Design and Specification for Safe and Reliable Battery Systems for Large UPS

White Paper 207
Revision 0

by Pearl Hu

Executive summary

A properly designed UPS battery solution is important for safe and reliable operation. This paper describes the main components and functions of a battery system, and discusses the reasons why vendor pre-engineered battery solutions are optimal. In cases where pre-engineered solutions don't meet the requirements, vendor-engineered solutions are next best. If third party custom battery solutions *must* be used, design guidelines are provided to ensure a safe and reliable design.

Introduction

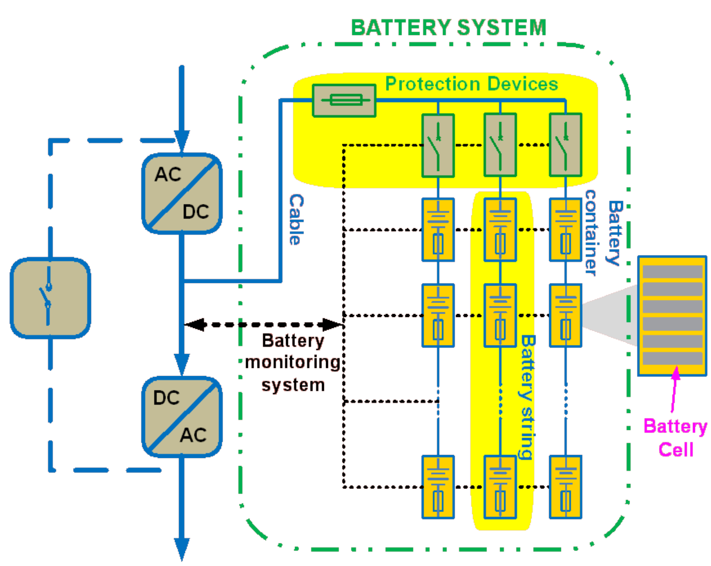
Although new battery technologies are emerging (e.g., lithium-ion, nickel-metal-hydride, etc.), lead-acid batteries continue to have the best cost/performance ratio for UPS applications. Two types of lead-acid battery technologies are utilized for almost all data center UPS systems[1]: vented (flooded) and valve-regulated (VRLA). VRLA come in one of three formats: top terminal, front terminal, or modular cartridge. Regardless of lead acid technology or format, battery systems must incorporate routine safety and reliability design practices established over years of field experience. White Paper 39, *Battery Technology for Data Centers and Network Rooms: VRLA Reliability and Safety*, discusses this topic for VRLA specifically.

Unlike any other power sources, batteries exhibit variable short circuit current which presents a bigger challenge in selecting and rating the protection devices. The design process introduced in this paper will help battery system designers and people who are specifying or purchasing battery systems better understand the battery system and ensure that battery system providers supply safe and reliable solutions.

The battery cell is the smallest single electrochemical component, consisting of positive and negative electrodes and an electrolyte to transport ions. The nominal voltage of a lead-acid cell is two volts. A battery container (or unit) can contain a single cell or multiple cells (for example the common 12-volt unit contains 6x2-volt cells). Cells are connected in series to achieve the voltage required to operate the equipment, in this case a UPS inverter (e.g., 384 volts). Strings can be connected in parallel to achieve higher power (watts). For safety purposes, the installed overcurrent devices provide protection during abnormal conditions (e.g. overcurrent / fault) and can often be used to disconnect the batteries from the UPSs (e.g. UPS off or malfunctioning). A battery monitoring system can check the health status of battery blocks. The block diagram of a double-conversion online UPS and battery system consisting of three parallel strings is illustrated in **Figure 1**.

Figure 1

Block diagram of a UPS and battery system



This paper describes the main components of a battery system, discusses the key electrical design steps for battery system protection, and describes design best practices used in vendor integrated UPS battery systems. Finally, a checklist is provided for custom battery solutions.

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[1] WP30, *Battery Technology for Data Centers and Network Rooms: Lead-Acid Battery Options*

Design of battery system

An example of a vendor-engineered modular UPS including, modular batteries, conductors, protection devices, and monitoring, is shown in **Figure 2**. It is an engineered and validated battery system by a UPS vendor who has already taken into account parameters such as UPS performance, charge and discharge characteristics, battery service life, types of potential faults, customer maintenance plan or schedule, environment, etc.

Figure 2

Example of a modular UPS and battery system

Whether a vendor-engineered standard solution or a custom battery solution is selected, the design steps of the UPS battery subsystems should be the same. Specifically, they should follow the six steps below:

- Step 1 – Select and size the battery
- Step 2 – Calculate discharging current
- Step 3 – Select conductor size
- Step 4 – Calculate short circuit current
- Step 5 – Select protection devices
- Step 6 – Implement the whole battery system assembly

The ONLY difference should be who is responsible for the design and validation and who takes on the potential risk.

Step 1 – Select and size the battery

Table 1 lists the key questions required for sizing a battery along with an example answer.

Table 1

Key sizing questions and an example answers

Key sizing questions	Example
How many battery strings are in parallel?	6 strings
How many individual battery units (in series) per string?	32 x 12-volt units per string
What is the battery model?	APC: M2AL12-134

Note that the battery capacity in amp hours (Ah) or watt hours (Wh) for a specific C-rate[2] is NOT enough information for UPS battery sizing[3] because the characteristics of each battery model are unique.

In order to answer the questions in **Table 1**, some design parameters must be determined:

- Detailed load profiles, such as load rating in kW
- Specified back-up time in minutes or hours
- UPS characteristics, such as inverter efficiency, battery charger efficiency, nominal DC voltage, etc.
- Battery specifications, such as float voltage, cut-off voltage (which generally defines the "empty" state of battery charging), maximum charging voltage/current limitations, and discharging performance, all of which are generally specified in the battery datasheet
- Parallel battery strings, to avoid failure mode due to cell reversal[4]. Cell reversal is mostly associated with large strings of batteries and is primarily restricted to VRLA batteries due to the battery degradation or manufacturing defect.
- Battery redundancy requirement, i.e. 1N, N+1, 2N strings, is critical to design a reliable battery system rather than simply oversizing the battery.

The design process is iterative and continuously optimized to get the final battery sizing and configuration.

Step 2 – Calculate discharging current

In order to ensure the battery system operates in a safe and reliable state, the charging and discharging states must be analyzed. The lower battery charging current is always set by the UPS battery charger circuit according to the recommended value of the battery. The higher discharging current must be calculated based on the load, load power factor, UPS inverter efficiency, and the battery voltage as shown by **Formula 1**. The battery discharging current is correlated with the battery charge state, the load, and the UPS inverter efficiency.

Formula 1

Battery discharging current

$$I_{discharging} = (P_{load} * PF)/\eta/V_{batt}$$

P_{load}: The equivalent UPS loading in VA;
PF: Load power factor;
η: UPS inverter efficiency (which is different for the different UPS models);
V_{batt}: Battery voltage correlated with the battery state of charge.

Step 3 – Select conductor size

The conductors in the battery system include the connection of each individual battery unit (called inter-cell connectors) and the conductors between UPS and battery banks. For large rack-mounted batteries, inter-tier and inter-aisle conductors must also be chosen. The impedance of the entire battery system (necessary for arc flash calculations) includes the impedance of all conductors. In most data center UPS battery applications, copper conductors are preferred over aluminum.

The key design criterion is the voltage drop of conductors, which should be less than 1% of the UPS DC voltage, measured at the point where the battery connects to the UPS. By

[2] MIT electric vehicle team, "A Guide to Understanding Battery Specifications", December 2008

[3] http://www.openelectrical.org/wiki/index.php?title=Battery_Sizing

[4] For more information on cell reversal see page 6 of White Paper 39, *Battery Technology for Data Centers and Network Rooms: VRLA Reliability and Safety*

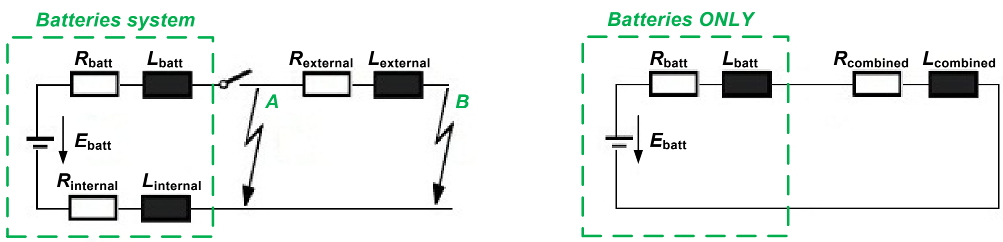
analyzing the worst case current of the battery discharging scenarios and the distance between UPSs and batteries, the minimum conductor cross-section can be calculated. The international standard specifies the nominal cross-section areas in the range of 0.5mm^2 to 2500 mm^2. Some countries at present use conductor sizes and characteristics according to the American Wire Gauge (AWG) system.

Step 4 – Calculate short circuit current

In addition to the charging and discharging states, short circuit scenarios must also be analyzed because the circuit has the potential to deliver an extremely high current. The potential short circuit locations and the equivalent circuit of the battery system are shown in **Figure 3**. IEC 61660-1, "short-circuit currents in DC auxiliary installations in power plants and substations – part1: Calculation of short-circuit currents", describes the method for calculating battery short-circuit currents based on the above equivalent battery short circuit.

Figure 3

a) UPS battery short circuit location; b) the equivalent short circuit



(a) Short-circuit locations (b) the equivalent short-circuit

The inductances (L_{batt} and $L_{combined}$) shown in **Figure 3b** limit the short-circuit current initial rate of rise to a peak value (I_p) at time (t_p), but not the short-circuit current (I_{sc}) which trips the protection devices shown in **Figure 4**. The short-circuit current, which helps to set the trip current of the protection devices, can be calculated using the following formula:

Formula 2

Short-circuit current

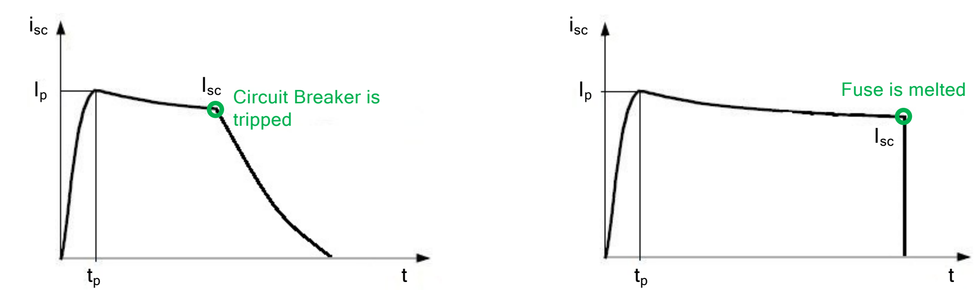
$$I_{sc} = E_{batt}/(R_{batt} + R_{combined})$$

E_{batt}: Open-circuit voltage of the battery
R_{batt}: The equivalent internal battery resistance
$R_{combined}$: Combined resistance of the total system except the batteries, including internal and external cable and their connections (i.e. terminations), and protection devices

Figure 4 shows typical short-circuit current curves using a breaker (**Figure 4a**) and a fuse (**Figure 4b**). **Without some form of protection such as a fuse or breaker, a DC short circuit condition can cause permanent battery damage, including the potential for fire.**

Figure 4

Diagram of typical short-circuit currents as a function of time



(a) Short-circuit current with DC circuit breaker (b) short-circuit current with DC fuses

Note that all of the equations above apply to all modes of UPS operation; a good battery system designer uses these formulas to calculate short circuit current for key UPS modes. The battery system voltage (E_{batt}) and internal battery resistance (R_{batt}) vary with the state of charge[5] and battery state of health[6]. As a battery is close to the end of discharging or as it gets older, its voltage decreases and its resistance increases, both of which act to decrease short circuit current. **If the short circuit current becomes too low, it may not be enough to open the protective circuit breaker or fast fuse which leads to heating and potential fire.** An example of a battery fire is shown in **Figure 5**. This illustrates why it's critical that the protection devices account for these varying amounts of short circuit current during diffident modes of operation. **Table 2** lists some battery currents and their relationship to the battery status.

Figure 5

Example of a battery fire

Table 2

Battery currents and relationship to battery status

Current type	Current description	Battery status		
		End of Life*	Full charge	End of discharge
$I_{rated\_discharging}$	Rated battery discharging current		Y	
$I_{max\_discharging}$	Maximum battery discharging current			Y
I_{sc_nom}	The normal short-circuit current		Y	
I_{sc_EOD}	End-of-discharge short-circuit current			Y
I_{sc_EOL}	Short-circuit current with end-of-life batteries	Y	Y	
$I_{sc\_EOL\_EOD}$	End-of-discharge short-circuit current with end-of-life batteries.	Y		Y

* The end-of-life column refers to the standard lifespan of the batteries. VRLA batteries in an IT equipment room typically have a life expectancy of three to five years with regular maintenance.

Generally battery providers specify the internal resistance **at full charge**, so the calculated short-circuit current is $\mathbf{I_{sc\_nom}}$. However, a good battery system designer calculates short circuit current for varying states of charge. For example, when batteries are close to the end of discharge AND at end of life, a typical VRLA battery voltage can decrease to 80% of its full-charge voltage and the resistance can increase by 30% or more compared to its specified resistance. Therefore, short-circuit current $\mathbf{I_{sc\_EOL\_EOD}}$ is only 61% of $\mathbf{I_{sc\_nom}}$ or less. If the

[5] Scott D.Gerner, Paul D. Korinek, Tom E. Ruhlmann, "calculated vs. actual short circuit currents for VRLA batteries", Battcon 2003.

[6] C&D Technologies, "impedance and conductance testing", Technical bulletin 41-7271.

design is only based on the short-circuit at full charge I_{sc_nom}, the protective devices would likely not open fast enough when a fault occurs while on battery, which could lead to a fire.

When designing a battery system it is critical to account for the battery and UPS performance to calculate the discharging and short-circuit currents correctly. **Solely referring to a battery specification is NOT enough to design a safe and reliable battery system**.

Step 5 - Select protection devices

Based on the analysis in step 4, an acceptable time-current curve for the protection device should be similar to the GREEN curve shown in **Figure 6**. The GREEN shaded area represents the normal operation zone in which the protective devices allow the required discharging current to flow during on-battery operation. This shaded green area must be located to the left of the time-current curve of the protective devices. The RED shaded area represents the abnormal operation zone in which the protective devices should open to disconnect the batteries from the UPS system. This shaded red area is supposed to be located to the right of the time-current curve of the protective devices. In general, the short-circuit time is always **several tens of milliseconds** to ensure the fault can be isolated apart from the batteries as quickly as possible. The longer it takes to open the protective device, the more fault current and energy is supplied by the battery which may lead to damage and even fire. As we discussed in step 4, short circuit current varies with the battery status, the BLUE dashed curve would not be a good time-current curve because the short-current time will be **tens of seconds** at $I_{sc\_EOL\_EOD}$.

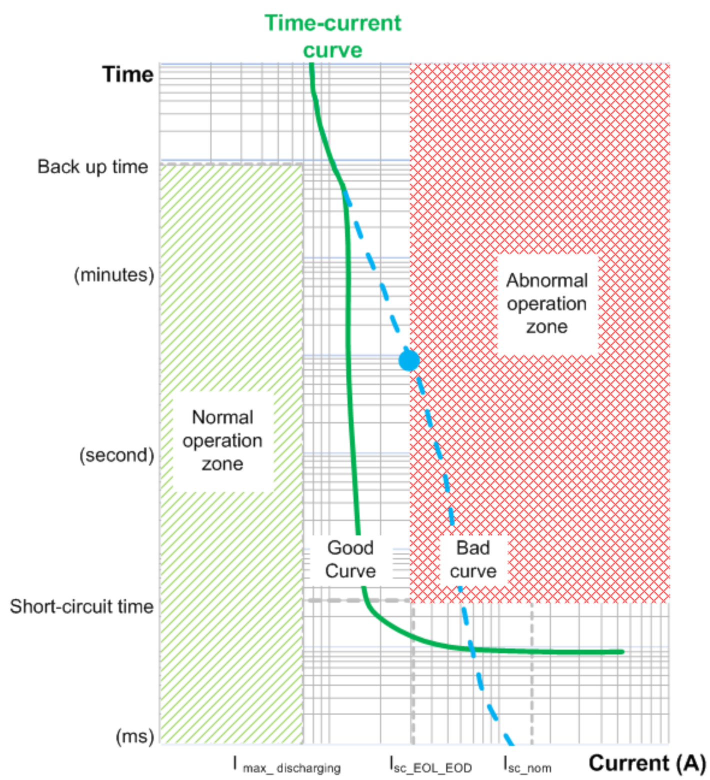


Figure 6

Time-current curves of the protection devices

Protection devices including DC circuit breakers, DC fuses, or DC switches integrated with the battery monitoring system are always assembled into a switchboard or panelboard. The switchboard or panelboard is typically located in the battery room and is sometimes integrated with the battery cabinet. **Table 3** provides a feature-by-feature comparison of the merits of some DC protective devices. Both fuses and thermal-magnetic circuit breakers operate based on the heating produced by over-loads or fault currents flowing through them. As a result, the ambient temperature can have an effect on the trip characteristics of both types of devices. Use of electronic-trip circuit breakers is recommended as these trip units are not affected by ambient temperature levels.

Table 3

Comparison of the DC protective devices

DC devices	Trip or melting range	Advanced features[1]	Derating	Resettable	Cost
DC circuit breaker with thermal-magnetic trip unit	Adjustable trip setting from 8 to 10 I_n [2]	Embedded	Thermal effect	Yes	High
DC circuit breaker with electronic-trip unit	Adjustable trip setting from 1.5 to 10 I_n	Embedded	Non-thermal effect	Yes	High
DC disconnect switches	Rely upon the upstream circuit breaker or fuses to clear the short-circuit fault	Embedded	Non-thermal effect	Yes	Middle
DC fuse with fast melting	Fixed melting value by the current-time curve	None	Thermal effect	No	Low
DC fuse with time-delay melting	Fixed melting value by the current-time curve	None	Thermal effect	No	Low

[1] Advanced protection and control/monitoring features, including:
- Overvoltage/undervoltage alarm/trip
- Metering capabilities: voltage, current, and power etc.
- Supporting of communication protocols that allow trip unit to be tied into the system-level monitoring system
- Supporting the communication with UPS, such as UPS off due to emergency power off (EPO)

[2] I_n is the rated current of the devices.

The use of AC devices, such as AC circuit breakers, AC fuses, or AC switches, in DC battery protection circuits is not recommended. Some AC devices are certified for the DC applications but their use should be verified on a case by case basis. See **Appendix** for detailed information on DC and AC devices.

In most projects, the selected DC protection devices may include one or more kinds of devices depending on advanced features, redundancy requirements, maintenance plan, cost, etc. The design checklist of step 4 is listed in **Table 4** along with example answers.

Table 4

Design checklist for protection device selection

Design checklist	Example
Select the protection devices based on the battery configuration.	Schneider Electric NS630DC
How many protection devices should be assembled?	one NS630DC
Choose the device ratings based on the discharging current and the back-up time.	684A for 15 minutes
Set the tripping current based on the short-circuit currents and its duration.	1200A less than 20ms

Step 6 – Implement the whole battery system assembly

Battery protection solutions are typically a tradeoff between performance and cost. The best solutions monitor the health status of each individual battery unit, ensure normal operation during charging and discharging modes, and open the circuit and/or alarm under specified abnormal conditions (such as the one in **Figure 2**). Unfortunately, many battery protection solutions specified by solution providers or end users provide only rudimentary system-level protection, as shown in **Figure 7**.

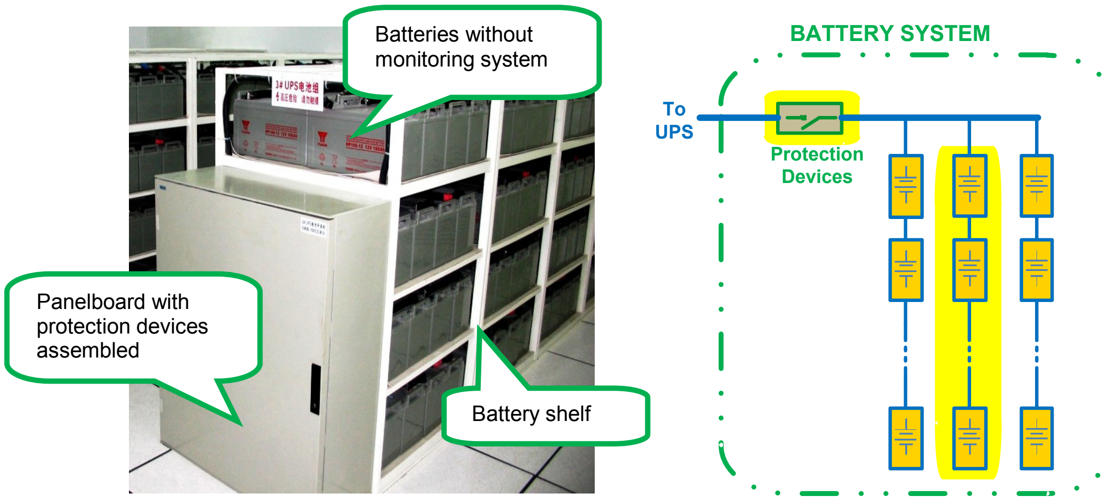


Figure 7

A rudimentary battery solution

Vendor-designed UPS battery systems

There are basically two types of vendor-designed UPS battery systems: vendor-engineered battery systems and pre-engineered modular battery systems. The following sections discuss each of these.

Vendor-engineered battery system

A vendor-engineered, also known as "engineered to order" battery system refers to a battery solution recommended and validated by the UPS provider based on custom end user requirements and preferences. The following are common design practices used by UPS vendors which are based on validated testing that improves electrical safety:

- Batteries sized according to UPS back-up time requirement
- Battery protective devices selected based on range of short circuit current
- Battery cables sized according to distance
- System installed based on standardized best practices
- Integrated battery monitoring system

Vendor-engineered battery solutions leave the design process to the UPS providers who are experts in UPS performance and have the ability to validate the protection functions under any specified condition. UPS providers work with end users to develop the battery protection system as part of a holistic UPS system and perform validated system-level testing.

Finally, if a battery system is to be reliable, it must be installed, operated, serviced, and maintained by qualified personnel.

Pre-engineered modular battery system

A pre-engineered modular battery system refers to a standardized and qualified battery solution. The UPS vendor specifies the product performance criteria such as run-time, voltage, discharging current characteristics, etc. A modular battery system is generally compromised of the following:

- Qualified batteries connected in series or parallel – Each module is fused and performance of batteries is monitored, so health status of the module or batteries is known at all times.
- Cable crimps – Improper crimping is one of the causes of high resistance and conductor overheating, which in turn can cause an entire string to fail. All battery cable connection crimps are made at the factory where quality control is highest compared to crimps made in the field.
- Protective devices such as DC circuit breakers with preset trip curves – Validation testing completed in the factory that accounts for potential risks such as overcurrent/fault, undervoltage, overheating, or isolation function for maintenance.
- Integrated monitoring system and communication interface to notify operational personnel of weak or defective batteries.
- Battery cabinets designed for safety, reliability, shipping, certification, etc.

Pre-engineered solutions are analyzed, designed, tested, qualified, and proven out over many systems. System architects or designers need only select standardized modular battery systems for a specified back-up time.

Checklist for custom battery systems

In terms of electrical safety and reliability, pre-engineered modular battery systems are always recommended. When no suitable pre-engineered battery solution is available, a vendor-engineered solution is second best. In some cases, data center owners may choose to implement their own custom-engineered battery solution. Though not recommended, if data center owners choose this option, the following checklist is recommended:

- Follow the five design steps discussed in this paper
- Analyze and validate the safety of the entire UPS system under normal and abnormal operation, as well as at full charge and end-of-discharge
- Perform strict quality control of critical devices including UPS, batteries, protective devices selected, etc., **as well as during system assembly**
- Ensure that enough spare parts are kept in inventory
- Set up a periodic maintenance plan and ensure the implementation of the defined plan

Conclusion

People assume a battery system is simply a group of batteries connected together. There's much more that goes into a battery system and mistakes can be costly and dangerous.

In far too many projects, the battery protection solution is relegated to a tradeoff between cost and performance. Cost usually wins out at the risk of system damage and fire. Specifying vendor integrated UPS battery systems is the optimal approach to minimizing risk while increasing reliability of critical loads. Furthermore, standardized designs eliminate non-recurring (i.e. one-time) engineering.

Pre-engineered, standardized, modular battery solutions are recommended as the best practice solution. Vendor-engineered battery solutions are the second best solution to address customized requirements. However, if custom-engineered battery solutions are still required, end users should follow the checklist provided in this paper to ensure a safe and reliable system.

About the author

Pearl Hu is a Senior Research specialist at Schneider Electric's Data Center Science Center. She holds bachelor's degree in Electrical Engineering from the Taiyuan University of Technology and a master's degree in Power Electronics from the South China University of Technology. Before joining Schneider Electric, Pearl worked in General Electric R&D center (China) and Emerson Network Power. She is now designated as a "Data Center Certified Associate", an internationally recognized validation of the knowledge and skills required of a data center professional.

Resources

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Appendix:

In some customer projects, AC devices, including AC circuit breakers, AC fuses, and AC disconnect switches are designed and assembled into the DC battery switchboard. These devices are *not* recommended for UPS battery systems due to safety and reliability reasons.

AC circuit breaker vs. DC circuit breaker

A circuit breaker is a mechanical switching device that clears the overcurrent and fault current from the system through opening a set of contacts. Both AC and DC circuit breakers have a trip unit, arc chute, contacts, and other mechanisms. However, the type of current (AC or DC) represents a major difference between AC and DC circuit breakers. Because alternating current naturally passes through a zero point at each half cycle (e.g. 10ms for 50Hz AC system and 8.33ms for 60Hz AC system), it's easier to extinguish the arc as the breaker begins to open. With direct current, there is no "zero crossing" during a fault, which makes it more difficult to extinguish the arc. This means that the mechanism for a DC circuit breaker must be designed to handle the extra energy. For example, a 100A DC breaker is more robust than a 100A AC breaker.

Circuit breakers can be tripped open using three main techniques; thermal, magnetic, and electronic. The use of AC breakers in DC applications is not recommended for magnetic and electronic techniques. An AC circuit breaker with a thermal trip mechanism can sometimes be used in DC applications that require only thermal tripping. This is because both AC and DC breakers react equally to the heating caused by the current flow. This is strictly a function of the bi-metal strip inside the breaker. However, for protection against fault currents, the magnetic or electronic tripping mechanisms are used; the thermal mechanism is never used for fault currents. This is important because magnetic and electronic trip mechanisms for an AC breaker will trip at different values than a DC breaker. This is why coefficients are used to "oversize" AC breakers for use in DC applications. The use of AC breakers in DC applications must always be tested and validated.

AC fuse vs. DC fuse

A fuse is a relatively simple device that removes faults from a battery system using a filament. The heat energy caused by an overcurrent or fault current, through the filament, brings it to its melting temperature. When the melting phase reaches completion, an electrical arc occurs immediately prior to the "opening" of the fusible element. So in principle, the fuse-links are suitable for use in alternating and direct voltage. However, the breaking capacity for direct voltage is considerably lower than for alternating voltage. Therefore, with electrical safety and reliability considerations in mind for the UPS battery system, a fuse with DC certification and testing is recommended.

The melting process is a "one-way" process. Once the fusible element is melted, it must be replaced. So in a real project, a substantial inventory of spare fuses must be maintained to ensure minimum downtime.

AC disconnect switch vs. DC disconnect switch

The disconnect switch is a mechanical switching device that is capable of breaking currents under normal conditions such as planned maintenance, but not breaking fault current. In actual applications, a disconnect switch relies upon the upstream circuit breaker or fuse to clear the short-circuit fault. AC disconnect switches are not rated for DC use and must not be used in battery systems.