FUSES FOR BATTERY ENERGY STORAGE SYSTEMS

How to Properly Protect a BESS Power Circuit from Overcurrents

TECHNICAL PAPER

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Introduction

From a drop of rain to the shining sea, an energy storage system is like the earth's bodies of water (hear us out).

In a battery energy storage system (BESS), the energy in the battery cells is like raindrops that combine to form a brook. Made of the combined energy from cells, these brooks combine to form a river—the battery-module energy. The modules are combined in series to form a rack. The hills' slope on which these rivers flow down represent the rack. The rivers flowing down the slopes combine to form a "sea" of energy. And whether it be the picturesque open water or your energy investment—all things precious must be protected.

Circuit protection becomes necessary when each of these levels from the cells to the racks form a combination of energy. Fuses are an efficient and effective way to protect a BESS from overcurrents. Overcurrents not only frequently damage systems, but are also the culprit of downtime, which is detrimental to a company's bottom line.

The advantages fuses bring to a BESS are immense. Without a need for complex wiring or additional components, fuses are a great way to protect a system simply and cost-effectively.

Fuses can be easily replaced without the accumulation of additional downtime. BESS fuses' low watt loss prevents energy loss, which efficiently minimizes wasted power from components. Their compact size makes designing high-energy density systems possible. BESS fuses have a dc-breaking capacity of up to 250 kA (or potentially more) at 1500 V dc, which enables the design of a long-duration BESS, but have a low minimum breaking capacity that offers protection for lower fault-current levels. All in all, fuses are a win for a BESS.

Circuit protection must be adequately sized to prevent catastrophic failure. The optimal circuit protection component to use depends on the

- system voltage,
- system nominal current,
- time constant,
- withstand rating of the interconnecting components,
- ambient conditions, and
- location of the component within the system.

This paper discusses the different fault-prone points of a BESS, and how to adequately size the fuse for optimal overcurrent protection.

Acronyms

ac	alternating current
BPU	battery protection unit
BESS	battery energy storage system
dc	direct current
ESR	energy-storage rack
IEC	International Electrotechnical Commission
IGBT	insulated-gate bipolar transistors
NEC	National Electrical Code
OEM	original equipment manufacturer
UL	Underwriters Laboratory
UPS	universal power supply

The Difference Between a BESS and a UPS System

People sometimes confuse BESSs with universal power supply (UPS) systems.

The NEC makes this distinction in 706.2's second informational note, which says a BESS differs "from other storage systems such as a UPS system, which is a power supply used to provide alternating current power to a load for some period of time in the event of a power failure." A BESS, however, is "one or more components assembled together capable of storing energy and providing electrical energy into the premises wiring system or an electric power production and distribution network," the NEC 706.2 says.

Where Circuit Protection Is Important in a BESS

According to UL 1741 32.4 (third edition), units that are intended for connection to a battery circuit should be provided with overcurrent protection. Circuit protection is important at

- the level of the module,
- the battery rack,
- the dc panel (also known as the *dc-array combiner cabinet*), and

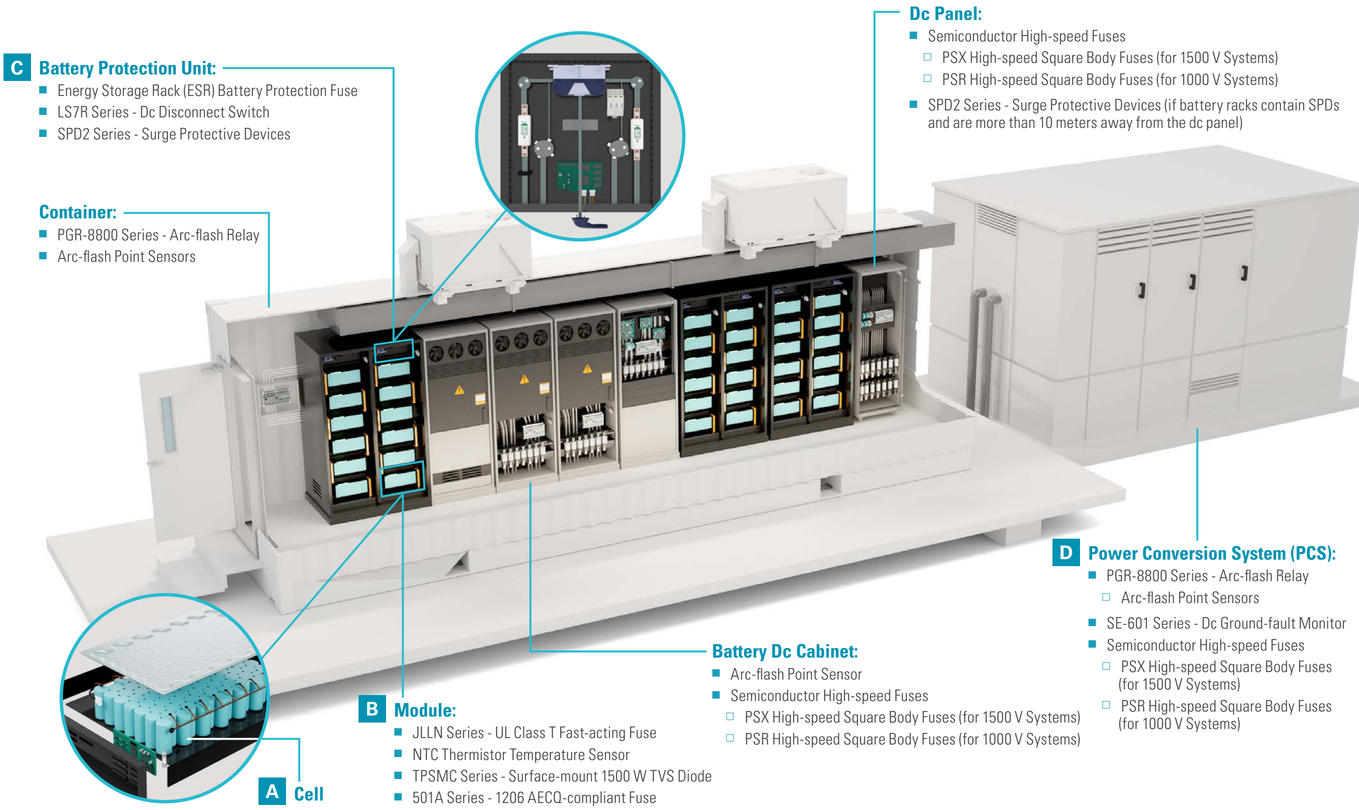

FIGURE 1. A battery energy storage system (BESS).

- the inputs to the power conversion system (also known as an *inverter*).

There are two circuits within a battery system: the power circuit (also known as the *main circuit*) and the control circuit (also known as the *secondary circuit*). The control circuit monitors and collects data, provides information about the system's operation, and sends trip signals where and when necessary. The power circuit carries the electricity that operates the load.

A BESS requires many different types of circuit-protection (see **Figure 1**):

- Fuses
- Arc-flash relays
- Ground-fault relays
- Surge-protective devices

This paper solely focuses on the protection against overcurrents in a BESS power circuit. To learn about the other types of protection for power circuits, contact the Littelfuse Techline at techline@littelfuse.com or +1 (800) TEC-FUSE (800-832-3873).

Fuse Protection for the Power Circuit

The cell (see **Figure 1(A)**) is the smallest component within an energy storage system. A module (see **Figure 1(B)**) is made up of cells that are combined in parallel and series configurations. The modules are stacked in series to form a rack. The rack voltage is generally the same as the system.

A rack is comprised of modules that are stacked in series together. When each of the module's voltages are added together, they form the battery rack's voltage.

To get the system's voltage, add the battery-rack modules' voltages together. The battery rack's voltage is equal to the dc system's voltage. For example, with a 1500-volt system, each rack will be 1500 V dc. If the module voltage is 50 V dc, then the rack will need to contain 30 modules in series.

It is important to protect the module from short circuits that may occur within the modules or the battery rack. Overloads that occur within a BESS are usually managed within, (e.g. the BMS [battery management system]), so most circuit protection is mainly for short-circuit protection—and not overloads.

The next area to protect is at the battery rack. This circuit protection is usually at the battery protection unit (BPU), which is found at the top of the battery rack (see **Figure 1(C)**), and consists of the aggregated energy from each of the modules. The circuit protection at this level is usually rated at a higher system voltage than the voltage in each module.

Therefore, you need circuit protection (such as a fuse) to isolate the battery rack in the event of a fault. To get to the required amount of energy, many racks are combined in parallel into the dc panel. The dc panel uses fuses to protect every rack in the event of a short-circuit fault.

The total energy of the BESS is made up of the battery racks' energy combined in parallel.

A power conversion system (see **Figure 1(D)**) converts dc to ac, and when charging batteries, it converts ac to dc.

To protect the inputs of the power-conversion devices that are connected to the BESS, use circuit-protection devices (such as fuses). These will isolate the BESS from the power-conversion system in the event of a fault.

Fuse Coordination

'Reverse' Coordination: A Modified Version of Selective Coordination

"Reverse" coordination is a little bit different than typical standard coordination (see **Figure 2**). With reverse coordination, you only want the fuses at the top of the battery rack to blow when a fault occurs. This prevents an unwanted number of fuses from blowing.

Typical selective coordination synchronizes the overcurrent protection devices' time-current characteristics so that when an overcurrent occurs, only the closest upstream device on the line side of the fault opens. This way, only the section of the electrical system with the issue will be taken offline. This makes the overloaded circuit easier to locate, and minimizes the time required to remove the equipment from service and then restore to full service operation.

With typical selective coordination, only the fuse closest to the fault or the faulted branch (the branch fuse) will clear when a fault occurs keeping either the main or the feeder fuse unaffected. However, when fuses are not sized properly, selective coordination can be difficult.

With "reverse" coordination, the goal is a little different. When a fault occurs close to the BPU, "reverse" coordination prevents multiple fuses from blowing by coordinating the rack fuse (the feeder fuse) in the BPU and the module fuse (the branch fuse). In this case, we want the

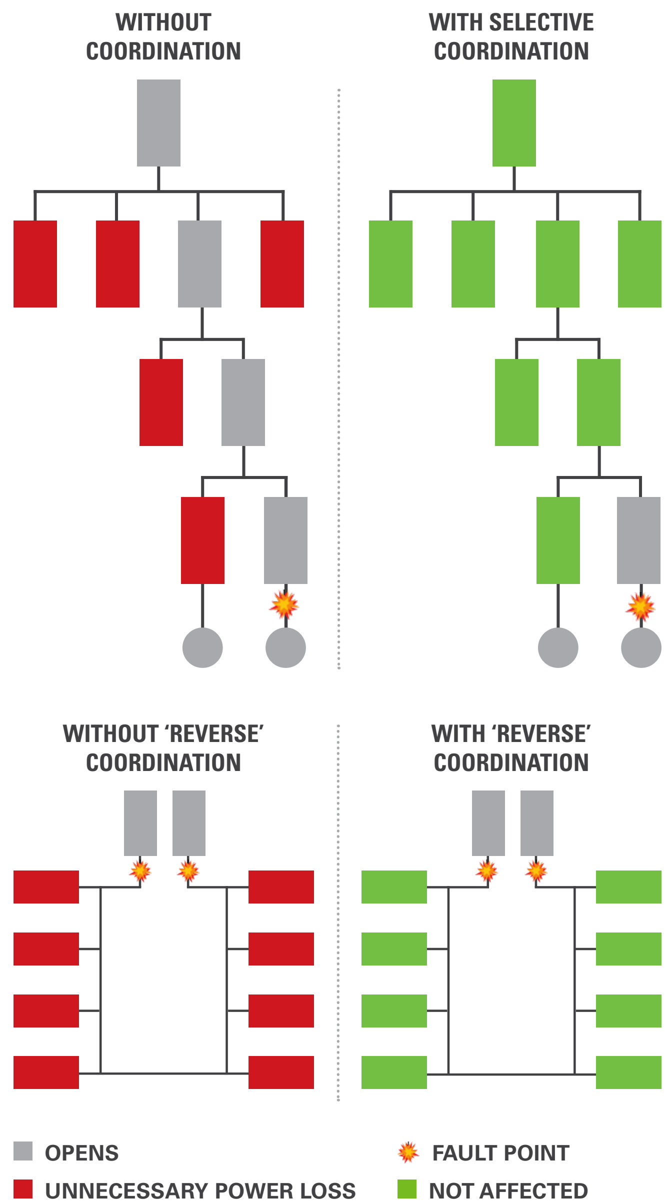

FIGURE 2. Selective coordination versus "reverse" coordination.

rack fuse to open while the branch fuse remains unaffected.

It's a good idea to implement "reverse" coordination when you want the BPU fuse to open without the module fuses being affected. This will minimize repair needs and downtime.

Even though you could use the fuses' different melting and clearing I^2ts to determine some level of coordination, you should work with the fuse manufacturer to pair fuses together that will meet this performance criteria.

How to Size Fuses to Protect Against Low-Resistance Short Circuits

Both high-resistance and low-resistance short circuits discharge batteries (see **TABLE 1**). High-resistance short circuits slowly discharge the batteries, while low-resistance short circuits rapidly discharge batteries.

How to Size Fuses at the Module

In applications where the rack voltage is 1500 V, the module fuse must be at least 1500 V dc. Never use a fuse that is not rated to the system voltage.

UL 1973 7.9.10 says:

> Fuses provided for battery overcurrent protection including short circuit protection shall be evaluated for both short circuit and overload conditions. Fuses that are evaluated for short circuit conditions only (type aR fuses), shall be provided with supplementary protection (e.g. the BMS [battery management system]) to ensure protection under overcurrent conditions in ranges below those covered by these types of fuses.

Additionally, UL 1973 7.9.11 says, "Protective components of battery modules intended for series connection in battery systems shall be rated for the maximum voltage of the intended battery system."

In general, fuses within a BESS should be designed to meet IEC 60269-7, *Supplementary requirements for fuse-links for the protection of batteries and battery systems.*

You can use JLLN fuses to protect the module if the module is in an application where the system voltage is equal or less than the voltage of the JLLN fuse (which are 300 V). However, when modules are stacked in series together, the system's overall voltage will increase. When you stack modules together, you must use a fuse for each module that has a voltage rating greater or equal to the overall voltage of the stacked batteries, as per UL 1973 7.9.11.

To calculate the fuse's current rating at the module, use the formula,

$$I_N = \frac{I_L}{(F_{AT} \times F_L)}$$

where:

I_N = Rated current of the high-speed fuse for the application

I_L = Nominal load discharge current rate

F_{AT} = Temperature derate factor

F_L = Fuse load factor

Example

Consider a system with a battery operating at a nominal current of 10 amperes. To size intermodule fuses, you should consider the ambient temperature and the fuse load constant.

TABLE 1. Cause and effects of high-resistance and low-resistance short circuits.

	POSSIBLE CAUSES	EFFECTS
High-Resistance Short Circuits	■ Internal battery-cell defect or contamination ■ External short circuit	■ Creates a false "self-discharge" ■ Creates a slow drop in cell voltage ■ Slowly discharges the batteries
Low-Resistance Short Circuits	■ Internal battery-cell defect or contamination ■ Manufacturing defect or circuit failure within the battery string or the dc panel ■ External short circuit	■ Fast decrease in cell voltage ■ Rapidly increases the cell temperature ■ Backfeed from healthy battery racks into faulted point on the battery string or the dc panel on a common dc busbar ■ Rapidly discharges the batteries

The 48 °C ambient temperature implies a 10% derate as per the derate curve (see **Figure 3**).

The fuse load factor must be considered so that the fuse is operating at 75% of its current-carrying capacity at 48 °C.

If:

I_L = 10 A

F_{AT} = 0.9 (10% derate)

F_L = 0.75

Then:

$$I_N = \frac{10\ A}{0.9 \times 0.75} = 14.81\ A$$

Since the rated current (I_N) is 14.81 A, the closest size for the fuse is 15 amperes.

How to Size Fuses at the Battery Rack, the DC Panel, and the Power Conversion System

At the level of the battery rack, you need fuses that will not only protect against short-circuit currents, but also have a low minimum breaking capacity so that the contactors will be protected. The energy storage rack (ESR) fuses are perfect for protecting the battery rack.

You only need to protect against short-circuit currents at the dc panels and the power conversion system, which make semiconductor fuses ideal for these two areas. For 1500-volt systems, use high-speed PSX battery protection fuses, and for 1000-volt systems, use high-speed semiconductor PSR fuses.

To size fuses for protection at

- the battery rack;
- the dc panel; and
- the power-conversion system,

use the formula,

$$I_N = \frac{I_L}{(F_{AT} \times F_L \times F_{SS} \times F_{WR} \times F_{FC})}$$

where:

I_N = Rated current of high-speed fuse for the application

I_L = Nominal load discharge current rate

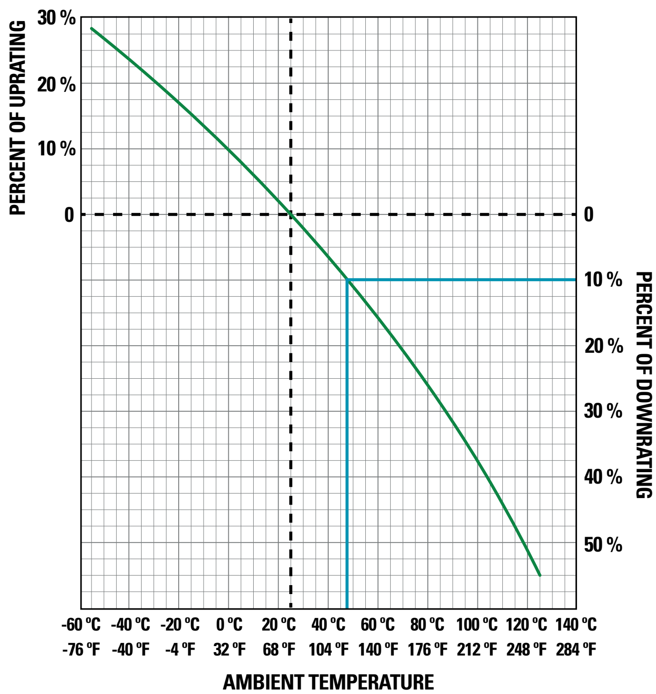

FIGURE 3. Temperature derating curve.

TABLE 2. Switching correction factor.

FREQUENCY OF SWITCHING	SWITCHING CORRECTION FACTOR
Less than 12 stops per year	1.00
More than one stop per month	0.95
More than two stops per week	0.90
More than one stop per day	0.85
Several stops per day	0.80

F_{AT} = Temperature derate factor

F_L = Fuse load factor

F_{SS} = Switching correction factor (see **Table 2**)

F_{WR} = Thermal correction factor (see **Figure 4**)

F_{FC} = Forced cooling correction factor (see **Figure 5**)

Figure 5 shows how to determine the thermal correction factor. Our high-speed fuse technical paper shows an example for determining the thermal correction factor. For any questions, contact the Littelfuse Techline at +1 (800) 832-3873.

The fuse's voltage must be higher than or equal to the batteries' voltage. The fuse's short-circuit current rating must be higher than or equal to the fault current at the location where it is installed within the battery system. The system's time constant must be less than or equal to the fuse's time constant.

Example

Consider a 200-Ah battery rack that is operating between 720 V dc and 960 V dc, and charging and discharging at a 0.25 charge rate. Assume the ambient temperature within the battery rack is 70 °C and there is no forced cooling within the battery rack. The system discharges and charges several times a day.

There are eight racks in parallel on a common dc bus, each of which has an 8-kiloampere fault current.

To find the fuse rating:

I_L = 50 A (0.25 charge rate – 0.25 x 200 Ah)

F_{AT} = 0.8 (due to 20% or 0.2 temperature derate factor per derating curve)

F_{FC} = 1.0 (no forced air cooling within rack)

F_{WR} = 0.8 (average industry standard of between 2 A and 3 A per mm^2 for busbar sizing)

F_{SS} = 0.8 (per switching correction table, see **Table 2**)

In this example, you will calculate the fuse's current rating, I_N by using the equation

$$I_N = \frac{50}{1.0 \times 0.8 \times 0.8 \times 0.8 \times 1} = 97.66\ A$$

The next available fuse amperage is 100 A.

In this example, you should use a fuse of 1000 V dc 100 A. The fuse's interrupting rating should reflect the total fault current across all the racks. Because each of the eight racks in this example have an 8-kA fault current each, the fuse should have an interrupting rating of at least 64 kA (64 kA = 8 kA × 8 racks).

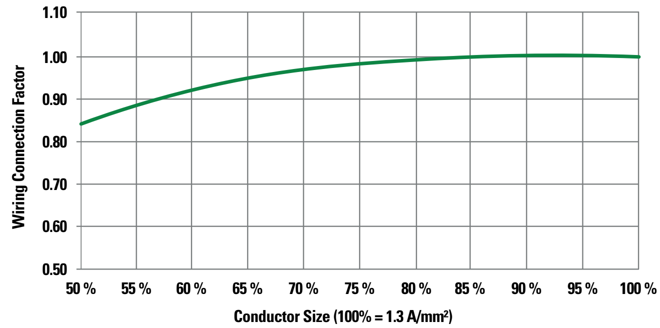

FIGURE 4. Thermal correction factor.

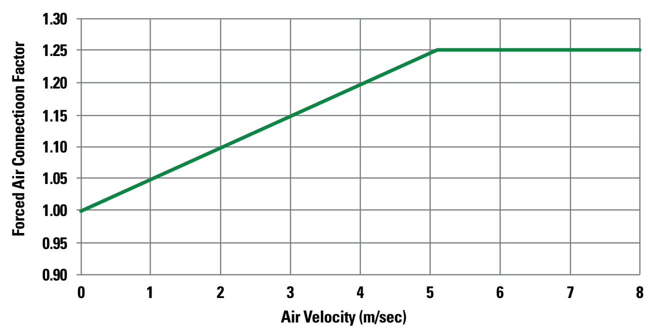

FIGURE 5. Forced cooling correction factor.

Case Studies

Integrator Increases BESS Capacity to Meet Extended Peak Power Demands

An integrator, who supplies solar-power systems and BESSs, needed to increase the capacity of their BESS so their utility customers could meet peak power demands for a longer time. To do this, the integrator's engineers added more battery banks to their BESS. The designers also switched from using flow batteries to higher-capacity, lithium-ion battery cells.

Challenge

A higher energy density in the new BESS can lead to a much larger fault current. At high power levels, a fault can create catastrophic damage and even injure personnel. Therefore, their BESS needed a much higher level of circuit protection.

Solution

By adding additional battery banks into the BESS, the design engineers could source a fuse with a higher short-circuit current interruption rating than what their BESSs used at the time. This type of fuse had to be the type that operates very quickly so that it could protect the sensitive electronics within the BESS power converter.

Outcome

The design engineers began to test fuses from several manufacturers. They ultimately chose the Littelfuse PSR series high-speed square-body semiconductor fuses because they had the highest short-circuit current ratings amongst their competitors. The higher ratings, 150 kA dc and 200 kA ac, also allowed for fewer dc panels, which reduced their cost and design's complexity.

In addition, the PSR fuse series enabled the integrator's designers to use a fuse that had a square-body form factor, which was similar to the fuse in their existing design. Using the PSR fuse avoided the cost of making significant design changes.

By using Littelfuse PSR series fuses, the integrator reduced the dc panel count to one per container and added two more battery units. The BESS container increased by 7% in energy density, so the utility can rely on the BESS for a longer period during high peak-power demands while also lower its operating costs.

With New Inverter Design, Engineers Look for a Higher Power

Challenge

A solar-power original equipment manufacturer (OEM) was developing a new inverter design with an increased capacity between 30 kW and 150 kW to meet the market's demands. Reliability and efficiency were vital to the engineers. However, when an energy storage system increases, so do its basic needs.

Their new inverters needed, at a minimum, a fuse with a higher interrupting rating and a faster trip time. Other features, such as built-in indication, were also important to the engineers' needs.

The engineers were using high-power[1], insulated-gate bipolar transistors (IGBTs) in the solar inverters, which convert the dc output from the solar panels into ac output for power transmission and user consumption. The power IGBTs minimize power loss with fast switching, which maximizes the inverter's efficiency. The engineers needed to figure out how they could prevent case rupture during short-circuit fault conditions in the IGBTs, which operate at both high voltage and high current.

Inadequate protection of the IGBTs can result in their catastrophic failure. In addition, the high temperature that builds up in an overheated IGBT can lead to a fire. The fire can cause significant downtime and expensive repairs. What's more, an inverter failure can force an electric utility to purchase expensive power to meet peak power demand when its energy storage system is not in service. Furthermore, the engineers had a tight schedule and needed to move quickly on selecting overcurrent protection for the new inverter.

Solution

IGBTs open very quickly, so they need a high-speed semiconductor fuse to eliminate any faults that occur. The engineers needed semiconductor fuses with a high interrupting rating to accommodate the high power of their new design.

The engineers used Littelfuse's 1000-volt dc PSR high-speed fuses, which have a 150-kiloampere interrupting rating, because compared to other fuses they tested, the Littelfuse fuses had

- the fastest interruption time,
- low-power consumption,
- built-in indication and remote monitoring, and
- a fast lead time.

The engineers swiftly selected the PSR high-speed fuses, which ultimately exceeded their new inverter's basic requirements. By promptly providing the fuse series' certifications and resources under the engineers' tight schedule, the engineers said they saw Littelfuse more like a partner than a supplier.

Outcome

The OEM has used thousands of Littelfuse components in various applications since then—all without quality issues or failures. The OEM's positive experience opened the door to additional adjacent products including thermally-protected metal oxide varistors and surge protective devices.

THE BESS CONTAINER INCREASED BY 7% IN ENERGY DENSITY, SO THE UTILITY CAN RELY ON THE BESS FOR A LONGER PERIOD DURING HIGH PEAK-POWER DEMANDS WHILE ALSO LOWERING ITS OPERATING COSTS.

1 In BESS applications, IGBTs have current ratings from 450 A to 2400 A, and voltage ratings from 1200 V to 2300 V.

Codes and Standards

Codes

National Electrical Code

NEC ARTICLE 706 Energy storage systems

International Electrical Code

IEC 60269-7 Supplementary requirements for fuse-links for the protection of batteries and battery systems

Standards

UL and North American Standards

UL 1741 Inverters, converters, controllers and interconnection system equipment for use with distributed energy resources

ANSI/CAN/UL 1973 Batteries for use in stationary and motive auxiliary power applications

Additional Resources

BESS Protective Devices

Fuses

- Class T Fuses
- Energy-Storage Rack (ESR) Fuses
- PSX High-Speed Fuses
- High-Speed Semiconductor Fuses
- Surface-Mount Fuses

Other Modes of Protection

- Arc-Flash Detection
- Ground-Fault Protection
- Surge Protective Devices

Other BESS Products

- Dc Disconnect Switches
- Surface-Mount TVS Diodes
- Temperature Sensors

BESS Informational Resources

- High-Speed Fuses **Technical Paper**
- Fuse Fundamentals **Technical Paper**
- Battery Energy Storage Systems Demand a Comprehensive Circuit Protection Strategy **Technical Paper**
- BESS Resource Hub
- Arc-Flash **Knowledge Center**
- Ground-Fault **Knowledge Center**
- BESS Capability Guide
- How to Protect BESS to Increase Reliability and Maximize Return on Investments **On-Demand Webinar**
- Solutions for Battery Energy Storage Systems **SlideShare**
- Temperature-Sensors Product and Application Information

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