

IEEE Guide for the Protection of Stationary Battery Systems

Sponsor

**IEEE Standards Coordinating Committee 29
on Stationary Batteries**

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Abstract: Guidance in the protection of stationary battery systems is provided. For the purposes of this guide, stationary battery systems include the battery and dc components to and including the first protective device downstream of the battery terminals. This guide does not set requirements; rather, it presents a number of options to the dc system designer of the different types of stationary battery system protection available.

Keywords: circuit breaker, current limiting, equipment grounding, fuse, grounding, lead-acid batteries, nickel-cadmium batteries, overvoltage protection, short-circuit current, stationary battery, system grounding, temperature compensation, undervoltage protection

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Introduction

(This introduction is not part of IEEE Std 1375-1998, IEEE Guide for the Protection of Stationary Battery Systems.)

Stationary batteries are used in a wide variety of industry applications including electric generating stations, substations, telecommunications installations, petrochemical installations, large industrial and commercial installations, large uninterruptible power supply (UPS) installations, and renewable energy plant installations. Stationary batteries are often classified as the emergency power source to critical facility loads, and the loss of the battery supply could result in significant damage to facility components or to the facility itself. When developing the design of a stationary battery supply for a new or existing facility, the protection of the stationary battery is just one of a number of items the dc system designer has to consider. Proper protection of the stationary battery, along with the proper installation and maintenance of the stationary battery system, will ensure the reliability of the battery supply to the facility's dc loads.

There is a wide variety of existing standards concerning the sizing, installation, maintenance, testing, and replacement of stationary batteries. This guide provides guidance to the dc system designer for the electrical and physical protection of stationary batteries. This guide does not set requirements; rather, it presents a number of options to the dc system designer of the different types of stationary battery system protection available. This guide also provides an in-depth discussion of the protective devices available for use in the protection of stationary battery systems as well as in-depth discussions of stationary batteries and the short-circuit characteristics of battery chargers.

This guide provides references to other published industry standards as applicable. The reader is cautioned to use this guide in conjunction with applicable IEEE standards and industry standards.

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IEEE Guide for the Protection of Stationary Battery Systems

1. Overview

1.1 Scope

This document provides guidance in the protection of stationary battery systems. For the purposes of this guide, stationary battery systems include the battery and dc components to and including the first protective device downstream of the battery terminals. The recommendations provided are not intended to set requirements; rather, they present options to the designer of the battery system concerning the types of protection available.

This guide provides discussions and recommendations regarding the forms of stationary battery protection as well as characteristics, sizing, application, and ratings of protective devices used in dc circuits and the short-circuit characteristics of batteries and battery chargers. A discussion of physical protection of battery systems as well as electrical protection is provided within this guide. Discussions are also presented in Annexes B and C regarding dc system time constants.

A discussion of coordination of protective devices for selective tripping is not treated within this guide and is considered beyond its scope. The user of this guide is referred to IEEE Std 242-1986¹ for guidance concerning coordination of protective devices.

Both grounded and ungrounded dc battery systems are used widely in different industry applications. The philosophy employed in the protection of stationary battery systems shall take into consideration whether the dc system is a grounded or ungrounded system. This guide provides guidance in the protection of both grounded and ungrounded stationary battery systems.

1.2 Purpose

This document provides guidance concerning items to consider in the protection of stationary battery systems. The guide is intended for use in the protection of battery systems in a wide industry perspective including electric generating stations, substations, telecommunications installations, large industrial and commercial installations, large uninterruptible power supply (UPS) installations, and renewable energy plant installations. While voltage levels indicated within this guide may be applicable to a particular industry, the concepts and recommendations provided apply to most installations of stationary battery systems.

¹Information on references can be found in Clause 2.

2. References

This guide shall be used in conjunction with the following publications.

ANSI C37.16-1988, American National Standard for Switchgear—Low Voltage Power Circuit Breakers and AC Power Circuit Protectors—Preferred Ratings, Related Requirements, and Application Recommendations.²

ANSI C37.17-1979 (Reaff 1988), American National Standard for Trip Devices for AC and General Purpose DC Low-Voltage Power Circuit Breakers.

ANSI T1.311-1991, American National Standard for DC Power Systems—Telecommunications Environment Protection.³

IEEE Std 100-1996, The IEEE Standard Dictionary of Electrical and Electronics Terms.⁴

IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.

IEEE Std 242-1986 (Reaff 1991), IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems.

IEEE Std 450-1995, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications.

IEEE Std 484-1996, IEEE Recommended Practice for Installation Design and Installation of Vented Lead-Acid Batteries for Stationary Applications.

IEEE Std 485-1997, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications.

IEEE Std 946-1992, IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations.

IEEE Std 1106-1995, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Nickel-Cadmium Storage Batteries for Generating Stations and Substations.

IEEE Std 1115-1992, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications.

IEEE Std 1187-1996, IEEE Recommended Practice for Installation Design and Installation of Valve-Regulated Lead-Acid Storage Batteries for Stationary Applications.

IEEE Std 1188-1996, IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve Regulated Lead-Acid (VRLA) Batteries for Stationary Applications.

²ANSI C37 standards are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA. They are also available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

³ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁴IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std 1189-1996, IEEE Guide for Selection of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications.

IEEE Std C37.14-1992, IEEE Standard for Low-Voltage DC Power Circuit Breakers Used in Enclosures.

IEEE Std C37.100-1992, IEEE Standard Definitions for Power Switchgear.

NEMA KS-1-1996, Enclosed and Miscellaneous Distribution Equipment Switches (600 Volts Maximum).⁵

UL 98-1994, Enclosed and Dead-Front Switches (DoD).⁶

UL 198L-1995, D-C Fuses for Industrial Use.

UL 198M-1995, Mine-Duty Fuses.

UL 248-5-1996, Low-Voltage Fuses—Part 5: Class G Fuses.

UL 248-14-1994, Low-Voltage Fuses—Part 14: Supplemental Fuses.

UL 489-1991, Molded-Case Circuit Breakers and Circuit-Breaker Enclosures (DoD).

UL 977-1994, Fused Power-Circuit Devices (DoD).

NFPA 70-1996, National Electrical Code® (NEC®).⁷

NFPA 220-1996, Types of Building Construction.⁸

3. Definitions

For definition of terms contained in this guide refer to IEEE Std 100-1996 and the definitions contained in the referenced publications of Clause 2.

4. Philosophy of stationary battery protection

The protection of stationary batteries can take a number of different forms depending on the service requirements of the battery. Several options available to the designer are presented below. These options include the use of an interrupting device (fuse, circuit breaker, or fused circuit breaker) for short circuit and, if applicable, overload protection of the battery, and mid-span protection of the battery.

Also presented is an option where there is no interrupting device between the battery and the main dc bus it supplies (cable only) as well as one where there is a disconnect switch installed between the battery and the main dc bus it supplies. In these cases there would be no short circuit or overload protection for a fault either

⁵NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.

⁶UL standards are available from Global Engineering, 1990 M Street NW, Suite 400, Washington, DC, 20036, USA.

⁷The National Electrical Code is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA. It is also available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

⁸NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

on the battery cable supplying the main dc bus or at the bus. For these options, the stationary battery system includes the battery, the battery cable, the main dc bus, and the branch protective devices it supplies.

The philosophy of stationary battery system protection should begin with a knowledge of the application of the battery, its service requirements, and whether the dc system is grounded or ungrounded. It is important to note that *no one option presented below for the protection of stationary battery systems is more correct than another*. Rather, the option chosen by the designer of the stationary battery system is dependent upon its application.

For example, the designer of the system should consider whether the stationary battery is the last available electrical source to supply critical loads on an interruption of the ac supply or if there is an alternate supply available if the battery supply is interrupted on a short circuit or overload. If the overriding factor is that on a loss of ac power for an electrical auxiliary system there will be serious and significant damage to the installation because the dc supply to critical loads is interrupted, and there is no alternate means to provide dc service to these critical loads other than the stationary battery, the designer may wish to consider the installation of either a switch, or just a cable between the battery and the main dc bus supplied by it, to maintain the dc source as long as possible and reduce the probability of premature loss of the source.

On the other hand, if the overriding factor is that there has to be a dc supply available to plant loads, and there is an alternate means to supply the critical dc loads on a loss of the stationary battery supply without significant damage to the installation, the designer may wish to consider the installation of short-circuit protection (and overload protection if applicable) between the battery and the main dc bus it supplies. This form of stationary battery protection provides the user with the ability to interrupt a fault or overload on the stationary battery system; investigate, locate, and clear the fault that caused the interruption of the battery supply; and restore the battery to service.

The designer of the battery system should consider the physical installations of the battery, as described in Clause 9. In addition, physical protection of the stationary battery system should be considered in concert with the form of electrical protection of the battery. For example, if there is no short-circuit protective device installed between the battery and its main dc bus, then the designer should consider a separate enclosure for the battery with appropriate fire-rated walls. If the dc fault occurs on the cable between the battery and its main dc bus, then the battery will supply the fault until the circuit is broken or the battery is completely discharged. Significant heating may occur under these circumstances, resulting in possible combustion of materials in the battery cable or the battery itself.

This guide presents discussions on the electrical protection and physical protection of stationary battery systems. Discussions are presented on short-circuit characteristics of lead-acid and nickel-cadmium batteries, battery chargers, characteristics of fuses, circuit breakers and disconnect switches, conductors, use of ac rated devices in the protection of stationary battery systems, fire protection and detection, ventilation, and alarms among others.

5. DC system considerations

The function of the battery system should be understood. Battery systems are usually relied upon as the last and/or only source of reliable electrical power at a facility or installation. However, they can also be the prime source of electrical power in special cases. The operating philosophy of the electrical system determines the level of sophistication and the type of protective devices used in the battery system. Because dc systems and battery power sources differ from ac systems, it is important that the dc system protection designer be aware of some special considerations.

The two competing objectives when designing the protection scheme for a battery system are as follows:

- a) Minimize the risk of equipment damage during electrically faulted conditions.
- b) Limit the number and duration of the battery system service interruptions as a result of an electrically faulted condition.

The dc system protection designer should consider the aspects discussed below when balancing objectives and choosing protection schemes.

5.1 Use of a battery protective device

Protective devices at the battery serve to minimize the extent of damage to the battery system during electrically faulted conditions. The same devices also increase the risk of a battery system service interruption due to a malfunction or human error. Factors to consider are

- a) The conductor distance between the battery and the distribution bus;
- b) The physical configuration of the conductor (physical cable protection afforded by conduit and/or separation of positive and negative conductors);
- c) The facility staffing level (a continuously manned facility versus an unmanned, remote location);
- d) The expected level of fault current due to an electrical fault in the battery system;
- e) The effects of equipment damage or personnel injury due to a violent battery failure.

When a protective device is used in a battery system, the trip setpoint should be chosen to compromise between service continuity and possible battery system damage. High currents of sufficient duration may cause damage to cable insulation, conductor material, battery posts, battery intercell connectors, battery post seals, and battery cell covers. For example, an overcurrent protective device may be selected with a time-current characteristic just below that of the weakest element in the circuit.

5.2 Overvoltage and undervoltage protection

Overvoltage and undervoltage protection of lead-acid, nickel-cadmium, vented, and valve-regulated batteries is sometimes overlooked by the designer of the dc system. For the effects of overvoltage and undervoltage protection on other dc components, refer to IEEE Std 946-1992. Batteries can withstand moderate overvoltage and undervoltage for short periods of time. If a lead-acid battery is subjected to a prolonged undervoltage there may be heavy sulfation on the plates, which may be difficult to reverse. Loss of battery capacity will occur as a result of heavy sulfation on the plates of lead-acid batteries. If a battery is subjected to a prolonged or frequent overvoltage it can age more quickly and damage can possibly occur.

Undervoltage protection of the battery is desired when the battery charger is both energized and de-energized. If the charging voltage drops below the minimum recommended float voltage for the battery, the battery will not receive sufficient charging current to offset internal losses (self discharge), resulting in a gradual loss of capacity.

If the battery charger is de-energized, the battery will then power the load(s), which will eventually cause the battery voltage to drop below a level such that

- The dc system loads can no longer function; and/or
- The battery has exhausted its capacity and may suffer damage.

Overvoltage on a battery is a long-term charging voltage higher than the recommended float voltage for the battery. Under these conditions, the battery will

- Age at an accelerated rate;
- Accelerate the dryout process (in valve-regulated battery cell designs) potentially resulting in thermal runaway;
- Generate heat;
- Generate increased amounts of hydrogen gas; and
- Deplete fluid.

For attended stations or facilities, the usual practice is to only alarm undervoltage and overvoltage conditions. This is acceptable because batteries are the last line of defense in the emergency backup system, the failure modes occur over a long time period, and trained personnel are available on-site. Overvoltage and undervoltage alarms in these installations can usually be purchased as options for the battery charger and/or be specified as part of the dc system distribution equipment.

For unattended stations or facilities, a voltage sensing device to disconnect the battery from its loads can be used as protection from over discharging and irreversible damage. The designer of the dc system will need to evaluate and compare the risk of damage to the battery or the system when considering this option.

The battery charger design should incorporate a high-voltage disconnect that shuts off the charger should component failure result in high-voltage output. Battery chargers may have blocking diodes to prevent discharging through the charger.

5.3 Grounding

The term *grounding* is commonly used in electric power systems to include both *system grounding* and *equipment grounding*.

- a) A *system ground* is a connection from one of the current-carrying conductors of a system to ground.
- b) An *equipment ground* is a connection to ground from one or more of the non-current-carrying metal parts of the system or apparatus connected to the system (such as electrical raceways, the enclosures of distribution system equipment, motor frames, and other load enclosures).

The objectives of both of these parts of the grounding system are to provide protection for personnel and equipment and to provide a fault clearing path.

5.3.1 System grounding

There are two types of dc systems—grounded and ungrounded. In practice, both grounded and ungrounded systems are used extensively, with certain industries preferring one type over the other. The following definitions from IEEE Std 142-1991, though intended for ac systems, are applicable to dc systems as well:

- a) *Grounded system.* A system of conductors in which at least one conductor or point is intentionally grounded, either solidly or through a non-interrupting current-limiting device.
- b) *Ungrounded system.* A system, circuit, or apparatus without an intentional connection to ground except through potential-indicating or measuring devices or other very-high-impedance devices.

A grounded dc system provides a low-impedance path for fault currents, enhancing fast operation of protective devices to isolate the faulted branch to protect personnel and equipment.

A low-resistance ground fault on one of the polarities of an ungrounded dc system will not affect operation of the system, thus increasing system reliability and continuity of service. This benefit of an ungrounded dc

system is most easily understood for the case where a ground fault occurs on a feeder conductor to a dc bus or subpanel from which multiple circuits are fed. When contemplating the use of an ungrounded system, the requirements of applicable codes shall be considered. In general, when an ungrounded system is used, a ground fault detection system is prudent in order to identify and isolate ground faults.

5.3.2 Equipment grounding

Electrical equipment frames/enclosures are usually grounded. In industrial and power plants, electrical equipment is located in many different locations throughout the plant. Typically, electrical equipment frames/enclosures are grounded to nearby building steel (columns, frames, etc.) with electrical conductors. The building steel members and electrical raceways are electrically connected together via the plant grounding system for protection of personnel and equipment. A detailed description of this type of system is provided in IEEE Std 142-1991.

In telecommunications, electrical equipment frames/enclosures are frequently electrically isolated from nearby building steel and electrical raceways by conductors routed to a central “ground window” (isolated systems). An alternative is a combination of the above two techniques (integrated systems). A detailed description of these types of systems is provided in ANSI T1.311-1991.

5.4 Temperature compensation and current limiting

Elevated operating temperatures lower cell voltage for a given charging current, and raise charging current for a given voltage. Under constant potential charging, this results in higher rates of gas evolution and more heat to dissipate. If the rate of heat generation exceeds the rate of heat dissipation, the cell temperature will rise, resulting in more charging current to maintain the float voltage. The additional current causes the temperature to rise further, resulting in a further increase in the charging current, and so on. Normally associated as a failure mode with valve-regulated lead-acid (VRLA) cells, the net effect of this thermal runaway condition can be melting of the battery. (See IEEE Std 1187-1996 for more information on thermal runaway.)

The risk of this very dangerous phenomenon can be significantly reduced by controlling temperature and providing adequate ventilation (see Clause 9), and limiting charging current. Two popular means of limiting charging current are temperature compensation and charge current limiting. Temperature-compensated chargers sense the ambient temperature or battery temperature (preferably the latter), and adjust the charging voltage based on this temperature. As the temperature increases, the charging voltage is lowered. This effectively limits the current flowing into the batteries, and helps to prevent thermal runaway. The current flowing into the batteries can also be controlled by placing a charge current-limiter between the battery and battery charger. This device limits the charging current, but not the discharge current, and also helps to prevent thermal runaway.

Strong consideration should be given to the use of one or both of these techniques with VRLA batteries, especially those located in “unconditioned” environments (no air-conditioning).

6. Batteries

In a dc system, the battery is considered a finite source of power. The dc current delivered by a battery under fault conditions is dependent on the resistance of the battery and the circuit resistance between the battery terminals and the fault. If the circuit resistance is very low, large batteries can discharge up to 40 000 A for several seconds.

A battery stores electrical energy by virtue of the chemical reactions taking place at the electrodes (plates). The electrical energy that a battery can supply depends on the amount of chemical energy it contains and its ability to convert chemical energy to electrical energy.

A short circuit of a storage battery initiates rapidly changing high currents and high-voltage drops within the system. These conditions result in transient currents that dissipate rapidly to a steady-state level. The following parameters are important to the transient and steady-state response of a battery under short-circuit conditions:

- a) Electrochemical response of the battery;
- b) Internal and external circuit resistance of the battery;
- c) Inductance of the battery and the circuit;
- d) Capacitance of the battery.

6.1 Lead-acid batteries

Excluding the impedance of the short-circuit path, the magnitude of a lead-acid battery's output current under fault conditions is dependent on the battery's resistance. The resistance is a result of many design variables, such as

- a) Separator material and porosity;
- b) Spacing between the plates;
- c) Specific gravity of the electrolyte;
- d) Surface area of the plates; and
- e) Conductivity of the plates, connecting straps, terminal posts, and intercell connections.

Therefore, the maximum short-circuit current that a battery can deliver, assuming a zero impedance fault, is based on a battery's resistance and the effective emf of the battery. The total resistance of the battery is equal to the sum of the internal resistance of the series-connected cells, plus the resistance of the intercell connections.

Other factors affecting the resistance of the lead-acid battery are its state of charge and to a lesser extent, its age. Lead sulfate, which forms on the plates during discharge, is a non-conductor, and increases the internal resistance of the cell. At the same time, the loss of sulfate ions from the electrolyte reduces the electrolyte's conductivity and increases the cell's resistance. The resistance of a battery increases during the discharge, and can be two to three times the initial resistance at the end of the anticipated duty cycle. As the lead-acid battery ages, the corrosion process acting on the grid structure of the positive plate increases its resistance to current flow. VRLA batteries also experience progressive water loss, leading to a corresponding increase in internal resistance.

6.2 Nickel-cadmium batteries

As with lead-acid batteries, the magnitude of a nickel-cadmium battery's output current during fault conditions is dependent on the internal resistance of the cell. This resistance is the result of design variables, such as

- a) Separation between the plates;
- b) Surface area of the plates; and
- c) Conductivity of the plates, connecting straps, terminal posts, and intercell connections.

Unlike lead-acid batteries, the alkaline electrolyte, an aqueous solution of potassium hydroxide, does not enter into the electrochemical reactions. Instead, it merely acts as an ionic conductor of uniform resistance. Consequently, the specific gravity does not change with the state of charge, and internal resistance during discharge will not increase as much as in a lead-acid cell. This means that even when fully discharged at the end of its anticipated duty cycle, the nickel-cadmium battery will still have a substantial short-circuit current available.

6.3 Battery voltage characteristics during short-circuit conditions

When a short-circuit discharge begins, there is a sudden decrease of voltage at the battery terminals because of the voltage drop through the resistance, and then a gradual decrease in voltage caused by chemical changes occurring at the surface of the electrodes, as shown in Figure 1. The chemical changes within the battery produce a counter emf called polarization. This polarization can be approximated as a capacitance shunted by a leakage resistance. The capacitance is responsible for the initial slope of the voltage curve, while the leakage resistance is responsible for the curvature of the line. The subsequent slope can be approximated by using the time constant of the circuit.

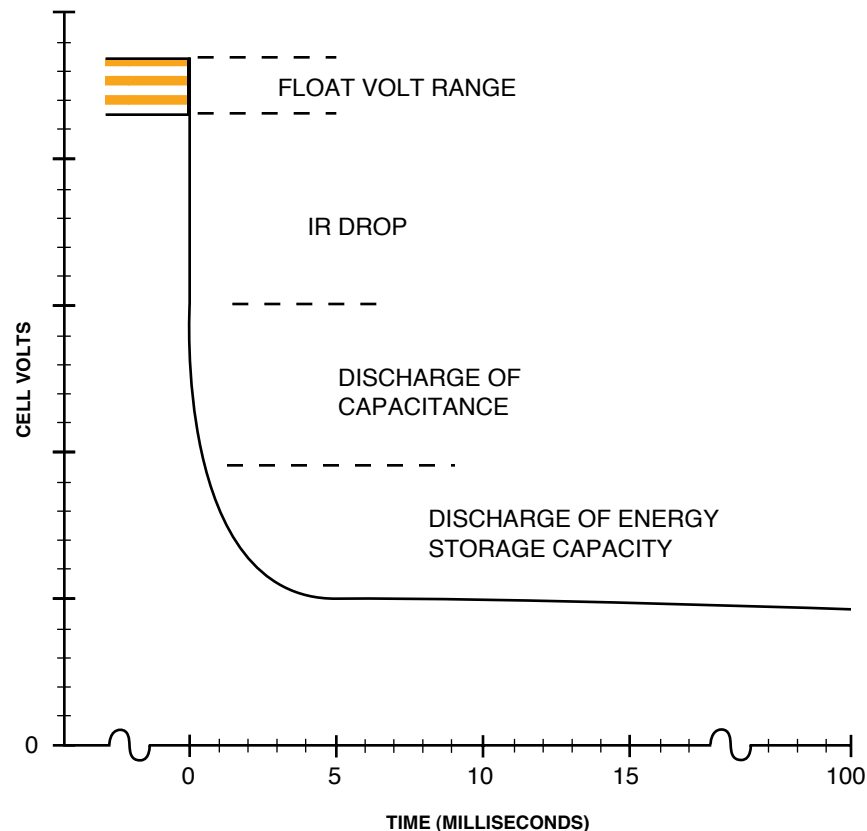


Figure 1—Lead-acid battery typical initial voltage characteristic during short circuit

6.4 Battery current characteristics during short-circuit conditions

The transient and steady-state currents are interpreted in terms of resistance, capacitance, and inductance of the battery and external circuit network. The transients from capacitance and inductance are influential typically during the first 15 ms after the short circuit is applied. After this time, the steady-state current is determined primarily by the resistance network of the battery and the external circuit, as shown in Figure 2.

The battery and battery circuit possess a measurable inductance, which has the effect of slowing down the rise of current when a short circuit is applied to the battery, and can be a significant factor when cables are employed in the circuit as intercell connectors. When a battery is subjected to a short circuit, the time constant is on the order of 1–3 ms for a fault at the battery terminals. Depending on the circuit inductance, the current will rise rapidly to a peak value within 5–15 ms.

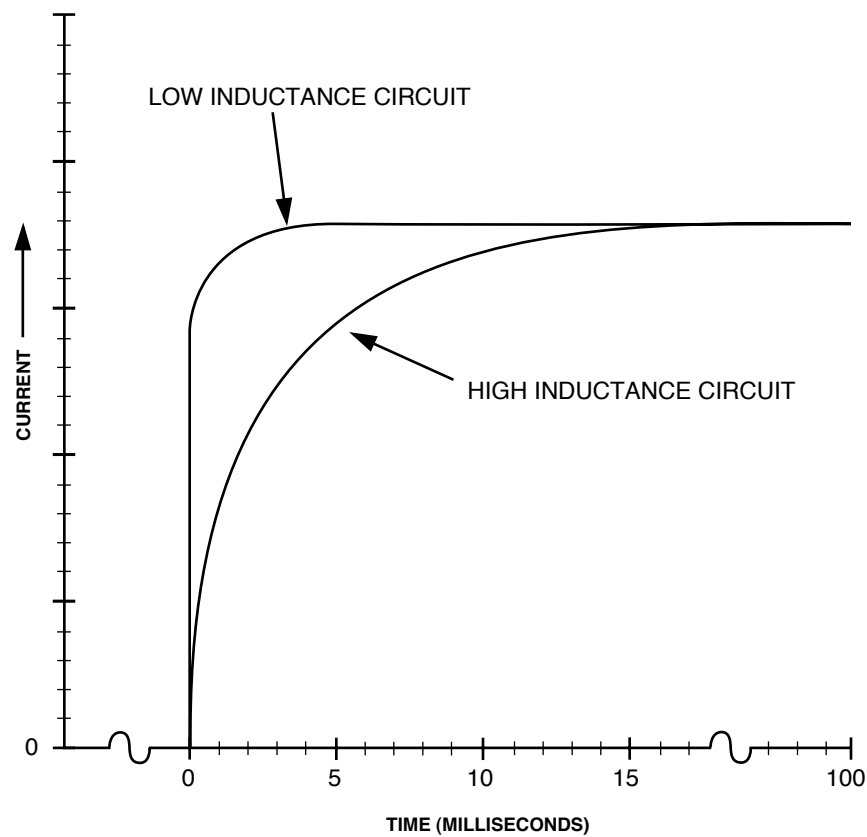


Figure 2—Lead-acid battery typical initial current characteristic during short circuit

6.5 Battery withstand capability during short-circuit conditions

From the battery's perspective, a short circuit is nothing more than a very high rate discharge through a constant resistance load (neglecting resistance changes due to temperature increase). After approximately 0.1 s, the battery voltage remains relatively constant for several seconds, then slowly declines as the transport of electrolyte to the reacting zones of the electrodes becomes limiting. From this point on, the current also declines with the voltage in accordance with Ohm's Law (see Figure 3).

6.5.1 Lead-acid batteries

The length of time a lead-acid battery can deliver current of the magnitude available under short-circuit conditions is dependent on the impedance of the fault and the design of the battery cell. The current-carrying capability of individual cells and multi-cell units of less than 200 Ah ratings is generally limited by the size of their terminals and connectors, which have small cross-sectional areas and are often made of lead or lead alloy. Given the high current density resulting from a low-impedance short-circuit discharge, these components are not able to dissipate the energy being generated, and in extreme cases, the temperature rise in the component can exceed its melting point within 10 s. On the other hand, larger cells, and particularly those designed for high discharge rate applications (i.e., those designs that feature copper inserted terminals and thick copper intercell connectors), can withstand the short-circuit current for several minutes, or even the duration required to completely discharge the battery.

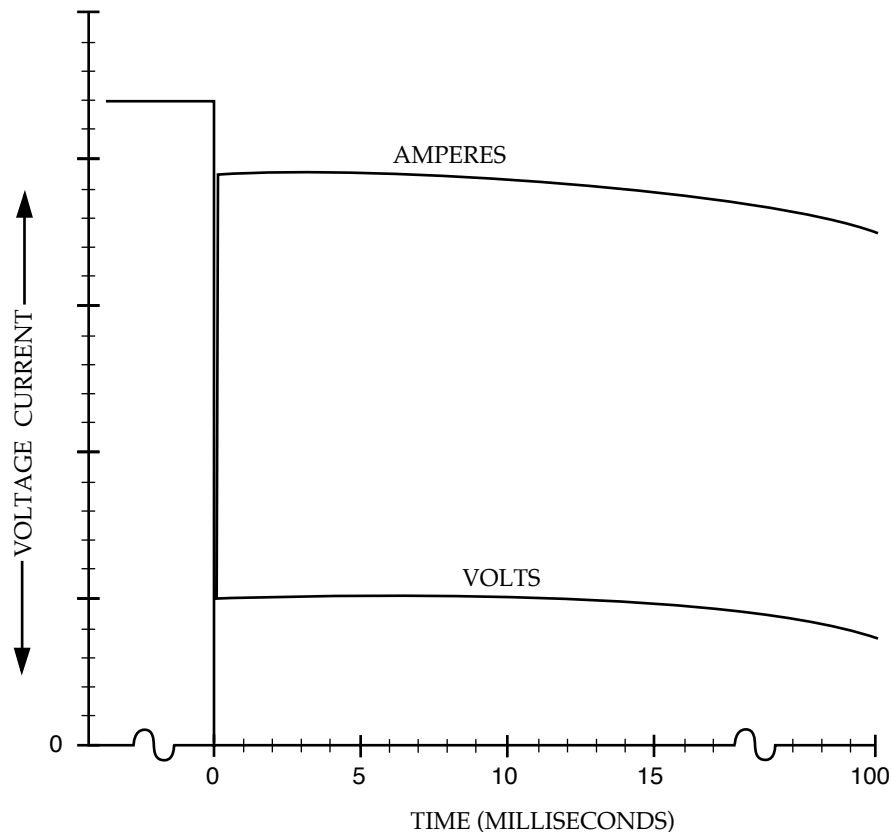


Figure 3—Lead-acid battery typical long duration characteristics during short circuit

6.5.2 Nickel-cadmium batteries

Nickel-cadmium battery cells employ nickel-plated steel for the conducting parts. The plates in the cell are bolted or welded to the current collectors and the cell terminals. The use of these strong, highly conductive metals allows the battery to withstand fault conditions for longer durations than comparable lead-acid batteries.

6.6 Environmental and operational effects on battery short-circuit current

6.6.1 Effect of elevated temperatures on battery short-circuit current

6.6.1.1 Lead-acid batteries

It is well established that the discharge capacity of a lead-acid battery increases with temperatures above 25 °C (77 °F) and decreases at temperatures below this value. At temperatures greater than 25 °C under normal discharge conditions, the conversion rate of chemical energy to electrical energy is improved, primarily due to the higher rate of electrolyte diffusion at the plate surfaces, and lower electrolyte resistivity. This results in the battery maintaining a higher voltage throughout the discharge, and consequently, a longer reserve time. Under short-circuit conditions at electrolyte temperatures greater than 25 °C, there is no significant increase in electrical energy because the conversion process cannot keep pace with the rate of current being discharged. Over the short duration that the battery discharges into a short circuit, the resistance of the current-carrying components determines the output current. Tests indicate that an increase in electrolyte temperature above 25 °C will have no appreciable effect on the magnitude of short-circuit current delivered by a lead-acid battery.

6.6.1.2 Nickel-cadmium batteries

Nickel-cadmium battery discharge capability is increased only slightly as electrolyte temperatures rise above 25 °C. As with lead-acid batteries under short-circuit conditions, the current is limited by the resistance of the current-carrying components. Therefore, an increase in electrolyte temperature will not significantly increase the magnitude of the short-circuit current that a nickel-cadmium battery is capable of delivering.

6.6.2 Effects of charging voltage on battery short-circuit current

To maintain a standby battery in a fully charged condition, the battery is connected to a charger having an output higher than the nominal battery voltage. This allows a small charging current to flow through the battery, compensating for inherent self-discharge losses. This higher voltage does nothing to increase the chemical energy available from the battery; however, during the first 0.5 s of a short circuit, the magnitude of the short-circuit current may be affected to a small degree by the initial battery voltage (i.e., float or equalize). Test results indicate that higher than nominal battery voltage may produce a slight increase (on the order of 1%) in the initial short-circuit current. This increase is not proportional to the increase in battery voltage, and disappears in less than 1 s.

6.7 Damage and failures of batteries

If properly maintained and operated, the battery is a very dependable and trouble-free device. The failure of the battery can be attributed to both internal and external failure mechanisms (internal failure mechanisms are considered failures of the stationary battery, including battery cells and their intercell connections).

The consequences of a battery system failure will be different for each individual application. For example, in the telecommunications industry, the considerations of the failure of a telecommunications switch will include possible hardware and software damage, interrupted revenue streams, and the cost of fault correction and restoration. Likewise, the failure of a vital dc system in a generating station may result in the false actuation or loss of the safety systems. Further, the loss of a battery in a power substation could result in the inability to trip faulted ac feeders. The designer of the dc system should first define the operability and maintenance requirements and capabilities of the system before attempting to design the protection requirements of the system. The following factors should be considered when attempting to define these characteristics:

- a) The ability to alarm and monitor to predict the failure/degradation of the dc system;
- b) The ability to restore power to the dc system from an alternate dc source or by correcting the cause of failure and restoring the power source;
- c) An evaluation of the possible failure modes and the associated postulated consequences due to a failure of the system or a malfunction of a component (e.g., protective device failures) in the dc system.

A facility in which there is continuous monitoring of the equipment following the recommendations of Table 2 of IEEE Std 946-1992, and a trained electrical maintenance staff, would require less automatic protection of the system than would be required in a non-manned installation. This is due to the fact that the battery would be regularly maintained in accordance with IEEE Std 450-1995 or IEEE Std 1188-1996 and surveillance testing would help predict failure prior to its occurrence. In addition, the staff would be available to take immediate corrective action to clear the fault, limiting damage to the system.

The ability to restore power to the dc system from an alternate dc source provides the user with equipment protection, additional time to clear the fault, and the ability to restore the system while minimizing downtime. This can be accomplished through redundant dc systems (battery-charger switchboard) or redundant components (battery or charger), or through alternate feeds from independent dc systems. In considering the ability to recover from a faulted situation, the designer should also consider the equipment's capability to be reset or the availability of spare parts (e.g., fuses) and the associated time to replace those components.

6.7.1 Internal failure mechanisms

Internal failure mechanisms common to both lead-acid and nickel-cadmium batteries are as follows:

- Container failures which entail the cracking of the container and the subsequent loss of electrolyte and loss of seal around posts, particularly for VRLA cells.
- Cell internal and external terminations and connections can cause degradation of the batteries' performance and subsequent failure. Loose or corroded (dirty) connections can lead to higher resistance points and subsequent higher voltage drops and "hot spots." If left undetected, these "hot spots" can eventually lead to arcing and under the correct combination of hydrogen gas and oxygen concentrations can result in an explosion. The high temperature at these "hot spots" can also result in the melting of the lead posts on lead-acid batteries.
- Material contamination can lead to reduction in battery capacity and the deterioration of the plates and posts (e.g., copper contamination for lead-acid cells).

Internal failure mechanisms specific to vented lead-acid batteries are as follows:

- Expansion and corrosion of the plate group due to oxidation of the grid and other current-carrying components.
- Loss of active material from the positive plate.
- Physical changes in the material (sulfation) of the plates which result in loss of capacity.

Internal failure mechanisms specific to valve-regulated batteries are as follows:

- Dryout of the cell.
- Thermal runaway.

Internal failure mechanisms specific to vented nickel-cadmium batteries are as follows:

- Gradual aging and degradation of the active materials in the plates. The degradation in the plates is due to the recrystallization of the nickel hydroxide in the positive plates.
- Carbonation of electrolyte (see IEEE Std 1106-1995).

6.7.2 External failure mechanisms

The following are external failure mechanisms common to both lead-acid and nickel-cadmium batteries:

- a) Personnel errors during operation, maintenance, and testing;
- b) Defective procedures or setpoints;
- c) Charger malfunction;
- d) DC system faults (short circuits) [see 6.7.3].

6.7.3 Battery failure modes under fault conditions

In an uncontrolled short-circuit situation, the battery cell or the cell connections can melt, sometimes with dramatic results and possibly disastrous consequences for the battery and its surrounding environment. Potential weak links in the current path and the consequences resulting from failure are described below.

It should be noted that the failure modes described below can occur in both lead-acid and nickel-cadmium batteries, but have a much higher probability of occurrence in lead-acid batteries due to the materials of

construction. The only credible failure modes under fault conditions for nickel-cadmium batteries involve cable connectors and the plastic cover/container.

- a) *Failure of the plate-to-connecting strap weld.* In valve-regulated batteries (particularly where the post seal, or jar to cover seal is compromised and the outside atmosphere is allowed to enter the cell), there is no free electrolyte to quench a resultant arc when the strap pulls away from the plate, and there is the possibility of igniting the hydrogen gas in the cell.
- b) *Failure of the terminal post.* In both vented and valve-regulated cells, the terminal can melt, either above or below the cell cover. The resultant arc or heat can ignite the cell cover and/or the hydrogen in the head space beneath the cover.
- c) *Failure of the intercell connection.* In both vented and valve-regulated cells, the consequences of this type of failure depends on the type and material of the connection, and the system voltage. Connectors outside the cell simply melt, opening the battery circuit. As the nominal system voltage increases (i.e., 24 V dc, 48 V dc, 125 V dc, etc.), the possibility of a sustained arc increases, resulting in a higher probability of cell cover, or hydrogen gas, ignition. Failed intercell connections that are inside the container (generally found in small, multi-cell valve-regulated batteries) have the same impact as the loss of the plate-to-strap weld.
- d) *Failure of the terminal lug connection.* The heat generated in cable connectors of either lead-acid or nickel-cadmium batteries can melt the insulation and the solder in terminal lugs.
- e) *Failure of the terminal post.* Copper or steel bar connectors outside the cell normally will not fail. However, the heat generated at the connector/terminal interface can result in failure of the terminal post of lead-acid batteries. In nickel-cadmium batteries, the cell cover can be compromised due to heat transfer from the steel terminal post.

The above failure mechanisms can have varying consequences that can result in a catastrophic failure (loss of service) of the battery.

7. Characteristics of other dc system components

This clause is intended to provide the stationary battery system designer with the background knowledge necessary to make prudent design decisions. Specific guidance is provided in Clause 8.

7.1 Battery charger short-circuit characteristics

When a charger is presented with a sudden fault at its output terminals, it provides fault current in short-term, mid-term, and long-term periods.

The short-term fault contribution comes from energy stored in the capacitive output filter elements. Mid-term current is the short-circuit output of the charger with no current limit. The long-term fault current is the steady-state output current of the charger under short-circuit conditions (current limit for chargers equipped with current-limiting capability).

Whether a charger actually produces the mid-term and long-term fault currents depends on whether output fault protection, if present, clears during the short-term fault current.

The magnitude and duration of currents in each period depend on several factors including the following:

- a) Charger types (SCR, controlled ferroresonant, etc.);
- b) Whether the charger is filtered;
- c) If filtered, the filter network design and degree of filtering;