Sensata EL

Maximizing circuit protection for enhanced EV safety

Pyrotechnic circuit breakers are a cutting-edge fuse technology for the high voltage (HV) circuitry found in electric vehicles (EVs) and industrial machinery. They interrupt current flow in the event of an overcurrent or short circuit with an order of magnitude shorter response time than conventional thermal fuses. When paired with the right contactor, these two components effectively prevent damage to the connected battery and power electronics (for instance, a DC/DC converter or inverter). Critically, these components protect the user from electrical hazards like shock, or cascading conditions that could cause thermal runaway of the battery itself, leading to potentially catastrophic events.

The PyroFuse by Sensata is a pyrotechnic circuit breaker that successfully interrupts current in less than 1 millisecond (ms) with a breaking capacity of 1,000 V/16,000 A or 500 V/20,000 A. The fuse is designed to extinguish electrical arcs at high speeds with high isolation resistance after breaking. As a long-time manufacturer of contactors, Sensata is an expert in high voltage switching technologies. With its in-house testing capabilities, Sensata can quickly characterize and build an HV system to replicate an application's specifications for product testing.

How does the PyroFuse work?

Pyrotechnic circuit breakers consist of a metal busbar, a plastic piece known as a piston or plunger, and an initiator composed of pyrotechnic powder similar to an airbag initiator, all housed within a sealed chamber (Figure 1).

The busbar conducts current from one system, such as the battery, to the downstream load, such as the motor control inverter. The pyrotechnic circuit breaker is triggered via a low-voltage signal input from an external source such as an electronic control unit (ECU), which will generate a spark in the initiator, or micro gas generator (MGG). This ignition generates gas, which, in turn, causes the pressure to expand within the chamber, pushing the plunger down to break the busbar and permanently deform it (Figure 2). This prevents any current from flowing through.

After the busbar is broken, electrical arcs from the high voltages and currents are stretched and extinguished inside the chamber. The PyroFuse has an innovative metal mesh and gel damping design, enabling high arc suppression. The cavity around the metal mesh also allows the inside gas to flow and disperse, reducing pressure without leaking gas. This is a critical consideration since physically breaking a circuit is not enough to completely stop the current flow. Electrical arcs can persist and maintain the current, so they must be suppressed to achieve an actual interruption.

Once the current is entirely suppressed and the plunger is engaged within the PyroFuse, the fully sealed chamber prevents outgassing and has a longer electric gap (i.e., creepage distance) for a high isolation resistance of over 50 MΩ at 1,000 V, ensuring continued safety and reliability.

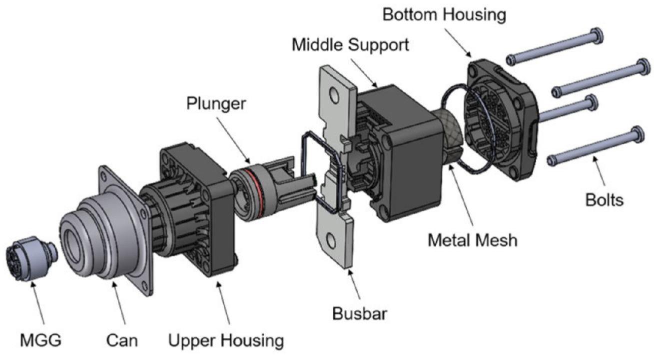

Figure 1: An exploded view of the PyroFuse pyrotechnic circuit breaker with MGG, can, plunger, housing, busbar and metal mesh. Source: Sensata

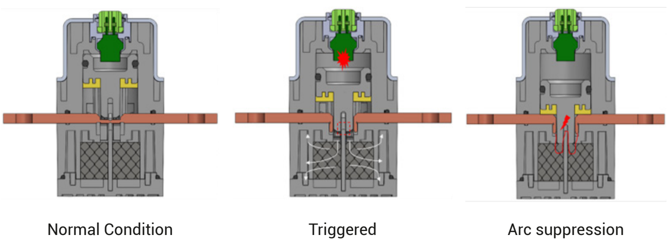

Figure 2: Cross-sectional diagram of the PyroFuse during normal conditions, at the time of initiation and after it has been engaged. Source: Sensata

When would a PyroFuse be needed?

There are two main circumstances for PyroFuse interruptions within an EV: internal and external.

An internal interruption is caused by a large overcurrent that can short the system and damage it. In this case, the current sensor or battery management system's (BMS) software will send a signal to the PyroFuse and cause an interruption to prevent any damage to downstream electronics.

A crash is another scenario where a subsystem within the EV, such as a crash detection system, will transmit a signal to the PyroFuse and trigger it to shut the circuit ahead of a crash to prevent any kind of catastrophic failure.

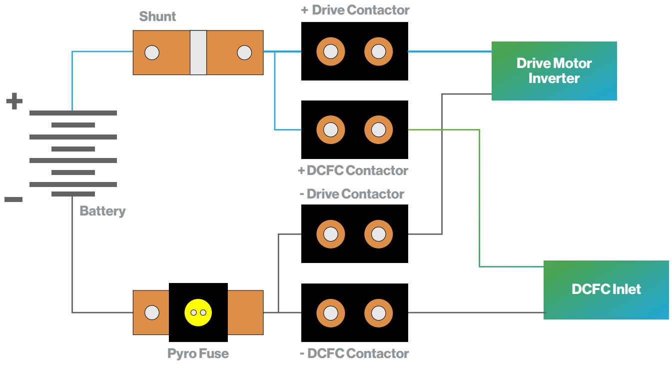

Figure 3: Basic EV protective circuitry for drive motor inverter and DCFC inlets. Source: Sensata

How is the PyroFuse used within a circuit?

The basic hardware for HV circuit protection includes contactors for galvanic isolation, fuses for overload protection, current sensors to monitor the current flow within the HV system and the necessary busbars, HV connectors and HV wiring for power distribution.

Within an EV, PyroFuses can be applied between the battery and the traction motor inverter, such as in a battery disconnect unit (BDU), and between the charging inlets for a charge station and the battery, often known as a power distribution unit (PDU) or HV distribution unit (HVDU). Consequently, protection is necessary whether power is being siphoned from the battery pack or supplied to it.

For EVs, two contactors are typically used to achieve redundancy per global safety regulations. This ensures sufficient isolation of the battery from the rest of the system when the battery is not in use and safely switches power on and off. The image shows that the two main contactors are installed between the battery's positive and negative poles and the traction inverter. The PyroFuse is typically series-connected with the contactor (either on the positive or negative battery rail) to stop fault currents that the contactors cannot safely switch off.

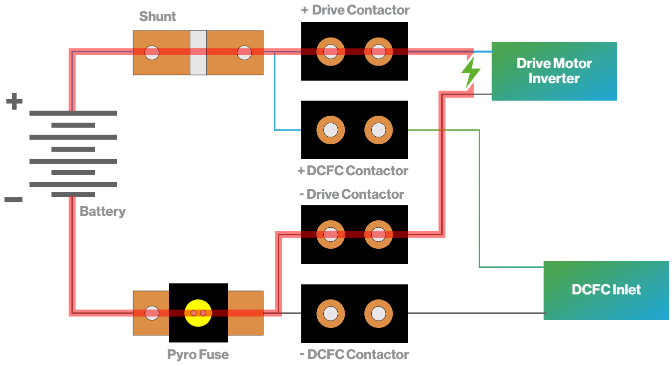

Figure 4: Path of a motor, a drive motor side fault and a timeline showing detection of a short circuit fault condition and PyroFuse initiation. Source: Sensata

In the event of a battery short-circuit, there is a sudden drop in resistance and rise in fault current in accordance with Ohm's law (V=IR). In the BDU, the shunt will measure the voltage drop across a fixed resistance. At this point, the vehicle controller will calculate current flow and, if the overcurrent threshold has been hit, decide to engage the PyroFuse by sending a fire signal to the PyroFuse's driver. This driver sends a voltage that initiates the PyroFuse and interrupts the battery fault. All of this generally occurs within 2 ms to 5 ms, including the PyroFuse function (Figure 4).

A practical look at the HV battery systems

The physical phenomena that guide the decision-making on whether to engage a PyroFuse often rely on monitoring current through the circuit. However, the circuit's overall inductance will strongly influence the timing and amplitude of the fault current in the event of a failure. These should also guide the user in selecting the correct HV circuit protection.

Short circuit current behavior

Ohm's law dictates the basic governance of a short circuit current and voltage (e.g., voltage drops, resistance drops and current jumps). In reality, there are nuances in a battery's short-circuit behavior. With aging and prolonged cycling, battery cells will lose their ability to discharge as they heat up. This leads to short circuits where an abnormal electrical circuit allows current to travel along an unintended low-resistance path. In this case, a short circuit can last for milliseconds and can cause local heating and potential thermal runaway.

Determining the short-circuit current establishes the maximum potential fault current; analyzing the battery's load profile can help define the minimum fault currents.

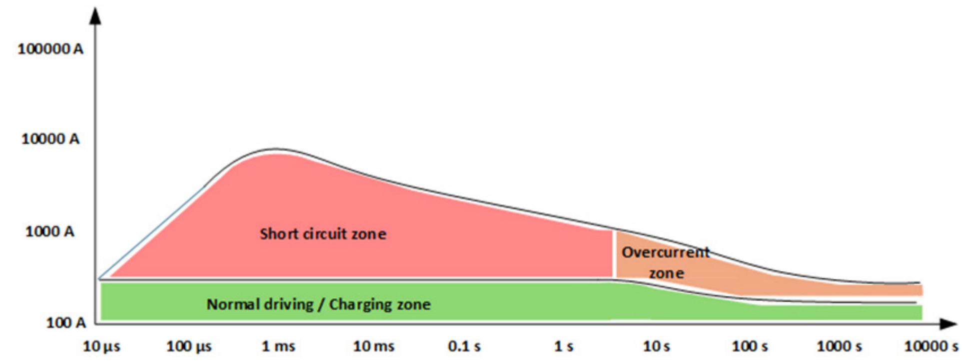

Figure 5. A basic example of characterizing EV current zones over time. Source: Sensata

Figure 5 shows an example of an EV's current versus time, highlighting the short circuit, overcurrent and normal operation zones. The fuse and contactor must be aligned to protect the circuit so that battery systems can safely manage the entire current range. This often means that the contactor should be able to withstand the overcurrent condition for a short period of time before the PyroFuse kills the flow. The PyroFuse will activate when the overcurrent detection (OCD) threshold is achieved. Resistance is also somewhat variable throughout a short circuit as contactors can levitate and strike arcs; the arc itself has a high resistance, which can instantaneously reduce current.

Short circuit inductance behavior

Inductance is another parameter that guides the timing and amplitude of the fault current during a short circuit. All current-carrying elements have an inductance that will contribute to the circuit's overall inductance. This total inductance can increase by long, winding runs of busbars or HV cabling, or can be minimized by long straight runs.

The system's layout and packaging generally dictate inductance, but typically, high single-digit to low double-digit microhenries (µH) of inductance are commonplace. More complex topologies (for instance, stator windings for DC/DC conversion) can increase inductance to the low triple digits. As inductance is increased, the time constant increases; this means it would take longer to reach the same maximum current (Figure 6). A high inductance prevents rapid changes in current, which can slow the rise time of a short circuit and limit the maximum current reached in a given duration; however, this can potentially store energy in a magnetic field and dump it into an arc while the PyroFuse is shutting off the fault.

Generally, most short circuits are detected during their initial rise. Once detected, action is taken, which then begins to limit the current as the PyroFuse is in the process of shearing the busbar. As a result, lower inductance faults tend to reach their maximum, while higher inductance faults tend not to since they take too long to get there before OCD. As such, lower inductance systems tend to have higher current and higher inductance systems have more energy.

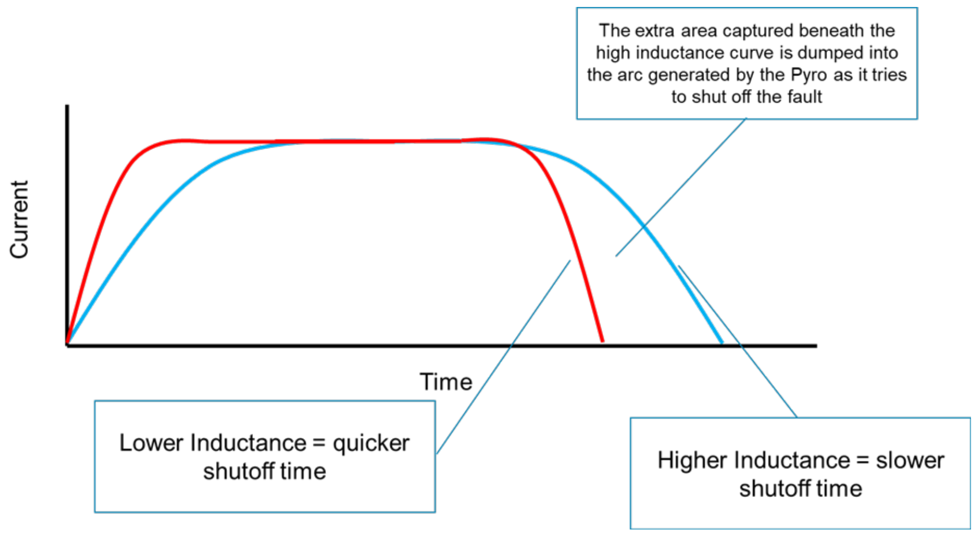

Figure 6. A lower total circuit inductance yields a quicker rise time, while a higher inductance will have a slower rise time that comes with a higher energy arc that the PyroFuse must effectively extinguish. Source: Sensata

Pairing a contactor with a fuse

Contactors that can withstand the expected OCD without levitation should be selected. Still, they must withstand these currents for a shorter period as the fault is quickly extinguished by the PyroFuse (Figure 7).

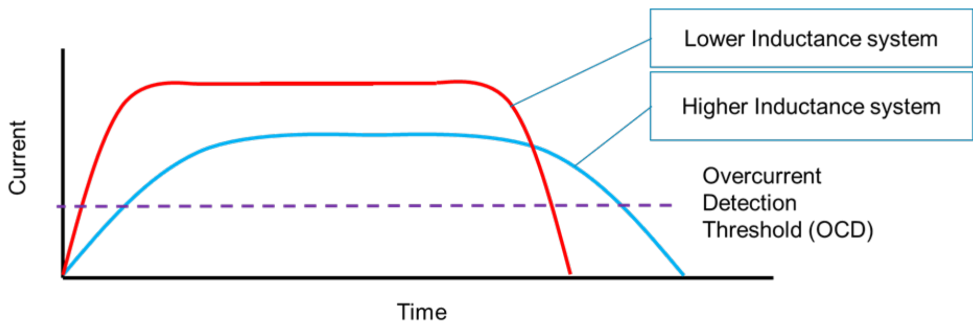

Figure 7. Current versus time for low inductance and high inductance systems with an OCD condition. Source: Sensata

The relationship between voltage, current, power, inductance and energy is made evident by the breaking performance summarized in Table 1. PyroFuse arcs dissipate less energy in low inductance systems, but higher current allows for greater power at a given voltage. Conversely, high inductance systems have lower current peaks, but contactors must prevent levitation due to higher energy arcs. The PyroFuse must also be able to extinguish the energy discharged into the arc in such systems.

Voltage (V)	Current (I)	Power (P = VI)	Inductance (L)	Energy (E = 0.5LI2)
500 V	20 kA	10 MW	15 µH	3000 J
1000 V	16 kA	16 MW	16 µH	2048 J
1000 V	6 kA	5 MW	110 µH	1980 J

Table 1: PyroFuse breaking capacity. Source: Sensata

PyroFuse pairing: A real-world example

Given the rapid interruption time of the PyroFuse and its responsiveness to feedback from in-vehicle monitoring systems, contactors can be sized more appropriately. The I-T curve of the Sensata STEV contactor can be seen in Figure 8.

The image shows that the contactor can withstand 10 kA for 5 ms. Since the PyroFuse can act in less than 1 ms, for a 10 kA maximum fault, the extra 4 ms can be allocated toward the decision to fire time. Given the inverse relationship between the current the contactor sees and the time it can withstand such current, if the system can react faster, the current the contactor sees can also be safely increased. This delicate relationship between current and time can be optimized so that the PyroFuse can dissipate the fault's power and energy while the contactors survive the fault.

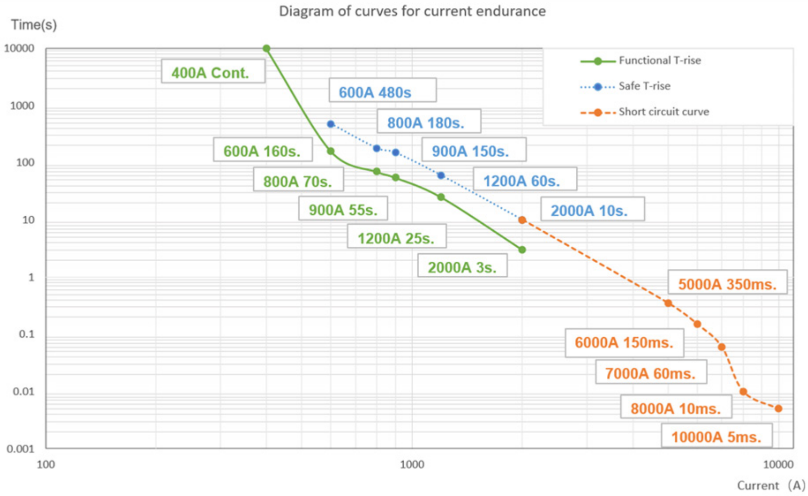

Figure 8. The Sensata STEV4000C contactor I-T curve. Source: Sensata

Maximizing circuit protection for enhanced EV safety

Performance and costs

The Pyrofuse's inherent controllability and fast response allows the user to safely shut off large fault currents and isolate the offending circuit. This grants more design flexibility in contactor selection. Utilizing appropriately sized contactors directly reduces the overall bill of materials (BOM). The lightweight design and small form factor for the PyroFuse also make it more ideal for use within space- and weight-constrained mobility applications.

Reduced supply chain complexity

The PyroFuse offers a significant advantage by being part of Sensata's established circuit protection ecosystem, which includes expertise in contactor technology. Since introducing the ceramic seal in 2006, a diverse portfolio of contactor technologies for high-reliability and mission-critical applications has been released.
This ecosystem in circuit protection offers a tangible benefit: reducing the supply chain complexity for OEMs and Tier 1 suppliers that must navigate complex supply networks. This integration within a mature ecosystem can lead to more efficient procurement, logistics and overall risk management efficiencies for OEMs and Tier 1s incorporating PyroFuses into their systems.

In-house validation

Since Sensata already manufactures these components, OEMs can fine-tune their systems with cost and performance in mind. Robust in-house test and validation capabilities enable Sensata engineers to run a battery of tests to characterize full systems at extreme power levels with precise timing control.

The Sensata advantage

Fuses are a critical safeguard against electrical faults in HV systems, enhancing passenger safety and as well as the environment surrounding the vehicle.

The rapid interrupt time of the PyroFuse allows customers to pair it with appropriately sized contactors, often yielding a better-performing circuit protection system. Sensata's established contactor ecosystem allows customers to partner with the company to select the right-sized contactor and validate their entire design at the system level. Contact the experts at Sensata to learn more.

rev.07/22/25