-limit circuitry may require two ac cycles (~33 milliseconds) to clamp. The maximum current that a charger will deliver into a short circuit after this period, coincident with the maximum battery short-circuit current, is determined by the charger current-limit circuit (as further described in Annex E of the Standard). The Standard states that when the battery charger is connected in parallel with the battery, the battery capacitance will prevent the battery charger contribution from rising instantaneously. Therefore, according to this Standard, the maximum current that a charger will deliver on short circuit will not typically exceed 150% of the charger full load ampere rating. It also states that Instantaneous battery charger current rise should only become a concern during periods when the battery is disconnected. The testing program showed that the short circuit contribution from the charger was not limited to the current limit value when connected in parallel and that the current-limit circuit did not (for the SCR charger) clamp for more than 300 milliseconds.

Annex E; Battery Charger, short-circuit current contribution

This annex provides a rationale for determining the maximum value of the battery charger short-circuit current that will occur coincident with the maximum battery short-circuit current. The reason for determining the maximum combined short-circuit current is to specify equipment with the correct interrupting rating that is suitable for the expected fault current. The Standard states that for a typical station battery and a current-limited charger, it can be shown that the peak short-circuit currents occur at different times so that the charger current-limited value added to the battery peak value provides a conservative total fault-current value and that the fault current contribution from a typical battery charger is current-limited to a value not greater than 150% of the charger current rating. The timing of the fault contributions from the battery charger and the battery obtained from the testing program revealed that when the current limit circuit of the charger was longer than 100 milliseconds (SCR Charger), its fault current contribution was greater than the current limit value at the same time the battery fault contribution was at its peak. This section of the Standard may require revision based on the testing results achieved.

Industry Standards that contain guidance related to the short circuit contributions of batteries and battery chargers are summarized in Table 2.

Table 2: Summary of Industry Standards Information Related to DC System Faults

Industry Document	Battery Info	Battery Charger Info	Comments
IEEE Std. 141-1993	States that procedures for dc short circuit currents are not well established and that it is necessary to consider the rate of rise of the fault current as well as the interruption time in order to determine the max current that will be obtained		Lists the sources of dc short-circuit currents including batteries and rectifiers
IEEE Std. 242-2001 ("Buff Book")	Batteries contain little inductance and, as stated by one large UPS manufacturer, a shorted battery is similar to a fault through a resistor. A shorted battery drains rapidly and gives rise to high *di/dt*.	Refers to NEMA PE-5	Provides basics on the nature of short circuit currents and protection coordination in dc systems
IEEE Std. 666-1991	The equivalent circuit of the battery includes the internal resistance of the battery, the resistance and inductance of the conductors, and the battery internal voltage.	A maximum fault current equal to the current limit value should be used if it cannot be obtained from the manufacturer.	Total DC fault current is the sum of the fault current contributed by the individual sources
IEEE Std. 946-2004	Depends on the total resistance of the short-circuit path; Annex C provides a way to calculate short circuit currents	Annex E describes the short circuit contribution from the charger; States that the peak charger and battery short circuit currents occur at different times	Total short circuit current is the sum of that delivered by the battery, the charger, and motors.
IEEE Std. 1375-1998	Batteries can discharge up to 40,000 A for several seconds.	Describes charger fault current in short-term, mid-term and long-term periods. Also depends on charger type and size of output filters. Response time of the current limit circuit to a severe overcurrent may be as long as 100 milliseconds.	Section 8 of this guide provides several different schemes that are deemed acceptable for battery protection.
IEC Std. 61660-1-1997	Provides equations and general response curve for a battery short-circuit. Takes into account conductor and connection resistance and inductance.	Provides equations and general response curve for an SCR type battery charger short-circuit.	Discusses maximum and minimum fault currents in DC distribution systems.
NEMA PE-5-2003	N/A	Charger must be able to withstand a short circuit across its output terminals and be able to return to normal service without any degradation in performance.	Primarily associated with equipment specifications and operating parameters

Summary and Preliminary Conclusions

Short-circuit testing has been completed on 3 sets of vented lead-acid batteries and 2 types of battery chargers that are used in safety related nuclear power plant DC distribution systems. The objective of the testing was to determine the short circuit contributions from these batteries and battery chargers when the fault was applied individually or in parallel, and to evaluate the potential impact on DC system components.

The key observations that were described in this paper are:

1. The magnitude of the currents obtained in this testing were much less than the vendor provided or rule-of-thumb values that estimate the current contribution from a short that occurs at the battery terminals. Calculations of the short circuit current performed without the external resistance of the test circuit compare favorably to the vendor provided values.
2. The magnitude of the short-circuit current from a battery charger is between 9x and 12x its rated current output.

3. The maximum short-circuit contribution from a battery charger is reduced by ~25% when it is connected in parallel with a battery.
4. 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.
5. 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.
6. The substantial battery voltage drop that occurs when a short-circuit is applied can result in the loss of important instrumentation and controls if the low voltage protective devices on the DC power supplies and/or inverters actuate.
7. No apparent damage to the battery or the battery chargers was detected as a result of the short-circuit testing. In fact, the recharge of the battery following a two second short-circuit was accomplished in less than one hour as compared to nearly 24 hours following a standard 4-hour performance test.
8. The empirical data obtained from this testing may be useful input to several IEEE Standards (e.g., IEEE Standard 946) that provide guidance on the short circuit response of batteries and battery chargers in DC distribution systems.

References

1. BNL Technical Report "BNL-107800-2015-IR", Evaluation of Battery and Battery Charger Short-Circuit Current Contributions to a Fault on the DC Distribution System at a Nuclear Power Plant; TASK 1 Report: Literature Review; March 2015.
2. NUREG/CR-7148, Confirmatory Battery Testing: The Use of Float Current Monitoring to Determine Battery State-of-Charge, 11/12.
3. NUREG/CR-7188, Testing to Evaluate Extended Battery Operation in Nuclear Power Plants, 5/15**.**
4. Short-Circuit Test Results of Current Limiting SCR Type Battery Charger, Kurt Uhlir, 1994 American Power Conference; Chicago, IL, April 27, 1994.
5. Short-Circuit Characteristics of Large Lead Acid Storage Batteries, Kurt Uhlir and Mark Bowman, 1991 Northeast Electric Utility Battery Conference, Albany, NY, September 25, 1991.
6. Update: Where do we stand on Stationary Battery Short Circuit Characteristics by M. Migliaro and R. Wellborn; Presented at the 1992 Northeast Electric Utility Battery Conference, September 1992.
7. Short-Circuit Current Test Results on AT&T Round Cells at Different Temperatures by K. A. Murugesamoorthi, R. Landwehrle, and M. Migliaro; Telecommunications Energy Conference, INTELEC '93. 15th International (Volume: 2).

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