STATIONARY BATTERY AND DC POWER SYSTEM ELECTRICAL PROTECTION DESIGN CONSIDERATIONS

Kurt Uhlir
Director, Technical Services
Standby Power System Consultants, Inc.
Downers Grove, IL

ABSTRACT

Performance of maintenance and testing on all stationary battery systems in accordance with the battery manufacturers' recommendations and the recommended practices of the IEEE Standards for stationary batteries is mandatory for protecting the battery and maintaining reliability of the dc power system. Another form of protection that is often overlooked and often not provided is overcurrent and/or short circuit protection. Lack of this electrical protection or improperly applied protection can lead to catastrophic failure of the battery, the dc distribution system, and the connected load should electrical trouble strike. There are a number of options available to the dc system designer when engineering and providing the electrical protection for the stationary battery and dc power system. This paper will discuss the different types of dc overcurrent and short circuit protective devices along with how they should be applied in a dc power system. The short circuit characteristics of dc power sources will also be examined.

BACKGROUND

Stationary batteries and the dc power system serve as the "lifeline" for medium and high voltage electric power systems, generating stations, alternative energy systems – photovoltaic and wind turbines, UPS, and telecommunication networks. As this "lifeline", the reliability of the system is of the utmost importance.

With each unique application there exist many different philosophies and requirements for the electrical protection of the dc power system. A common misconception prevails that dc power is somewhat straightforward compared to some of the complexities involved with ac power. This often leads to the mindset that selecting the appropriate protective devices is quite simple. It is true that the AC dynamics of capacitance, harmonics or transients become much simpler when the line frequency becomes zero hertz. However, there do exist transient conditions for dc under which protective devices must operate and which must be understood for the proper selection, application and operation of the protective device. To further complicate matters, many protective devices have been tested for and have data that relates only to ac applications and not dc. There is a tendency to assume that all published ac data may be used for dc system applications and as a result many of these types of protective devices are misapplied in dc power system applications. Therefore it is important for the designer to determine the dc applicability and capabilities of the protective device and to know the critical dc circuit parameters, which can vary from application to application, and the overcurrent and fault conditions under which the protective device is expected to operate.

DESIGN CONSIDERATIONS

Overcurrent protective devices used in the dc power system serve to minimize the extent of damage to the dc sources (battery and rectifiers/chargers), the distribution equipment (cables), and the connected dc load during overload and faulted conditions. Generally the operating philosophy of the dc power system determines the design and type of over current protection used. When determining an electrical protection design for the dc system there are two competing objectives:

- to minimize the risk of connected load and power source damage during overload and faulted conditions, and
- to prevent or minimize the number and duration of service interruptions of the dc power sources.

In order to determine the type of overcurrent protection best suited for the application, the designer should begin with a knowledge of the service requirements, the dc circuit parameters, and knowledge of the overcurrent protective devices and their ratings that are available for dc applications.

Service requirements will often dictate what type if any of overcurrent protection is best suited for the protection of the battery itself. The designer of the dc system should consider if:

- the stationary battery is the last available dc source to supply critical loads on an interruption of the ac supply as is often the case in a nuclear generating station application of a dc system, and
- the consequences of losing the supply will result in catastrophic failure of the equipment and facility and/or will jeopardize the safety and welfare of the public, or
- does an alternate supply of dc power exist for the connected dc loads (i.e. parallel battery strings or redundant battery system) where, if the battery supply is interrupted on an overload or fault condition, dc service is not entirely loss?

The dc circuit parameters that must be understood comprise the physical design of the system, the steady state parameters under normal operating conditions and the transient parameters under faulted conditions. Factors that need to be considered are:

- the conductor size and length between the battery and the distribution bus,
- the conductor size and length of the distribution circuits,
- the physical protection afforded the battery conductor between the battery and the distribution bus (i.e. conduit and separation of the positive and negative conductors),
- maximum dc operating voltage of the system,
- normal load current,
- expected level of fault current,
- time constant of the dc system, and
- whether the dc system will be a grounded or ungrounded system.

The proceeding section will discuss the types of overcurrent protection devices, their ratings, and the proper application to achieve dc system electrical protection.

FORMS OF OVERCURRENT PROTECTION

A number of options for overcurrent protection are available for the designer of a dc power system. These options include:

- Fuse
- Circuit breaker
- Fused circuit breaker
- Fused disconnect switch

It is important to note, that no one form of overcurrent protection is more correct than another. Rather, the form of dc power system overcurrent protection chosen by the designer is dependent upon the design considerations discussed in the previous section. Other forms of electrical protection not discussed in this paper for the dc system such as overvoltage and undervoltage, and ground fault protection for ungrounded systems are available and should be considered based on the application and service requirements. Fuse and circuit breaker applications will be examined only in the proceeding sections.

FUSE PROTECTION

Fuses 101

There have been many misapplications of fuses in dc power systems. A common misconception exists that all published ac data can be applied for dc systems. To understand these misconceptions, we must first look at how a fuse behaves. Most fuses consist of one or more elements which contain notches. The notches are reduced cross-section areas in the element designed to concentrate heat. The element is enclosed by a fuse body and typically surrounded by an arc quenching medium such as silica sand often referred to as filler. The element is either welded or soldered to the fuse contacts. Figure 1 shows a typical fuse construction. Heat is generated by the element at a rate dependent upon the element resistance, load current and time. Effective heat transfer is provided by the filler which conducts the heat away from the element, through the fuse body and to the medium surrounding the fuse. The filler aids fuse performance by absorbing the arc energy when the fuse clears an overload or fault current. When a sustained overcurrent occurs, the element generates heat at a faster rate than the filler can conduct it away from the element. The resulting rapid current rise causes the element to melt at its notches. The melting opens the metallic conductive path through which the current normally flows. However, the current flow continues via the arc developed between the open ends of the element. Arcing continues until the “arc voltage” or the voltage drop across the melted fuse element rises to a point that is equal to the system voltage. At that point, the arc will be extinguished and the current flow ceases. In a 60 Hz ac application, the current passes through zero 120 times per second. This natural zero crossing also helps the fuse extinguish any arcing that occurs across the melted fuse element. This however does not aid in fast acting current limiting fuses because arc extinction occurs long before current passes through zero. In a dc application, current does not inherently pass through zero, subsequently the voltage is sustained and the arcing across the melted fuse element continues until the voltage drop equals the dc system voltage. Therefore, it is important that the fuse be capable of absorbing and extinguishing all of the energy in the dc arc.

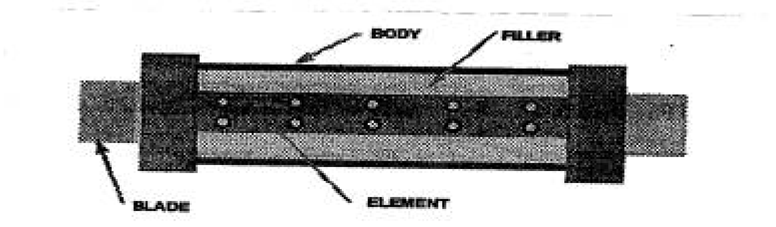
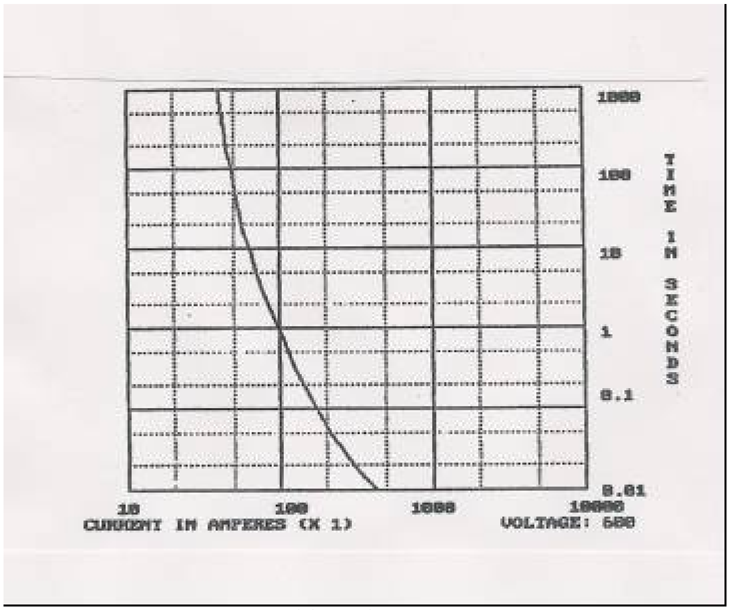


Figure 1

AC Versus DC Applications

Often, ac rated fuses will be applied in a dc application using ½ the ac voltage rating as the appropriate dc voltage rating. This voltage derating decreases the arcing time required to increase the arc voltage drop across the melted fuse element to a point that is equal to the system voltage so that current flow will cease. The lowering of the arcing time decreases the arcing I^2t (let-through energy) thus maintaining clearing let-through energy to below allowable levels. This however can not be applied to all classes of fuses without appropriate testing. As a result, a fuse must have been tested using circuit parameters representing the specific application to fully ensure that the fuse will safely interrupt a dc circuit.

For overload protection, a time-current curve as shown in Figure 2 provides the fuse opening time under ac overload conditions. These curves are typically supplied by the fuse manufacturers and are developed based on ac testing. They can often times be applied for dc overload applications because they are typically based on RMS current, which is thermally equivalent to dc. However, for fault protection of a dc system this will not hold true..



Average Melting Time Current Curve
30A, 600 VAC Fuse
Figure 2

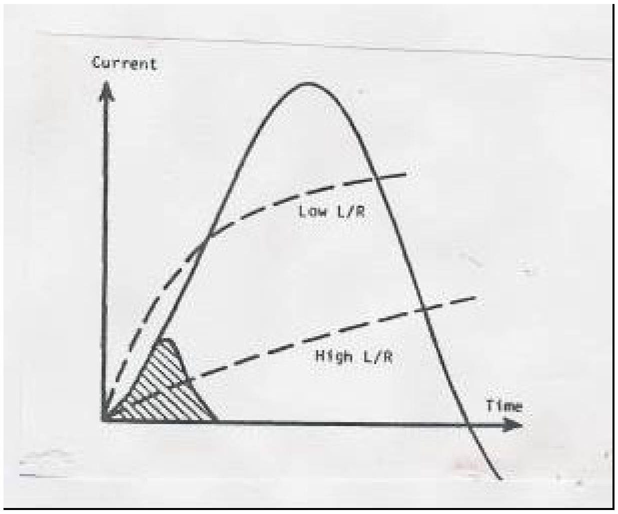
In an ac circuit, the rate of rise of fault current is a function of system frequency as shown in Figure 3. In a dc circuit this does not hold true. In a dc circuit, the fault current rises as a function of circuit inductance. This is referred to as the circuit time constant. If circuit inductance is high, current will rise more slowly as shown in Figure 3. The fuse will therefore take longer to melt. The let-through energy to the fault represented by I^2t may cause more damage because of the high value of time (t) opposed to a high value of current (I) for circuits with lower inductance.

The time constant is the dc circuit parameter most often overlooked in fuse selection. The time constant (г) is defined as:

$$\Gamma = L/R$$

where
Γ = time constant in seconds
L = inductance in henrys (H)
R= resistance in ohms (Ω)

By definition, if rated voltage is applied, 63% of rated current will be reached in one time constant. The time constant gives a measure of how quickly the current in a dc circuit can rise or fall under transient conditions. The time constant also provides a measure of the inductance and resistance in the circuit. The higher the voltage and time constant (inductance), the more difficult it is to interrupt the circuit because energy is stored in the inductance. When a fault occurs in a 60 Hz ac circuit, the current will reach its maximum value in ¼ to ½ cycles (4.17 to 8.33 mS) depending on the system power factor and where on the voltage sine wave the fault occurs. If the fault current is large enough so that the fuse is operating in its current limit range, the fuse will melt open in less than ½ cycles. On a dc fault, the current will reach its maximum value in approximately 5 time constants. A typical dc circuit with a 10 mS time constant will reach its maximum fault current in 50 mS or at least 6 times longer than for the ac circuit. Most dc rated fuses are UL listed and tested to a time constant of 10 mS. If the circuit dc time constant is less than 10 mS, then generally a UL rated dc fuse will be acceptable for the application. However, if the dc time constant is greater than 10 mS, the fuse may not be acceptable and should be further evaluated.



Fault current versus time in a dc circuit (dashed curves)
Initial fault current in an ac circuit (solid curve)
Figure 3

DC Fuse Selection Criteria

When selecting a fuse for use in a dc system the following items are recommended:

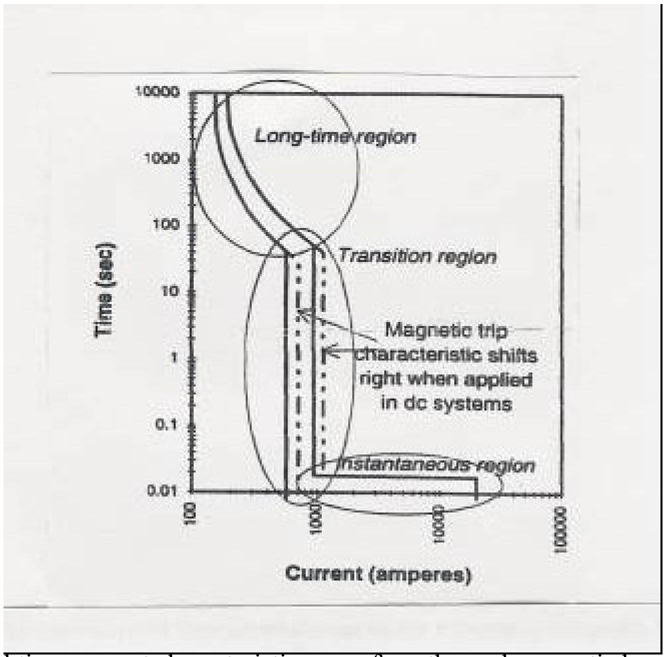
- the fuse should be rated and have been tested for use in a dc circuit,
- the voltage rating of the fuse should be greater than the maximum system voltage where the fuse will be applied,
- the interrupting capacity of the fuse must be greater than the maximum anticipated fault current it will be exposed to,
- the time constant of the circuit should be less than or equal to 10mS*, and
- the trip rating of the fuse must be greater than the anticipated continuous current.

*Note: where time constants are higher due to high circuit inductance then the fuse should be tested using the circuit parameters representing the specific application.

CIRCUIT BREAKER PROTECTION

Circuit Breaker 101

Circuit breakers must be properly designed for use in a dc system to differentiate between an acceptable load current and an overload and a fault current. Under fault conditions, they also must be able to respond in a proper time frame to protect the system by selectively disconnecting the minimum amount of equipment necessary to clear the fault. Figure 4 shows a typical time-current tripping characteristic for a thermal-magnetic circuit breaker. This curve is normally provided by the manufacturer as the ac curve and multipliers are given for the designer to convert it for use with dc circuits. The tripping characteristics fall into three regions: the long-time delay region at the top, the transition region at the center and the instantaneous region at the bottom.



Typical time-current characteristic curve for a thermal-magnetic breaker

Figure 4

The long-time delay region generally includes currents from 100% of rated which the circuit breaker will carry indefinitely to the level at which it will trip instantaneously. This is referred to as the thermal range. The sensing element for the thermal range is a bi-metal. The bi-metal heats up as current passes through the circuit breaker. Deflection of the bi-metal is proportional to I^2 so it is an ideal RMS current sensor. Deflection with dc will be the same as with RMS of ac so that the time current characteristics will be essentially the same for both ac and dc in the long-time delay. The transition region generally covers overcurrents just higher than the stalled rotor currents for motors, usually 400-1200% of rated current. Trip times in this region are not precisely defined since it is here that transition from thermal to magnetic tripping occurs. Depending on the level of overcurrent, tripping can be thermal, with the built in delay shown on the thermal curve, or magnetic with no intentional delay. The magnetic tripping is performed by an electromagnet which is activated by current flowing through the circuit breaker. The magnetic force is proportional to the instantaneous I^2 rather than the RMS value over some period. Current on an ac trip curve is expressed in terms of RMS values while dc is expressed as an instantaneous value. This difference in expressing current is an essential factor in adjusting ac curves to dc applications. As a result of these differences, the circuit breaker manufacturers will provide adjustments to the trip curves in the overload region in the form of multipliers or redrawn ac trip curves. Several manufacturers express this difference in a multiplying factor of 1.1 to 1.4 times the ac tripping current for dc applications. The instantaneous region is at current levels above transition. Tripping and clearing are instantaneous whether in ac or dc. Tripping is performed by the electromagnet as discussed in the transition region. Similar to fuses, dc rated circuit breakers are generally tested to time constants of 10 mS or less.

Circuit Breaker Selection Criteria

When selecting a circuit breaker for use in a dc system the following items are recommended:

- the circuit breaker should be rated for use in a dc circuit,
- the voltage rating of the circuit breaker should be greater than the maximum system voltage where the circuit breaker will be applied,
- the interrupting capacity of the circuit breaker must be greater than the maximum anticipated fault current it will be exposed to,
- the time constant of the circuit should be less than or equal to 10mS*,
- the trip setting of the circuit breaker must be greater than the anticipated continuous current, and

- time-current trip curves drawn for ac applications of circuit breakers are frequently provided by manufacturers for dc applications. Adjustment factors for instantaneous trip levels are normally available from the manufacturers.

*Note: where time constants are higher due to high circuit inductance then the circuit breaker should be tested using the circuit parameters representing the specific application.

DC SOURCE AVAILABLE SHORT CIRCUIT CURRENT

As mentioned in the previous section on fuse and circuit breaker protection, determining available short circuit current in the dc system is of the utmost importance when designing electrical protection for the dc system. The battery is considered a finite source of power. The short circuit current of a battery depends upon the resistance of the short circuit path, state of charge and internal resistance of the battery. The internal resistance of the battery depends on variables such as the material and dimensions of the grids and terminal posts, surface area and composition of the active material, spacing between the plates, specific gravity of the electrolyte, and thickness and material of the separators. In addition to the battery, the rectifier(s) will also contribute current to a fault as will any dc motors if applicable. These sources also need to be included in a fault analysis of the dc system.

The battery manufacturer can also be contacted for available short circuit values of a specific battery type and ampere-hour capacity. As an alternative, IEEE Std. 946-1992, IEEE Recommended Practice for the Design of DC Auxiliary Power Systems for Generating Stations provides guidance on how to determine the available short circuit current from a lead acid battery and the rectifier(s).

SUMMARY

There are a number of options available to the dc system designer for selecting dc system overcurrent protection and that no one form of overcurrent protection is more correct than another. Fuses, circuit breakers, fused circuit breakers, fused disconnect switches or a combination of these overcurrent protective devices may be used depending on what is best suited for the specific application. In order to determine the type of overcurrent protection best suited for the application, the designer should begin with a knowledge of the service requirements, the dc circuit parameters, and knowledge of the overcurrent protective devices and their ratings that are available for dc applications. The designer is encouraged to review IEEE std. 1375-1998, IEEE Guide for the Protection of Stationary Battery Systems for more comprehensive guidance on overcurrent protection for stationary battery system.

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