What designers need to know about wire protection

Application note

Family overview

Support

About this document

Scope and purpose

This application note provides a comprehensive overview of wire protection in low-voltage automotive applications, covering the significance of wire protection, common challenges, and the impact of an effective wire protection on system robustness.

Moreover, it presents the various technologies and techniques used for wire protection, including hardware-based protection, such as I^2t or I-t protection, overload detection, and fault isolation mechanisms.

This application note includes case studies and examples to demonstrate the use case of wire protection in real-world scenarios, highlighting the benefits and outcomes of robust wire protection strategies.

The purpose of this document is to support design engineers, promote best practices, and showcase innovations with the latest semiconductor solutions from Infineon.

Intended audience

This application note is intended for the following readers:

- Design engineers and system architects: The primary audience for this application note are design engineers and system architects involved in the development of automotive electronic systems in which wire protection is a critical consideration
- Technical decision-makers: It is also relevant for technical decision-makers within organizations, including engineering managers and product development leads who oversee the integration of wire protection features in their systems
- Professionals and researchers in the field of power electronics, automotive electronics, and system reliability can benefit from the technical insights and practical guidance offered in the application note

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1 Fuses: A legacy method for protecting wires

Melting fuses are designed to protect wires from overheating by melting when the temperature exceeds the fuse's metal threshold. This melting process interrupts the flow of current, safeguarding the wire and preventing further temperature increases. By melting at a specific temperature, the fuse acts as a critical thermal safeguard, ensuring that the wire remains within safe operating conditions and protecting electrical systems from the adverse effects of overheating.

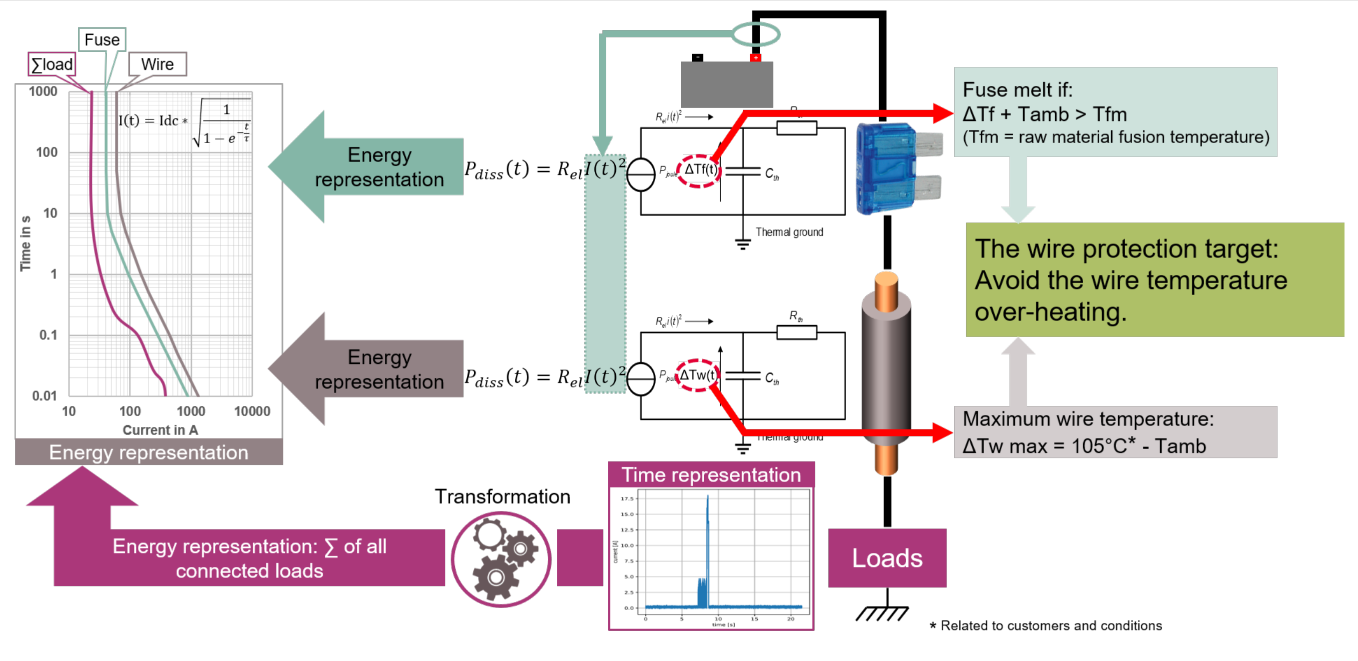

Figure 1 **Fuses: a legacy method for protecting wires**

Melting fuses are commonly used in low-voltage automotive systems and provide basic overcurrent protection by melting a fuse link when the current exceeds a certain threshold for a given amount of time. While simple and cost-effective, their non-resettable nature and relatively slow response times poses challenges in rapid fault isolation and dynamic system management, potentially impacting the responsiveness and adaptability of automotive electrical protection.

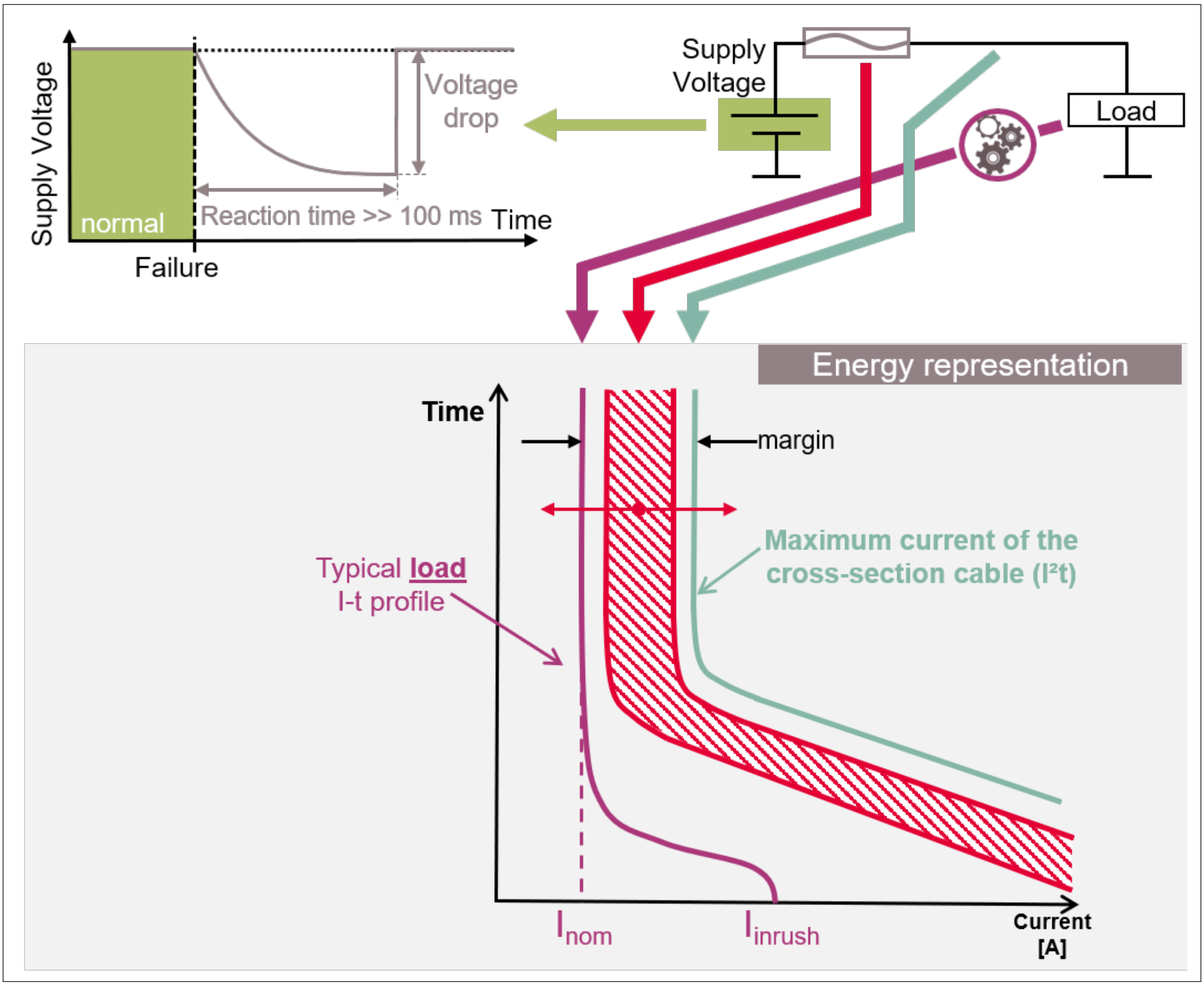

Figure 2 **Energy representation of the system using fuses**

The key requirements fulfilled by melting fuses in automotive applications include:

1. Wire overheating protection: Melting fuses are designed to protect wires against overheating by responding to overcurrent conditions and interrupting the circuit to prevent excessive heating and potential damage to the wire or surrounding components
2. Various wire protection levels with fuse classes: Melting fuses have various levels of wire protection through the use of fuse classes. By selecting the appropriate fuse class, various wire gauges and current ratings can be matched with corresponding protection levels, ensuring tailored protection for diverse wire types and load conditions
3. Standalone hardware protection: Melting fuses are used as standalone hardware protection components, offering self-contained overcurrent protection without the need for additional external control or complex circuitry. This ensures simplicity and self-sufficiency in providing fundamental wire protection within automotive electrical systems

The key requirements that are not fulfilled by melting fuses in automotive applications include:

- *automotive safety integrity level (ASIL)* requirements for fast failure isolation: Melting fuses do not meet the stringent ASIL requirements for rapid failure isolation, which are essential for ensuring functional safety in automotive systems

- Inability to optimize wire diameter/gauge: Melting fuses do not allow for further optimization of wire diameter or gauge to reduce wire harness weight, limiting the potential for enhancing system efficiency and weight-reduction efforts
- Not configurable using software: Melting fuses are not software-configurable, limiting the adaptability and customization of protection parameters to address specific operational requirements or evolving system needs
- Non-resettable by software: Resetting of melting fuses by Software is not feasible. This impacts the ability to manage *fault* recovery and system reconfiguration in response to transient or non-critical fault events
- Software Over-The-Air (SOTA) not supported: Melting fuses do not support SOTA capabilities, which are increasingly important for enabling remote updates, diagnostic functions, and adaptive behavior in modern automotive systems
- End-customer service accessibility requirements for electronic power distribution modules (fuse box): Melting fuses require end-customer access, which means placing fuses in accessible areas such as the engine room or passenger compartments, whereas power distribution designers prefer to be more flexible in the placement of the fuse box

Table 1 Fuses: fulfillment of requirements

Requirement	Fulfillment
Protect wires against over-heating	✓
Various wire protection for various wires	✓
ASIL requirements for failure disconnection	✕
Accurate protection characteristics for optimizing wire diameter and reducing harness weight	✕
Protect complex load profiles	✓
Standalone hardware protection (such as limp home function)	✓
Configurable wire protection using software (such as SOTA)	✕
Wire protection resettable by software	✕
Module access free	✕
Offload the microcontroller resource and effort	✓

2 New trends: Mechanical fuses and semiconductors in comparison

The latest trends in semiconductor fuses are shaped and fueled by the evolving needs of modern electronic systems, including automotive power distribution. These trends reflect the industry's focus on enhancing safety, reliability, and efficiency in power management and wire protection.

Comparing melting fuses and semiconductors in the context of wire protection provides valuable insights into the advantages and trade-offs of each approach. The figure below shows a breakdown of the comparison across different aspects:

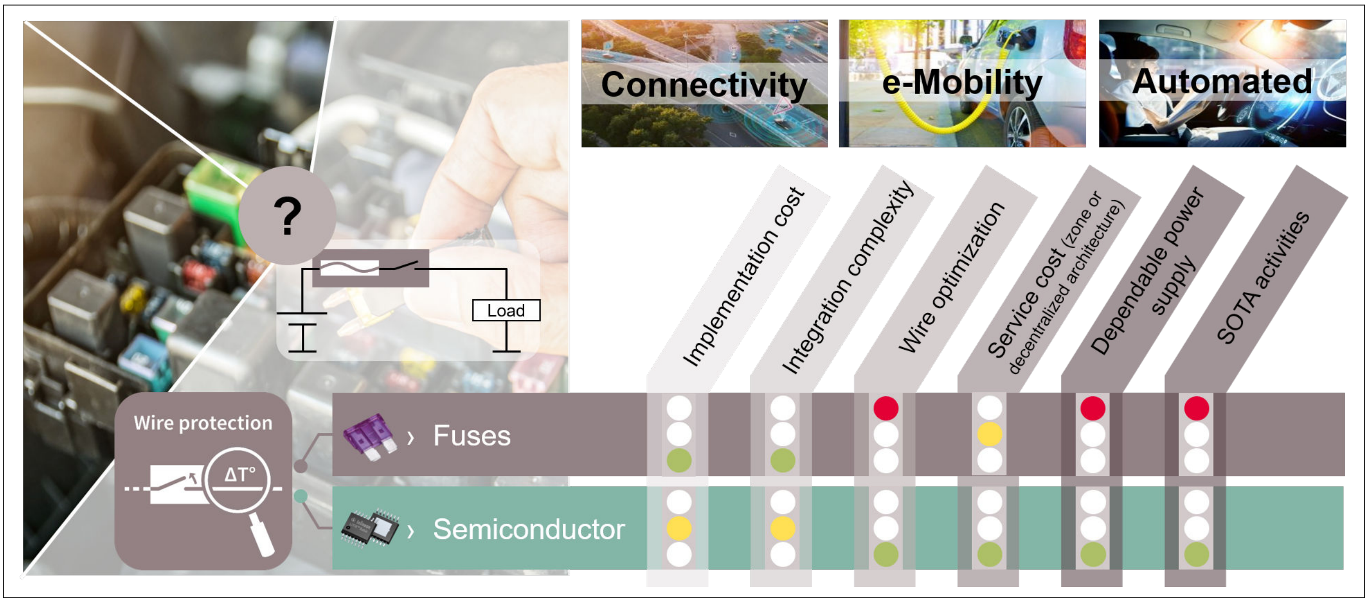

Figure 3 **Mechanical fuses & semiconductor comparison in new trends**

Fuses and semiconductors: Comparison in detail

- Features:
  - Melting fuses: Melting fuses offer basic overcurrent protection by melting the fuse link when the current exceeds a certain threshold. They provide a simple and cost-effective means of protecting electrical circuits. The melting fuse is also effective when a car is in a parked condition, as it remains ON without consuming any operating current
  - Semiconductors: Solutions, such as electronic fuses or eFuses, offer advanced features such as adjustable overcurrent protection, active during parking (idle mode), integrated I^2t, or I-t wire protection, *fault* detection, and precise current limiting capabilities. They are often integrated together with microcontrollers and offer more advanced protection and diagnostic features than melting fuses
- Implementation costs:
  - Melting fuses have lower material costs and are simpler to manufacture, leading to reduced production costs. The implementation of melting fuses involves straightforward circuit integration and replacement when a fault occurs. However, their non-resettable nature leads to increased downtime during fault recovery, as the fuse needs to be physically replaced. Fuse boxes are simple in design, have low complexity and low cost, but it is crucial to consider the long-term maintenance and serviceability aspects of fuse installation
  - Semiconductor fuses do not require a physical replacement. They are easily reset able by the microcontroller. This results in a flexible power distribution board development because they do not need to be access able. The design of semiconductor solutions require more complex designs and implementation due to their integration with microcontrollers and digital control interfaces. However, they offer the advantage of programmable features and diagnostics

- Integration complexity:
  - Melting fuses: Melting fuses are simple to integrate, with minimal complexity in terms of circuit design and integration. A main disadvantage for the end-user is physical access to the fuse in an overload event, which requires mechanical replacement of the melting fuse. Serviceability and end-user access are essential for melting fuses, leading to the need for additional wiring to convey the power signal to and from the fuse box across the vehicle. Since vehicles often have few fuse boxes, all fuses must be connected to the respective loads using wires that run to and from accessible locations that are usually close to the engine compartment or dashboard
  - Semiconductors: Electronics are much safer because they are not accessible by the end-user, so unwanted replacement of wrong fuse value is simply not possible. The integration of semiconductor solutions involves more complexity due to the need for digital control, configuration, and communication with the system
- Wire optimization:
  - Melting fuses: Melting fuses may not directly contribute to wire optimization, as their primary function is limited to overcurrent protection without advanced wire stress monitoring. Melting fuses have a wider parameter spread in terms of trip currents and response times. This variability limits the optimization of wire selection and routing, as the uncertainty in fuse behavior may necessitate conservative design margins to accommodate the parameter spread
  - Semiconductors can contribute to wire optimization through advanced current monitoring, precise protection, and features such as I^2t or I-t wire protection for enhancing wire longevity. eFuses offer more precise current-limiting capabilities and configurable current trip thresholds. This precise control enables optimization of wire selection, allowing for the use of smaller gauge wires while ensuring reliable protection against overcurrent events. Semiconductor fuses contribute to enhanced wire optimization by allowing design engineers to leverage the precise current-limiting capabilities to optimize wire routing, reduce weight, and improve overall system efficiency without compromising safety or reliability
- Service costs:
  - Melting fuses: Melting fuses potentially result in higher service costs due to the need for physical replacement and potential downtime during fault recovery
  - Semiconductors potentially contribute to lower service costs through diagnostic capabilities, remote fault monitoring, and the potential for predictive maintenance, reducing the overall service and maintenance expenses
- Dependable power supply:
  - Melting fuses: In overcurrent conditions, melting fuses exhibit limitations in providing rapid fault isolation and failure mitigation. This leads to challenges in maintaining dependable supply during fault events, potentially impacting the overall functional safety and reliability of the power distribution system. The slower response of melting fuses to overcurrent events may compromise the system's ability to swiftly isolate faults, posing a potential safety hazard and operational disruption
  - Semiconductors: with their advanced fault detection, precise current-limiting, and configurable trip parameters, semiconductor contribute to enhanced dependable supply concepts by facilitating rapid fault isolation and ensuring continuous power availability. This capability is instrumental in maintaining functional safety and reliability in automotive power distribution systems, particularly in rapidly disconnecting faulted sections and preventing undervoltage situations
- Software-Over-The-Air (SOTA):
  - Melting fuses do not support SOTA as they need to be replaced physically to alter the protection parameters of the wires. The static nature of melting fuses may restrict the system's ability to adapt

to evolving software and firmware updates, potentially posing challenges in supporting the dynamic demands of SOTA functionality in automotive systems

- Semiconductor, particularly electronic wire protection or eFuses, offer configuration features, digital control interfaces, and adaptive protection capabilities that align with the dynamic requirements of SOTA updates. This enables semiconductor fuses to support the reconfiguration, fault isolation, and dynamic management of power distribution systems in response to SOTA updates, enhancing the system's versatility and adaptability. The flexible nature and advanced fault detection capabilities of semiconductor fuses enable dynamic reconfiguration and adaptive responses to SOTA updates, ensuring that the power distribution system seamlessly accommodates evolving software and firmware requirements

3 Various methods for protecting wires

There are multiple ways to implement wire protection with semiconductors and address the specific requirements of automotive power distribution systems. The following explores three methods in detail. The figure below offers an overview.

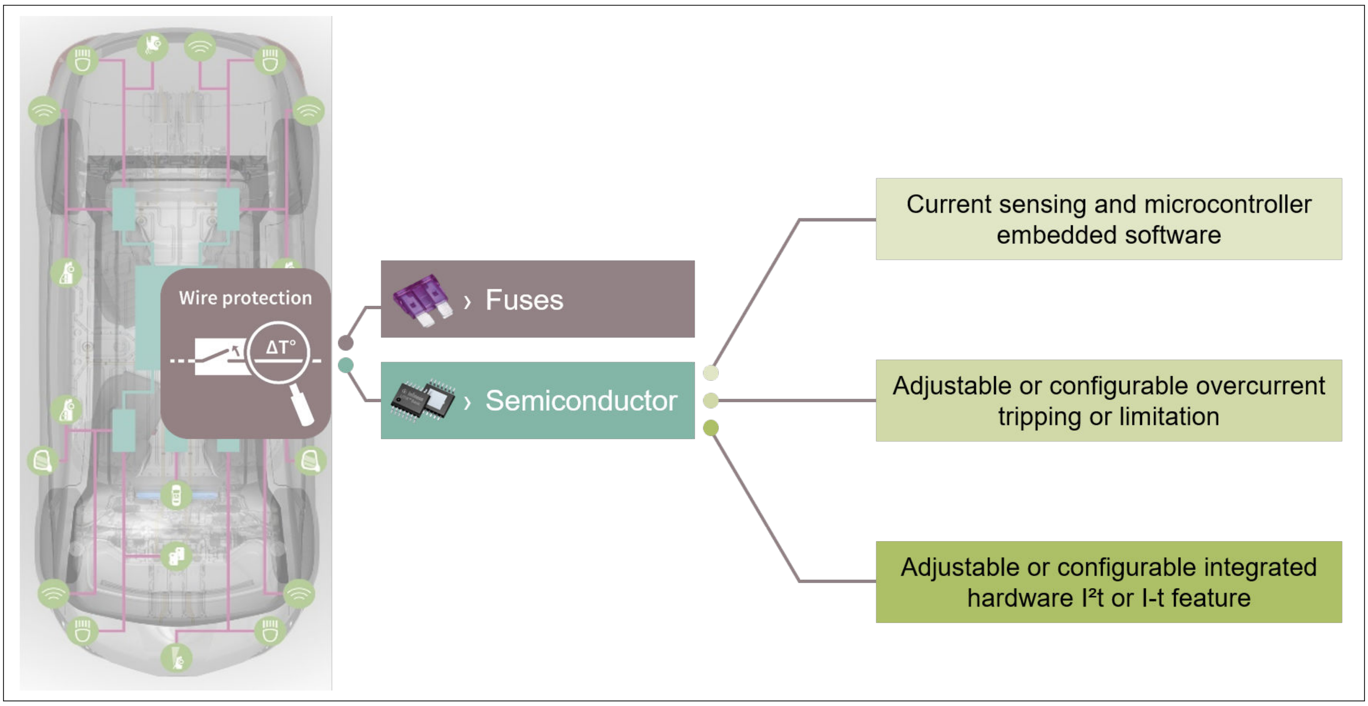

Figure 4 Various methods for protecting wires

1. Current sense feedback and microcontroller-embedded software processing

- Method overview: This approach involves using the current sense feedback from a protected high-side switch, such as the PROFET™, or an automotive gate driver, such as the EiceDRIVER™ APD, and processing the current sense information with a microcontroller. In this method, the microcontroller is responsible for implementing a current limit or a current integration algorithm (such as I^2t or I-t) in the software
- Implementation benefit: By leveraging current sense feedback and microcontroller processing, this method allows for dynamic and software-based control over current protection algorithms. It offers flexibility in implementing customized protection strategies and adapting to varying load conditions
- Considerations: The effectiveness of this approach relies on the accuracy, bandwidth, and responsiveness of the current sense feedback, microcontroller's *analog-to-digital converter (ADC)* performance, and the computational capabilities of the microcontroller to efficiently process the current information and implement the required protection algorithms and its resulting software verification efforts

2. Adjustable overcurrent protection feature of the smart high-side switch or gate driver

- Method overview: This method involves using an adjustable overcurrent threshold on the protected high-side switch or gate-driver to limit the maximum load current, thereby providing a straightforward and hardware-based means of wire protection

- Implementation benefit: The use of an adjustable overcurrent threshold offers simplicity and direct control over the maximum load current, allowing for quick and efficient protection without the need for extensive software processing or external components
- Considerations: Because this method offers a hardware-based solution, its adaptability to dynamic load conditions and fine-tuning protection algorithms may be more limited than software-based approaches

3. Adjustable or configurable hardware I^2t or I-t feature of the smart high-side switch or gate driver

- Method overview: This method involves enhancing the protected high-side switch or gate driver with a hardware integrator to implement a selectable or configurable I^2t or I-t function, providing a hardware-based approach to wire protection with embedded current integration capabilities
- Implementation benefit: By integrating a hardware integrator, this method offers an optimized solution for implementing I^2t or I-t functions, providing robust and hardware-accelerated current integration without heavy reliance on software processing
- Considerations: Although hardware integration offers efficiency and dedicated functionality, the level of configurability and adaptability to varying protection requirements depend on the specific capabilities of the integrated hardware

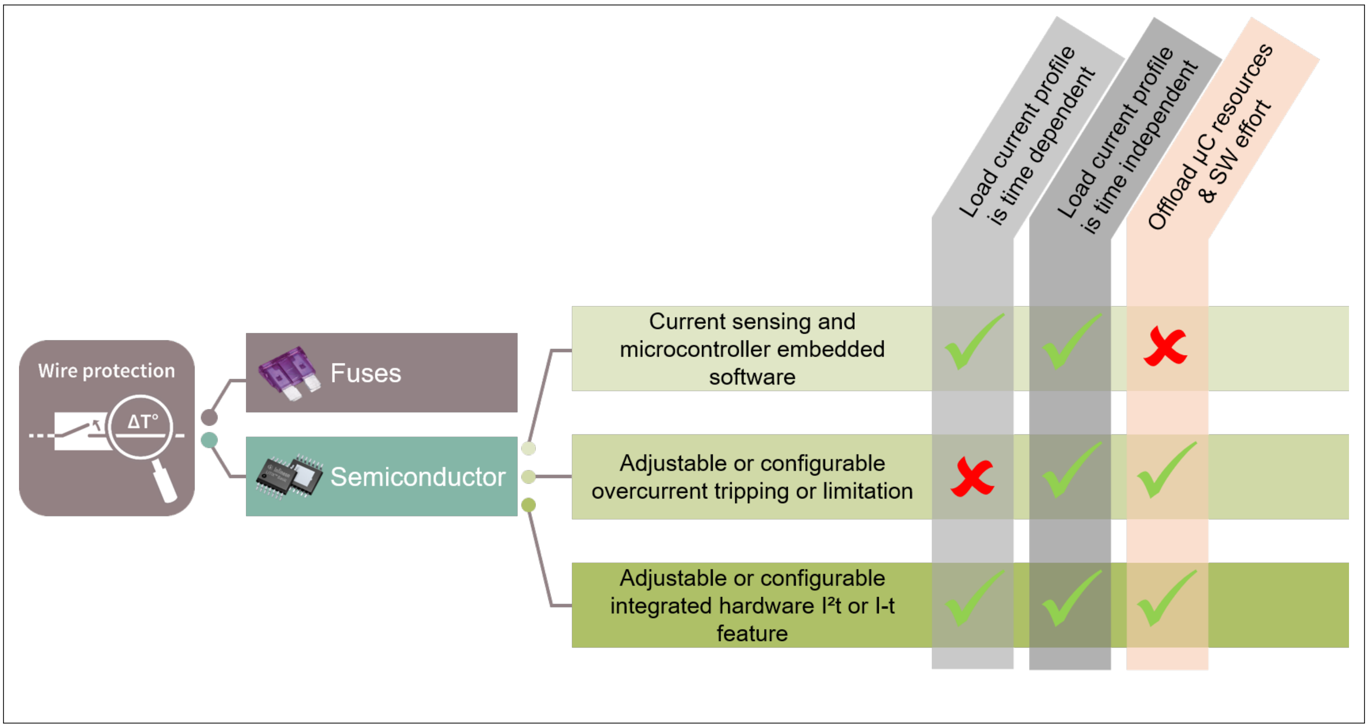

Figure 5 **Selecting a suitable wire protection method**

4 Using current sensing and microcontroller for protecting wires

Modern automotive systems often employ high-side switches with current feedback pins to provide real-time information about the current flowing through the connected wires. This current feedback can be:

- Analog: this feedback signal is sampled by a microcontroller using its *ADC* ports and converted into digital values for further processing
- Digital: the current value is converted into a digital information and made available to the microcontroller via a digital interface (such as a *serial peripheral interface (SPI)*)

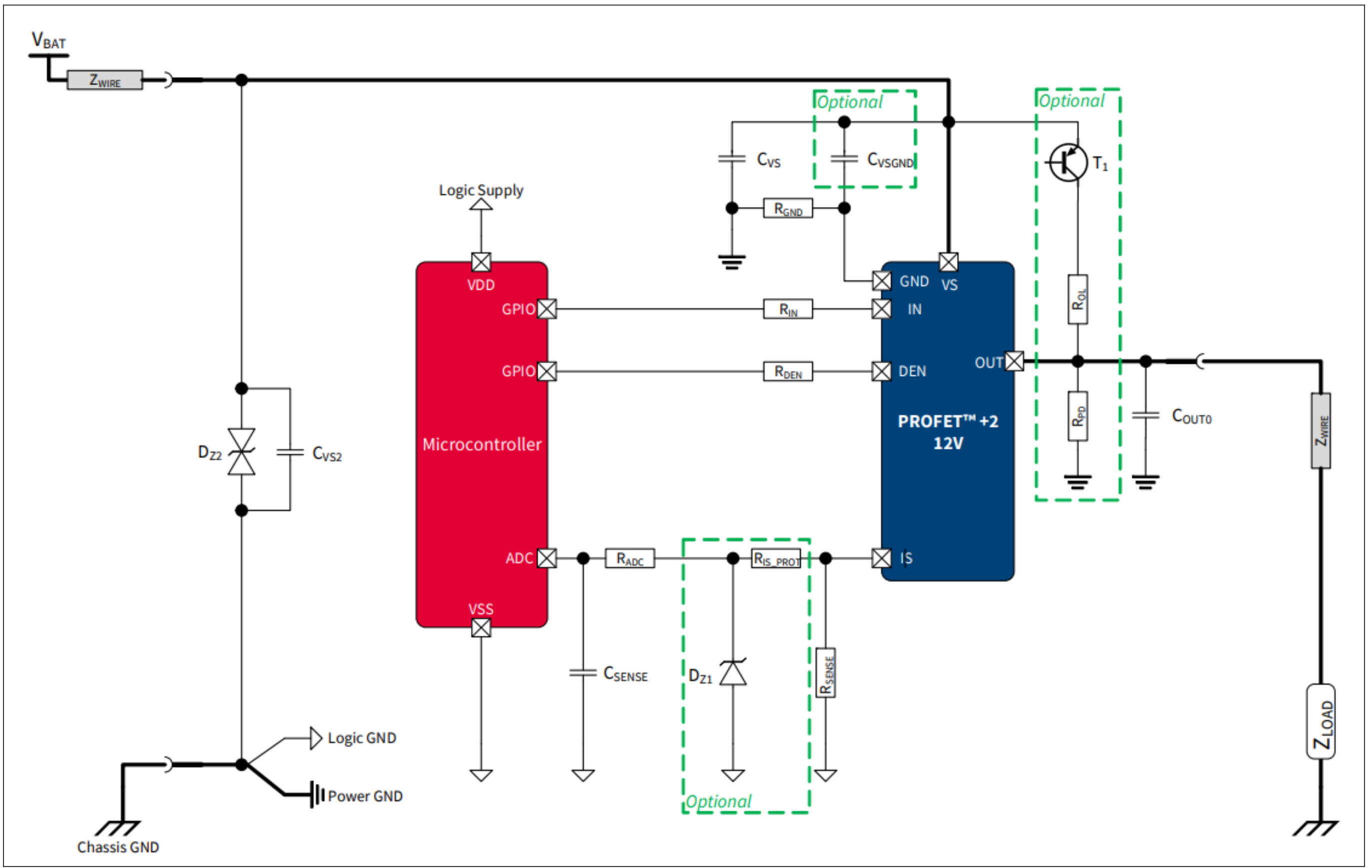

Figure 6 **Typical application circuit of a PROFET™**

By analyzing the current sense information from the high-side switches, the microcontroller can calculate the energy being dissipated in the wire, allowing for an estimation of the wire temperature. This capability enables the system to preemptively identify potential overheating scenarios and take corrective actions to protect the wires from damage.

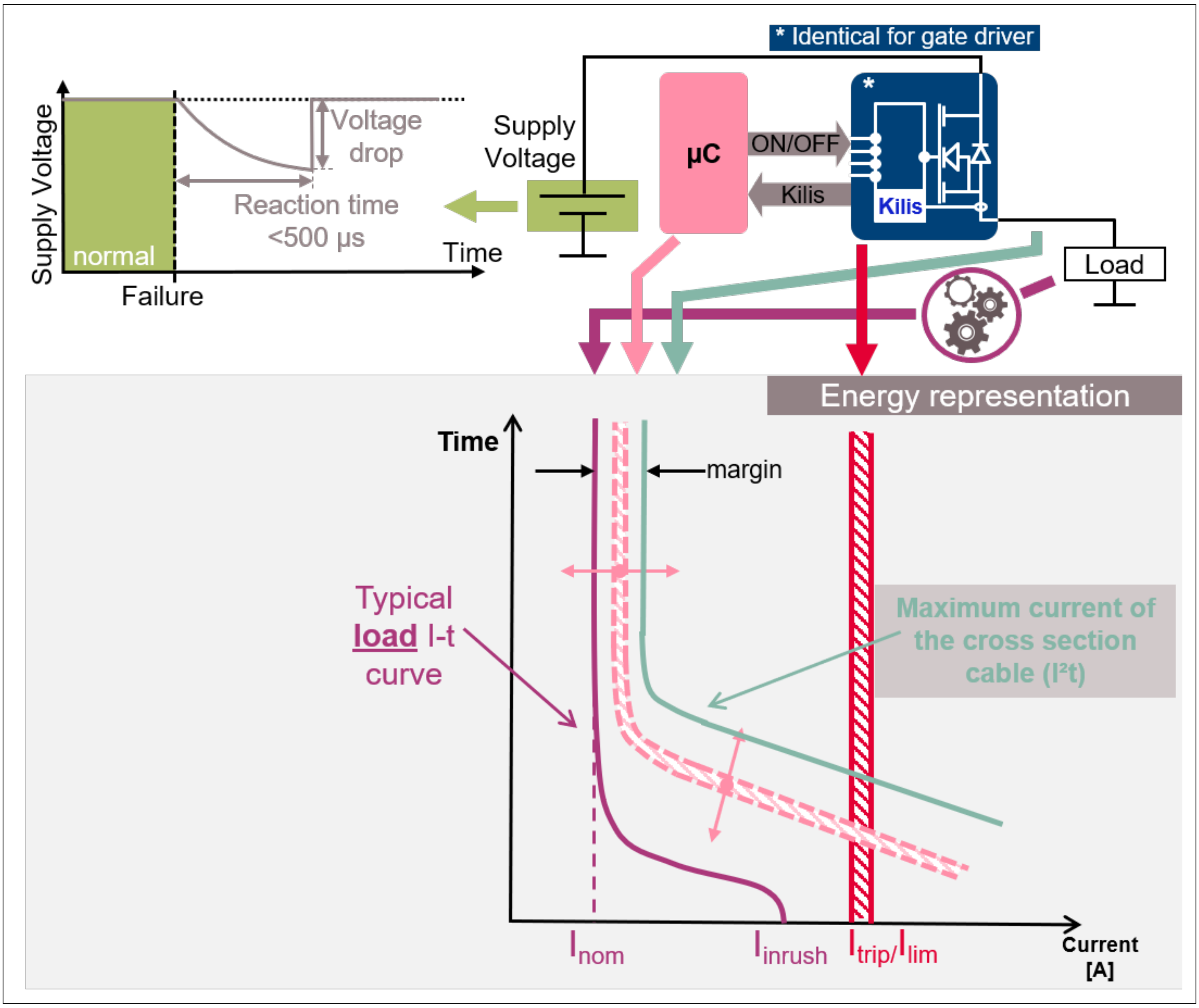

Figure 7 Using current sensing and microcontroller for protecting wires

An important advantage of this approach is the high degree of configurability offered at the system level. The wire protection strategy is not solely reliant on hardware features, as the microcontroller's software can be easily updated, allowing for seamless adaptation and optimization of the wire protection mechanism.

4.1 Challenges when implementing wire protection with current sensing

Despite its benefits, implementing wire protection through current sensing and microcontroller-based control presents several limitations and challenges that need to be carefully considered.

Sampling frequency considerations

According to the Nyquist-Shannon sampling theorem, the sampling frequency for accurate reconstruction of the signal should be at least twice the highest frequency component of the signal. This requirement mandates a sampling frequency of typically at least 5 kHz.

Analog current sensing poses a challenge for microcontroller resources and power consumption. By contrast, digital current sensing allows rapid transfer of information to the microcontroller without additional workload.

Impact on idle mode functionality

The high sampling frequency can hinder the functionality of idle mode in high-side switches, leading to increased power consumption at the module level. Consequently, the microcontroller must spend additional computational resources deciding when to stop the current sensing sampling so that the device can enter idle mode if the output current is low enough.

Wire protection absence during microcontroller reset, software update, or other issues

In the event of an error prompting a microcontroller reset or software update, the wire protection function cannot be computed. Additionally, the microcontroller is likely to enter limp home mode in which only some functions remain available. In this case, a computation-intensive task, such as wire protection, is unlikely to be available, at least for all loads.

4.2 Additional challenges with analog current sensing

Current sense range and measurement accuracy

For analog current sensing, you must select carefully the external resistor for current-to-voltage conversion. You must ensure that the maximum current sense signal remains within the acceptable range for the microcontroller's *ADC* input. This can impact the accuracy of measurements, particularly at low output current ranges.

Impact of external component errors

When analog current sensing, various sources of errors can introduce inaccuracies in the digital values obtained by the microcontroller, including:

- Resistors' tolerance such as R_{SENSE}, R_{ADC}
- Microcontroller ADC supply voltage tolerance
- Leakage from the ADC pin
- Leakage from other current sense pins when a single ADC port is shared among multiple high-side switches
- ADC non-linearities such as quantization errors

These errors can have a significant cumulative effect, potentially amounting to a substantial percentage of the overall current sense accuracy.

However, the overall current sense accuracy is better compared to the tolerances of traditional melting fuses. For example, a 10 A Mini Fuse at 135% ratings has a min./max. opening time from 0.75 s to 600 s, and at 200% ratings from 0.15 s to 5 s. In these current ranges, the overall accuracy of the current sense is typically below 10%.

The overall current sense accuracy can be calculated by using the Infineon Smart Power Switches kILIS Tool.

4.3 Current sensing and microcontroller for protecting wires scorecard

Although current sensing and microcontrollers offer a robust and versatile solution for wire protection, it is important to consider additional measures to enhance standalone hardware protection and alleviate resource pressure on the microcontroller.

Table 2 Current sensing and microcontroller: Fulfillment of requirements

Requirements	Fulfillment
Protect wires against over-heating	✓
Different wire protection for different wires	✓

(table continues...)

Table 2 (continued) Current sensing and microcontroller: Fulfillment of requirements

Requirements	Fulfillment
ASIL requirements for failure disconnection	✓
Accurate protection characteristics for optimizing wire diameter and reducing harness weight	✓
Protects complex load profiles	✓
Standalone hardware protection (limp home function)	✕
Software-configurable wire protection (such as SOTA)	✓
Wire protection resettable by software	✓
Module access free	✓
Offload the microcontroller resource and effort	✕

5 Overcurrent limitation and overcurrent tripping methods for loads with a simple current profile

Adjustable overcurrent limitation or tripping allows a simple and effective protective measure for wire harnesses, particularly in situations where mechanical constraints prevent further reduction of wire gauge for accommodating low current loads. Moreover, the capacitive load charging mode (CLS) is designed to address inrush current issues by facilitating the controlled charging of capacitive loads, thereby mitigating the impact of sudden high current demands on the system.

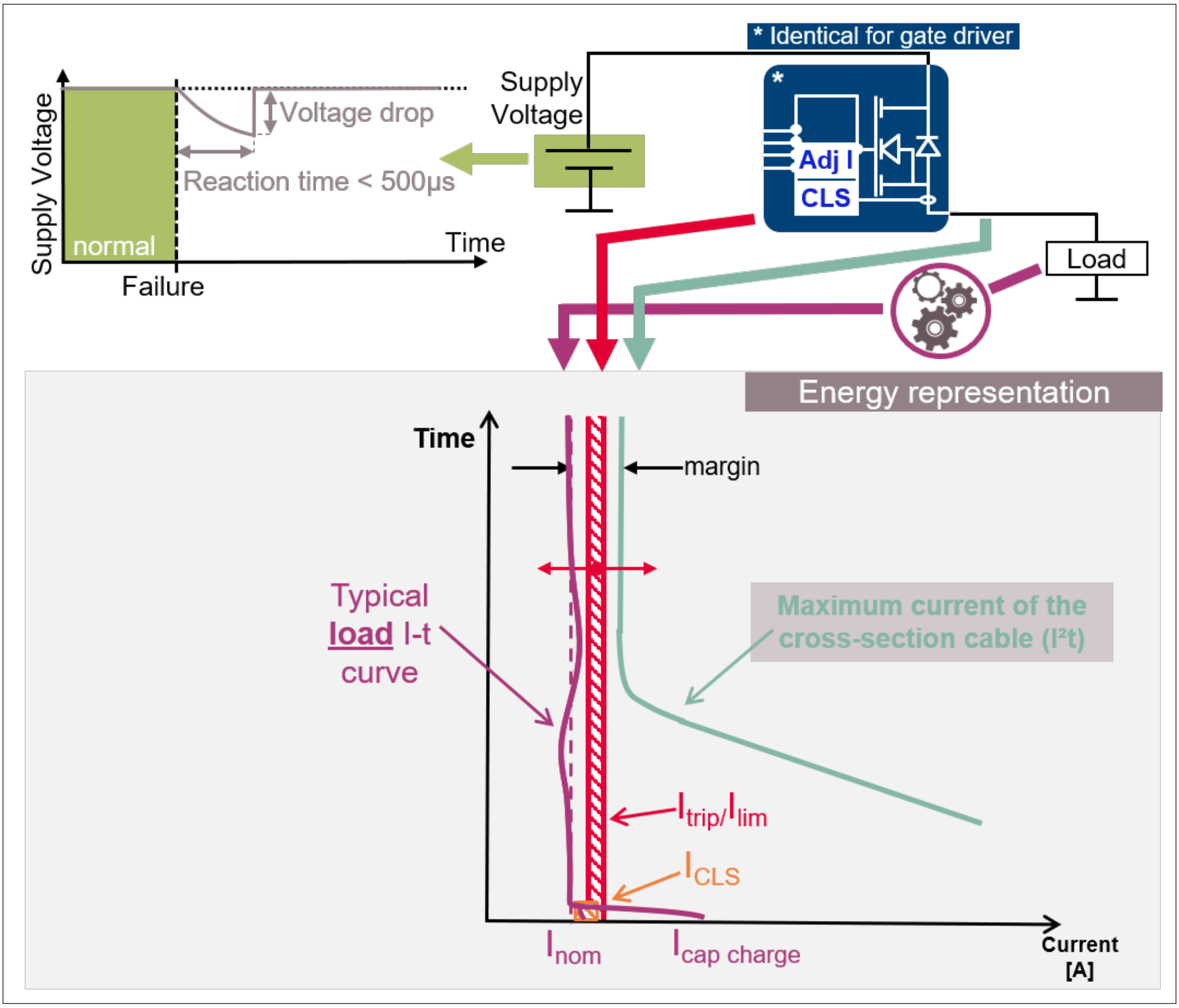

Figure 8 **Configurable Ilim/Itrip + CLS method for loads with a simple current profile**

Table 3 **Configurable current limitation/tripping: Fulfillment of requirements**

Requirements	Fulfillment
Protect wires against over-heating	✓
Different wire protection for different wires	✓
ASIL requirements for failure disconnection	✓

(table continues...)

Table 3 (continued) Configurable current limitation/tripping: Fulfillment of requirements

Requirements	Fulfillment
Accurate protection characteristics for optimizing wire diameter and reducing harness weight	✓
Protect complex load profiles	✕
Standalone hardware protection (limp home function...)	✓
Software-configurable wire protection (such as SOTA)	✓
Wire protection resettable by software	✓
Module access free	✓
Offload the microcontroller resource and effort	✓

5.1 Wire and load protection with PROFET™ Load Guard

The PROFET™ Load Guard portfolio consists of single and dual channel devices with two different $R_{DS(ON)}$ classes, 50 mΩ and 90 mΩ. They are equipped with various protection mechanisms, including an adjustable overcurrent limitation. This feature protects the load from high currents, and protects the wires from thermal hazards. This chapter provides detailed information on what the overcurrent limitation feature is and how to set it up in an application.

***Note**: PROFET™ +2 12 V portfolio offers two devices with a fixed overcurrent limitation, BTS7090-2EPL, and BTS7050-2EPL.*

What is the adjustable overcurrent limitation?

The adjustable overcurrent limitation is a standard feature across all PROFET™ Load Guard devices, offering different limitation values ranging from 0.38 A to 8.86 A. The basic principle of the overcurrent limitation is presented in the figure below.

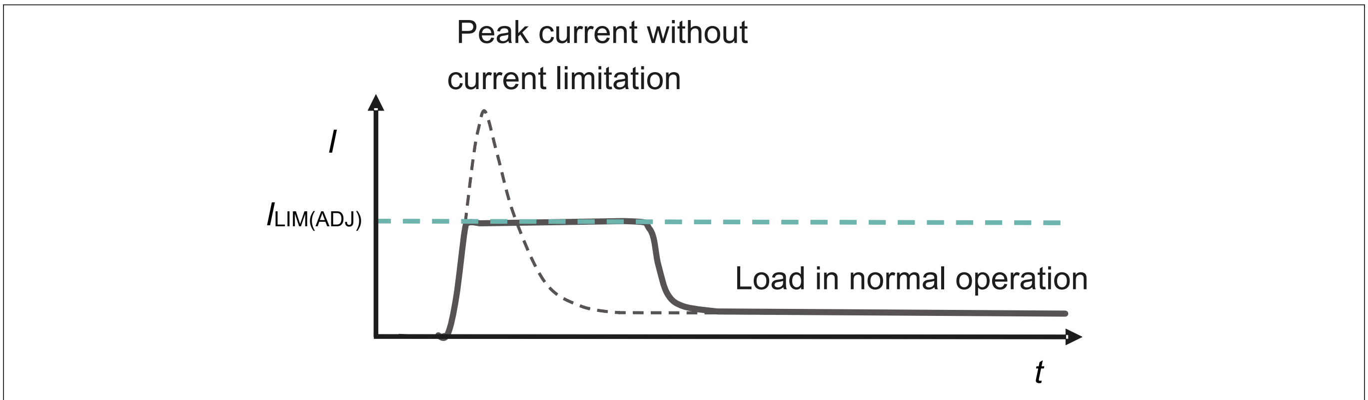

Figure 9 Basic principle of the adjustable overcurrent limitation

It can be seen that if the load current increases beyond the selected overcurrent limitation threshold, the device limits the load current to the set value $I_{LIM(ADJ)}$. When limiting the current, there are two possibilities:

- The load current decreases below the selected threshold within a certain time, resulting in no overtemperature switch-off
- The load current is limited to the overcurrent limitation level and, if necessary, triggers the overtemperature protection

With regard to power dissipation and as consequence of thermal self-heating, PROFET™ protects itself by applying various protection mechanisms, collectively referred to as the device's 'intrinsic fuse behavior.' Therefore, in addition to the overcurrent limitation, the device's intrinsic fuse behavior must be considered as it potentially intersects with the adjusted overcurrent limitation. In this case, the new protection curve is of the overcurrent limitation and the intrinsic fuse behavior of the device, as shown in the figure below. The intrinsic fuse behavior can be estimated by using the Infineon Smart Power Switches Intrinsic Fuse Tool.

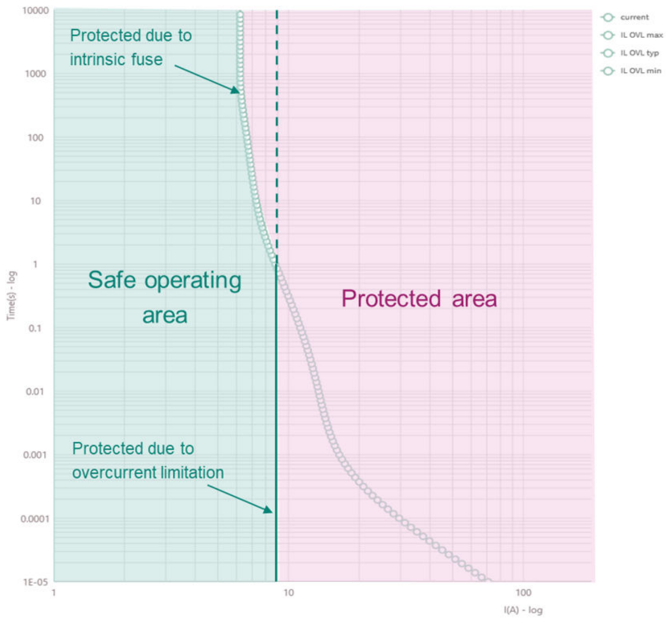

Figure 10 **How intrinsic fuse behavior and overcurrent limitation behavior interact**

***Note**:* *The intrinsic fuse behavior changes over temperature. Therefore, the temperature influence on the intrinsic fuse curve for every device must be investigated separately to set up the wire protection appropriately.*

The figure below is a visualization of the overcurrent limitation threshold. The energy representation graph shows that the set overcurrent limitation threshold does not change over time.

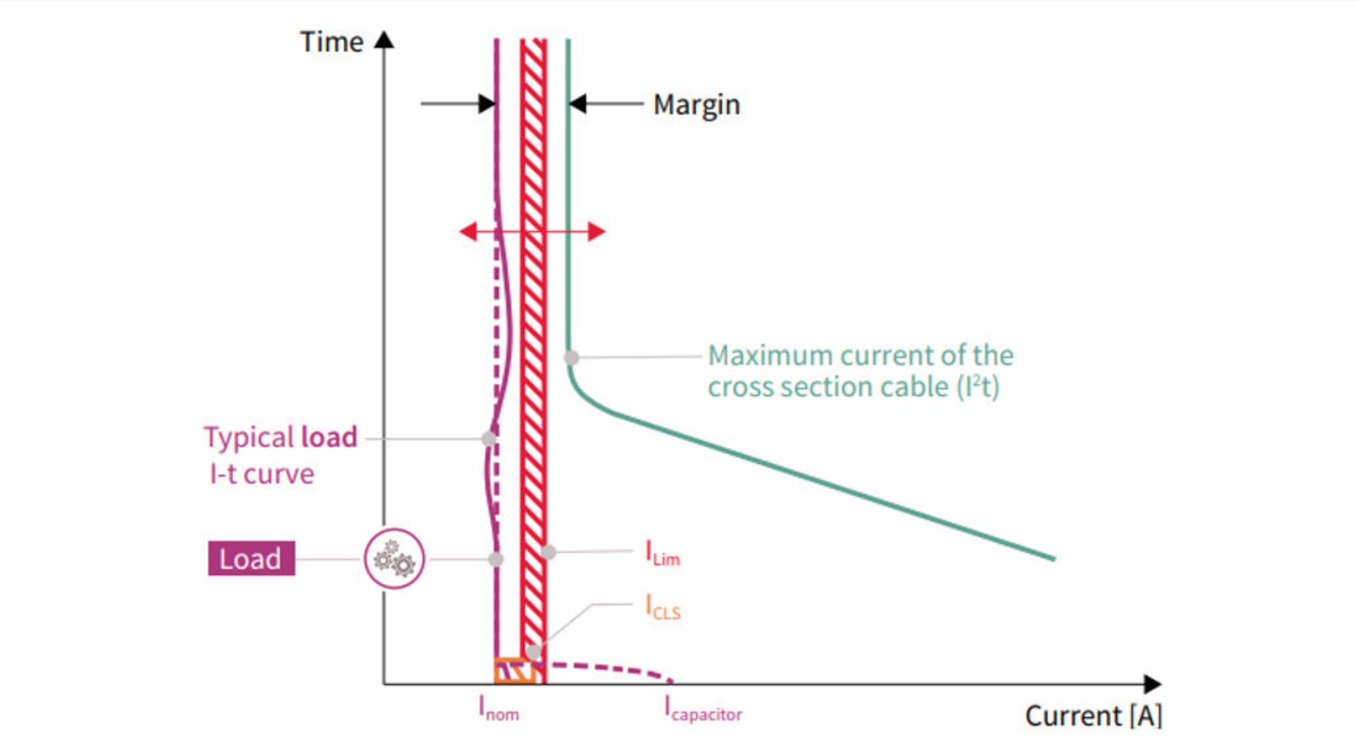

Figure 11 **Energy representation graph for overcurrent limitation threshold**

In a typical application, PROFET™ Load Guard supplies a load with a specific nominal current (steady state current) and an inrush current lower than I_{LIM} for a given amount of time. In addition, a specific wire is required to manage the target load current. The overcurrent limitation threshold should be selected as such to protect the load as well as the wire in the application, as shown in the figure below. The load profile and a corresponding adjustable current limit can be visualized by using the Infineon Smart Power Switches PROFET™ Guard Tool.

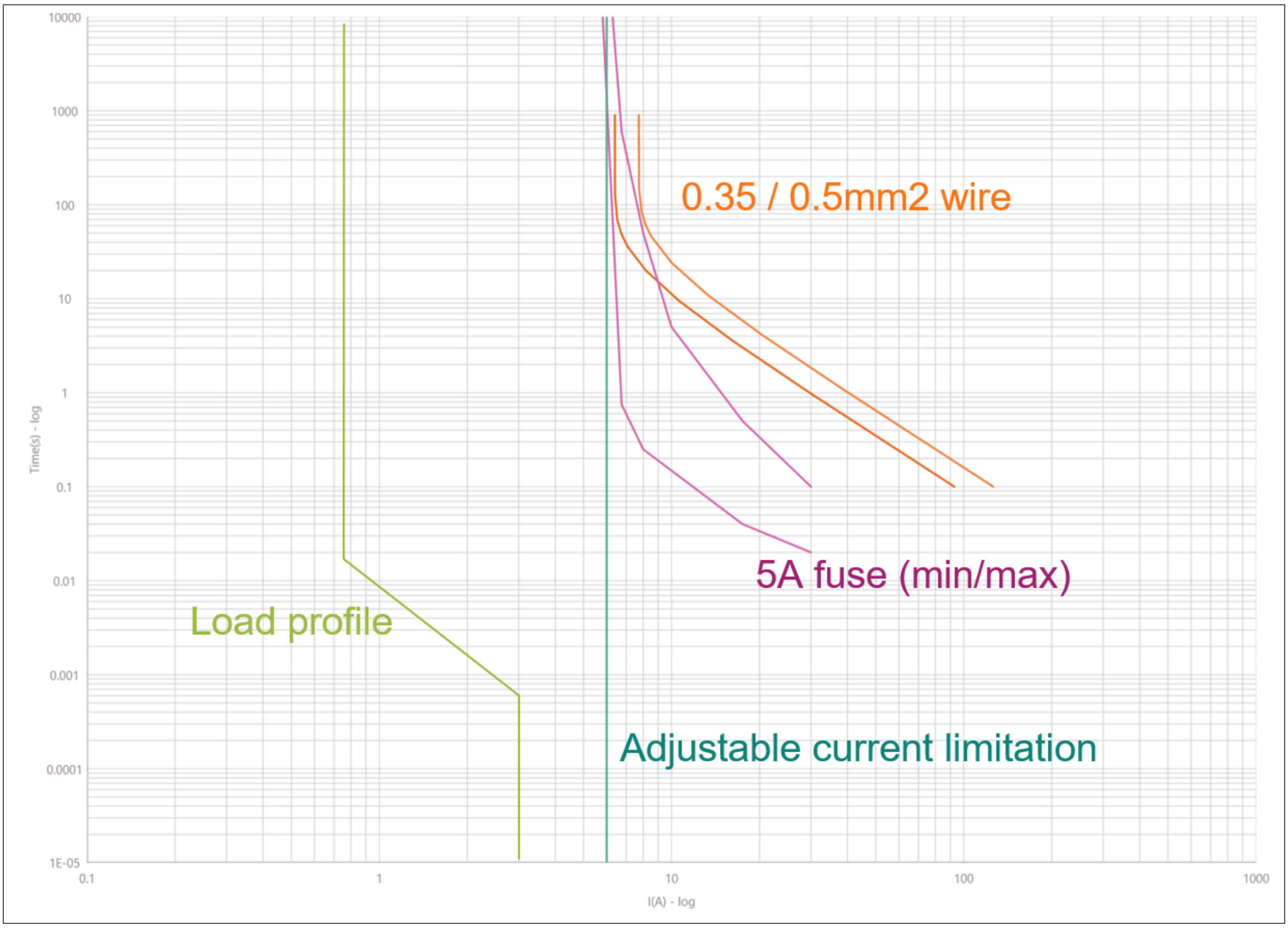

Figure 12 **The overcurrent limitation threshold for a given load and wire profile**

6 Configurable I^2t and I-t methods for loads with a complex current profile

There are multiple reasons why the previously mentioned wire protection methods may not meet application requirements. These include:

- Complex load profiles, which require frequent current sampling
- The requirement for wire protection in parking mode, while the microcontroller is in sleep-mode
- Limitations on the microcontroller's performance, whereby the microcontroller cannot provide protection for multiple outputs
- Unrealistic effort required for software qualification to ensure that it aligns wire protection with ASIL requirements

Consequently, Infineon offers hardware wire protection features to fulfill the above listed application requirements. These solutions include I^2t and I-t wire protection features.

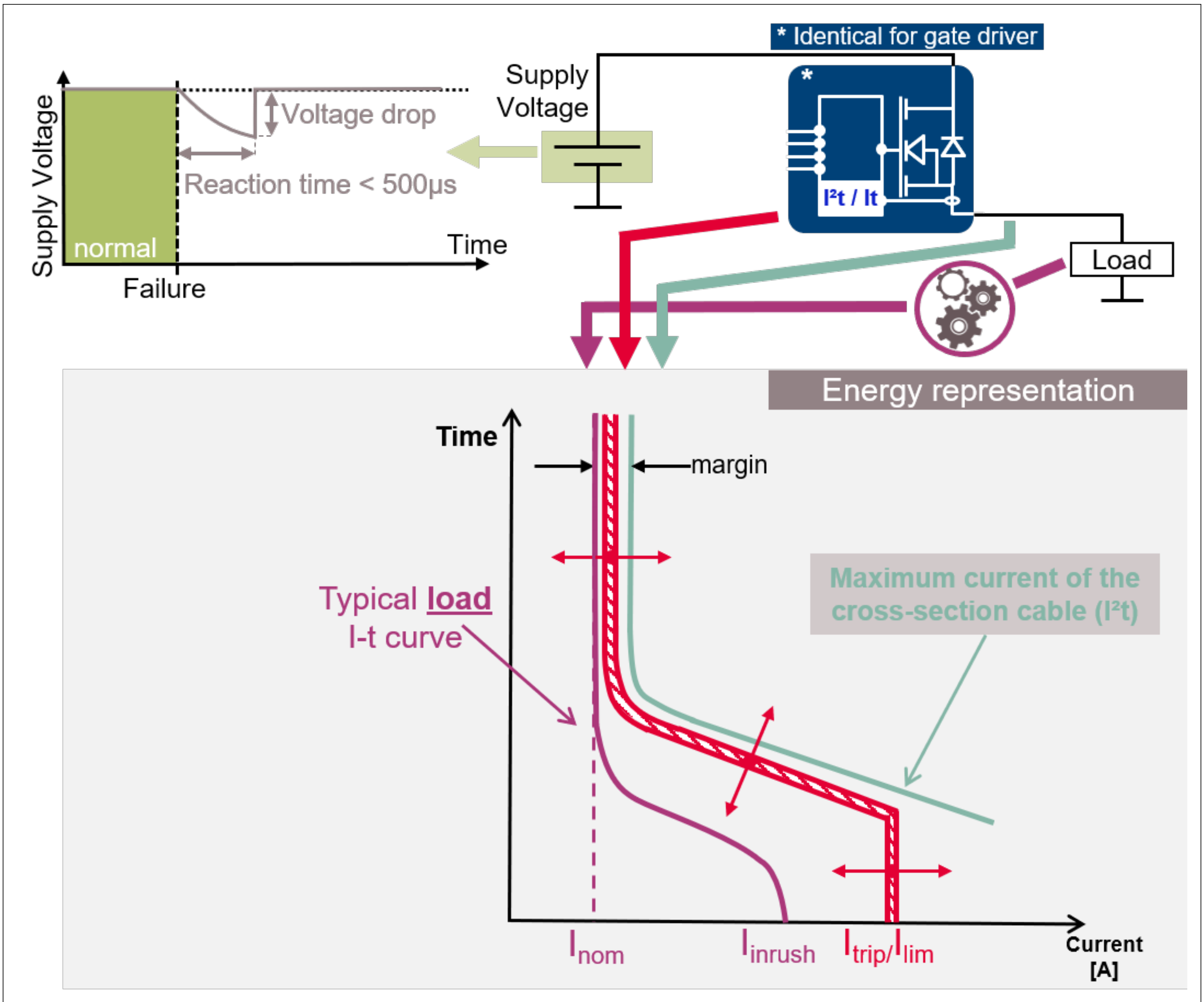

Figure 13 **Configurable I^2t and I-t method for loads with a complex current profile**

Table 4 Configurable I^2t and I-t fulfillment of requirements

Requirement	Fulfillment
Protect wires against over-heating	✓
Different wire protection for different wires	✓
ASIL requirements for failure disconnection	✓
Accurate protection characteristics for optimizing wire diameter and reducing harness weight	✓
Capable to protect complex load profiles	✓
Standalone hardware protection (limp home function)	✓
Configurable wire protection over software (such as SOTA)	✓
Wire protection is resettable by software	✓
Module access free	✓
Offload the microcontroller resource and effort	✓

6.1 I-t wire and load protection with EiceDRIVER™ APD 2ED2410-EM

The EiceDRIVER™ APD 2ED2410-EM is a smart high-side N-channel MOSFET gate driver with two outputs controlled via logic pins designed for the new upcoming automotive power distribution architectures for 12V and 24V board nets.

The 2ED2410-EM has three analog measurement interfaces and four integrated comparators for protection purposes, allowing flexible and versatile solutions for various E/E architecture requirements, for example: overcurrent protection, overvoltage and undervoltage protection and adjustable I-t wire protection.

The wire protection feature with the 2ED2410-EM gate driver offers several advantages that can enhance the overall performance and functionality of the system. Wire protection is primarily intended to protect the wires from overheating.

Wire protection also plays a role in detecting overloads, particularly when the overload current is lower than the fixed short-circuit threshold typically found in a smart switch. An overload current that does not immediately trigger a short circuit shutdown can cause the wire, PCB, MOSFET, or smart switch to overheat. Wire protection can be used to detect this type of overload and react before any components are damaged.

Wire protection can be implemented in software using the host microcontroller, however there are a number of limitations to this approach. The number of outputs from power distribution modules has increased due to the move to a zonal based architecture where power distribution is centralized. This new architecture trend requires more microcontroller resources to monitor and control the outputs leading to a larger microcontroller and faster software response times. A hardware wire protection solution can save microcontroller resources and provide a faster response to overload conditions.

Wire protection with the 2ED2410-EM can be visualized as an I-t function. The figure below shows the general picture of the protection. It shows the wire and the load profiles, the short-circuit limit, and finally, the wire protection achieved by the 2ED2410-EM. The primary goal of wire protection is to safeguard the wire, without interrupting the nominal load except during an overload condition.

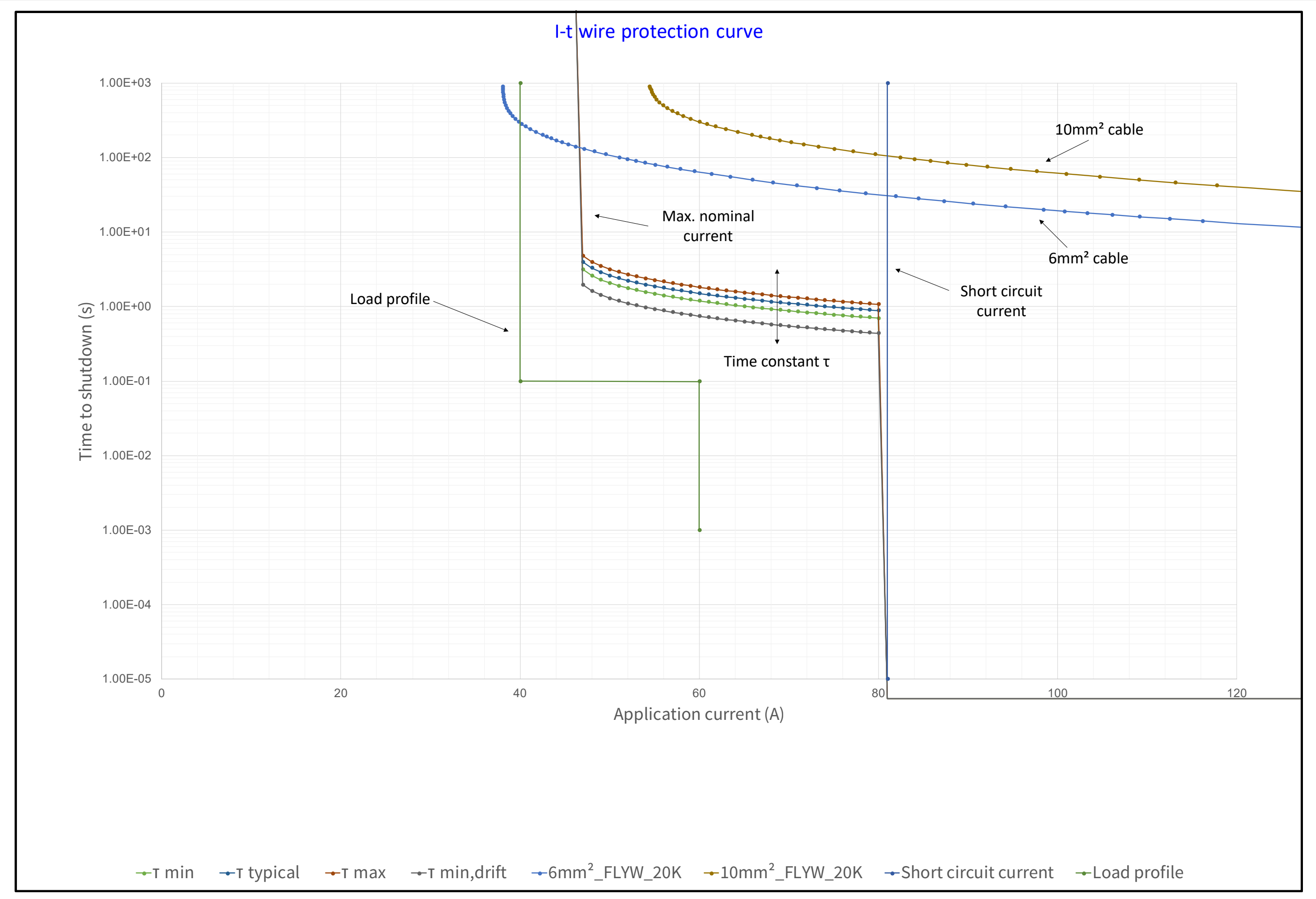

Figure 14 **I-t wire protection curve example for 2ED2410-EM**

The protection can be adapted by adjusting certain parameters:

- The short circuit current threshold (x-axis right limit of the protection) can be adapted based on the CSA1 amplifier

It is assumed that the shunt resistor value has already been selected based on the thermal requirements of the application. The EN pin voltage is essential in this calculation and must be set prior to any calculations. The EN pin is typically supplied with a fixed voltage. To set the correct current sense amplifier gain and protection threshold, resistors R_{ISP}, R_{ISN} and R_{CSO} must be selected to meet the requirements of the application.

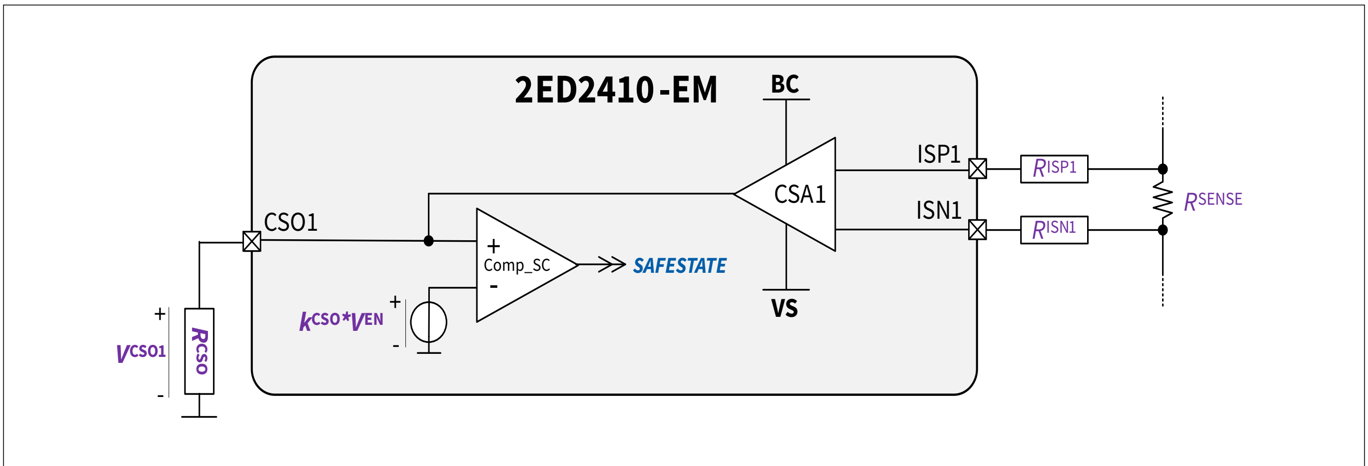

Figure 15 **Overview of bi-directional** ***CSA*****1**

Note: *CSA2 is identical to CSA1 but does not include a comparator (COMP)*

Based on the equation below, the parameters can be derived from the short circuit current.

$$I_{SC} = \frac{V_{EN} \cdot k_{CSO1(TH)}}{G_{CSA1} \cdot R_{sense}}$$

- The maximum nominal or steady state current (x-axis - left hand current side of the protection), beyond which the wire protection is active can be adapted based on the COMP. This is done by changing the reference voltage of the negative input of the comparator and the gain of the CSA2

After assigning the same gain value to CSA1 and CSA2, estimate the CP reference voltage based on the equation below:

$$V_{CP(REF)} = R_{sense} \cdot I_{nom(MAX)} \cdot G_{CSA}$$

- The detection delay (y-axis of the protection - time) is adapted by an RC circuit. The output of the second amplifier (CSO2) of the 2ED2410-EM is filtered by the RC circuit and provided to the positive input of the CP

  The wire protection time constant defines the time that the current trip level, set by CSA1, applies before the current limit reduces to the maximum nominal current limit set by CSA2 and CP. The time constant is set by an external resistor and capacitor network.

  The aim is to define a time constant that provides the maximum operating area for the load current, with the correct I_{SC} and I_{NOM_MAX} values

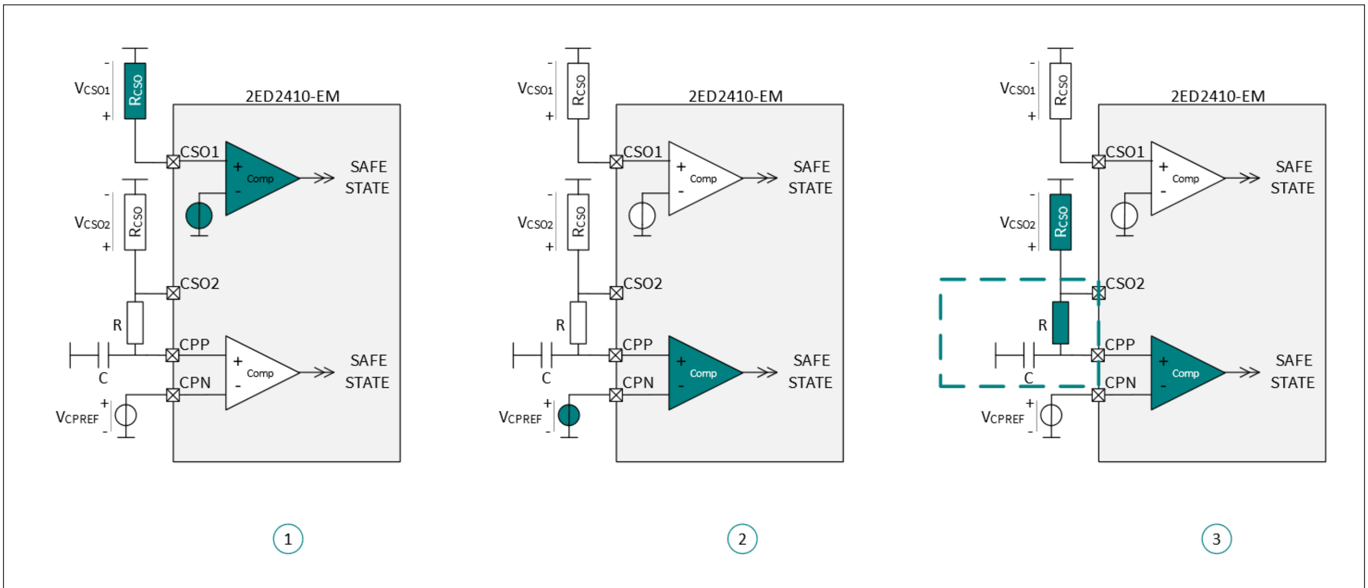

Figure 16 Overview of adjustable parameters

Infineon provides tools to assist with the selection of the resistor and capacitor values for the wire protection time constant:

- Getting Started Workbook available on myICP. This is a Microsoft® Excel-based tool that calculates the R and C values from the wire protection requirements and other related parameters entered by the user. The resulting wire protection function is shown graphically including maximum and minimum curves representing the resistor and capacitor tolerances
- EiceDRIVER™ Tool for 2ED2410. This is available in the Infineon Developer Center tool suite [4]. This tool also calculates the R and C values and represents the resulting wire protection curve graphically. Wire and load profiles can be added to the graphical output of the EiceDRIVER™ tool using the Infineon Smart Power Switches and Wire Entry Tool. Fine tuning of the R and C values then can be done to visually fit the WP current profile to the load requirements and wire curves

For more information, refer to the wire protection application for the 2ED2410-EM.

6.2 I²t wire and load protection with PROFET™ Wire Guard

In low-current applications, the adjustable current limitation concept might be the best choice, whereas in medium and higher-current applications, an integrated I²t or I-t protection is preferred. The PROFET™ Wire Guard family consist of five products in $R_{DS(ON)}$ range from 16 mΩ down to 1.3 mΩ. Each product includes six generic I²t protection curves, which are selectable by an external resistor. The customer can select the protection curve according to the application boundaries. Typical boundaries include load profile, ambient temperature, wire diameter, wire isolation material, conductor material and the safety margin. Additionally, the product family includes an adjustable overcurrent detection threshold to limit the maximum current in the system. The I²t ($I_{L(I2t\_n)}$) and the overcurrent detection threshold adjustment ($I_{L(LOCT)}$ to $I_{L(HOCT)}$) is done by an external resistors R_{I2t} and R_{OCT}. Using these two features, it is possible to adjust the protection for complex load current profiles.

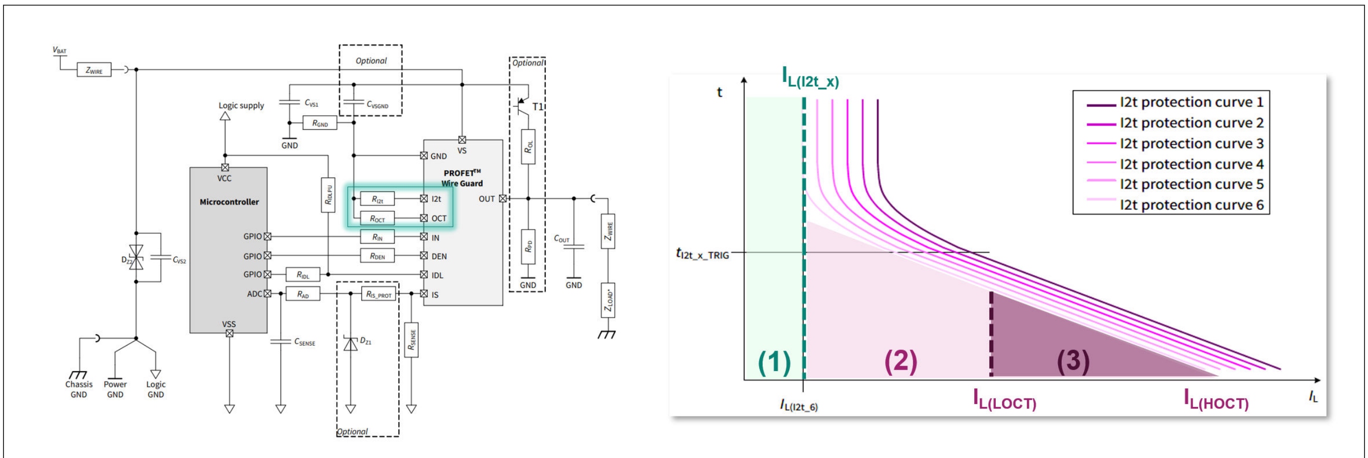

Figure 17 **Configuration resistors for I²t wire protection and adjustable overcurrent detection**

For optimal system dimensioning, the basis is the load profile with static and dynamic current behavior. To represent the load profile in the correct dimension, it must be transferred into the energy representation graph of the system. The static current of the load profile and the allowed power dissipation defines the correct product from the product family.

The next step is to select the lowest possible I²t curve. The system integrator must ensure that there is no overlap with the load profile and the spread. The overcurrent protection threshold must be adjusted to the correct value. This enables the maximum in-rush current of the load, while limiting the maximum current overshoots in the system. The dimensioning is supported by using the Infineon Smart Power Switches PROFET™ Guard Tool. A graphical representation of these steps is shown in the figure below.

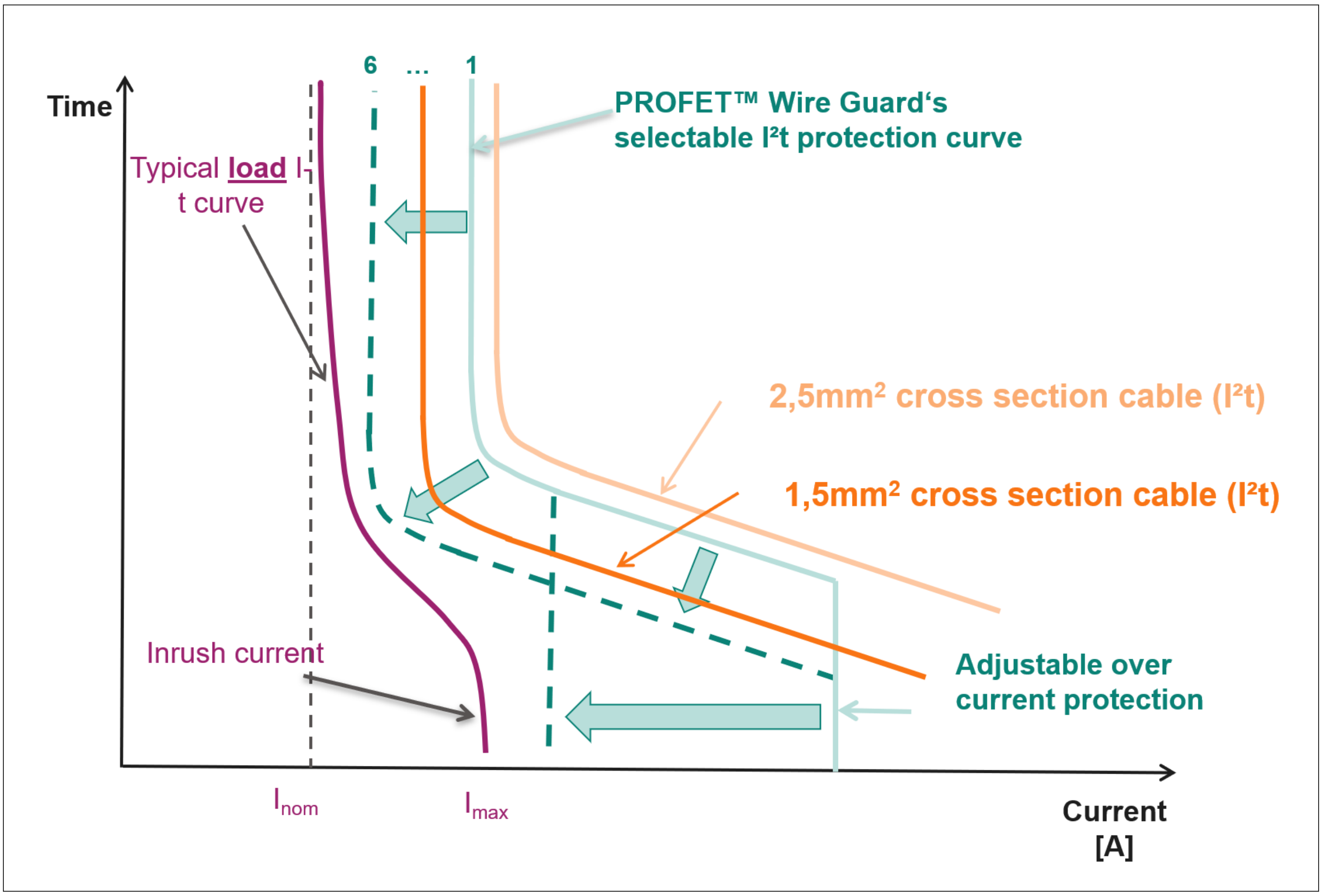

Figure 18 **Energy representation of the system including advanced protection with PROFET™ Wire Guard**

6.2.1 Calculating I^2t status

The I^2t protection feature calculates the I^2t status SI2t_A once the output is activated. The calculation depends on the load current, time constant of the selected device, and the I_{DC} of the selected I^2t protection curve. If the load current is above the I_{DC} of the selected curve, the channel is switched off as soon as the I^2t status S_{I2t_A} reaches 100%. When the power stage is switched off, the I^2t status calculation continues with a zero load current. This continues until the status is below the initial value, minus the I^2t hysteresis. This method ensures a correct I^2t status calculation for load profiles in typical power distribution applications.

The formula to calculate the triggering time of the I^2t protection is as follows: The initial value of the I^2t status depends on the mode transition and the actual I^2t status S_{I2t_A}. When the I^2t block is activated (for example: from Sleep or IDLE), the I^2t calculation is pre-loaded with the initial status values S_{I2t_I}.

Formula for calculating trigger time

$$t_{I2t\_x\_TRIG} = \begin{cases} \infty & for \quad I_L \leq I_{L(I2t\_x)} \\ \tau_{I2t} \cdot \text{In} \left(\dfrac{I_L^2 - I_{L(I2t\_x)}^2 \cdot S_{I2t\_A}}{I_L^2 - I_{L(I2t\_x)}^2} \right) & \text{for constant } I_L > I_{L(I2t\_x)} \end{cases}$$

6.2.2 I^2t sensing information

The sequential diagnosis supports the readout of various data, which can be accessed by selecting a specific address, such as the I^2t status address. For detailed information on how the sequential diagnosis functions, refer to the diagnosis section in the datasheet. The I_2t status readout provides many benefits for various applications and has additional use cases.

Additional use cases:

- Latent fault check: The I^2t status can be compared with an expected value that is coming from a calculation in the microcontroller or from a generic value defined for a dedicated load. This helps to identify potential issues with the load if the value differs too much from the expected value
- Predictive maintenance: Using cloud computing, the average status of a load can be compared with a similar vehicle in the same region. If a vehicle differs too much from the average, a maintenance flag can be set and is checked in the next planned maintenance
- Vehicle autonomy: Depending on the status of the vehicle, which can be retrieved by the diagnosis functions (for example, I^2t status) of the device, various levels of vehicle autonomy can be activated
- Load management: By combining the I^2t status information with a software-based threshold, the microcontroller can decide whether the load is still supplied or proactively disconnected
- Failure prevention: The observation of fast dynamic I^2t status changes during operation, the microcontroller can set countermeasures to prevent damage to the wire harness or load. Additionally, certain features such as automated driving can be deactivated
- Software flexibility: Setting a higher curve of the I^2t protection, together with several soft thresholds in the microcontroller, lower curves can be emulated by setting the correct software thresholds of the I^2t status
- Power management: In power distribution applications, where several loads are connected to one output, the I^2t status supports the power management. If there is not enough power delivered to the loads, low priority load can be deactivated. The I^2t status indicates the power limitation
- Optimization cycle: By collecting the I^2t status data of a vehicle fleet, the data can be used to optimize the power distribution system for future improvements of the vehicle

7 Using semiconductors to optimize the wire harness

In a legacy scenario with melting-fuse based automotive power distribution, the design process for wire protection and load switching begins with the selection of melting fuses and relays to ensure reliable and efficient power delivery to critical vehicle components. The following steps outline the systematic approach to selecting fuses and relays:

1. Ideal fuse rating calculation:

- The ideal fuse rating is determined by dividing the nominal operating current by the temperature derating factor. This calculation results in, for example, the selection of a 15 A fuse for a 10 A load in the cabin compartment and a 20 A fuse for a 10 A load in the engine compartment. This calculation method ensures that the selected fuses can protect the respective loads against overcurrent events while considering temperature variations and derating effects

2. Relays for load switching:

- Load switching requirements are addressed by selecting 15 A and 20 A relays for the cabin compartment and the engine compartment respectively. These relays are chosen to provide robust and reliable load switching capabilities, aligning with the selected fuse ratings and the operational requirements of each compartment

When transitioning from melting fuses and relays to semiconductors, several considerations and potential pitfalls may arise, particularly when matching the ratings and functionality of the existing relay and fuse configuration.

A common pitfall is attempting a direct 1:1 replacement of a traditional fuse and relay setup with a semiconductor solution; for example, replacing a 15 A fuse and relay with a 15 A *direct current (DC)* rated smart power switch. The semiconductor needs to be designed according to the load (10 A) and not the fuse and relay it is replacing.

The designer must ensure that the semiconductor fuse accurately matches the load requirements. Additionally, it is important to assess external boundary conditions, such as mission profiles, to guide the selection of the appropriate product from Grade 1 and Grade 0 device offerings.

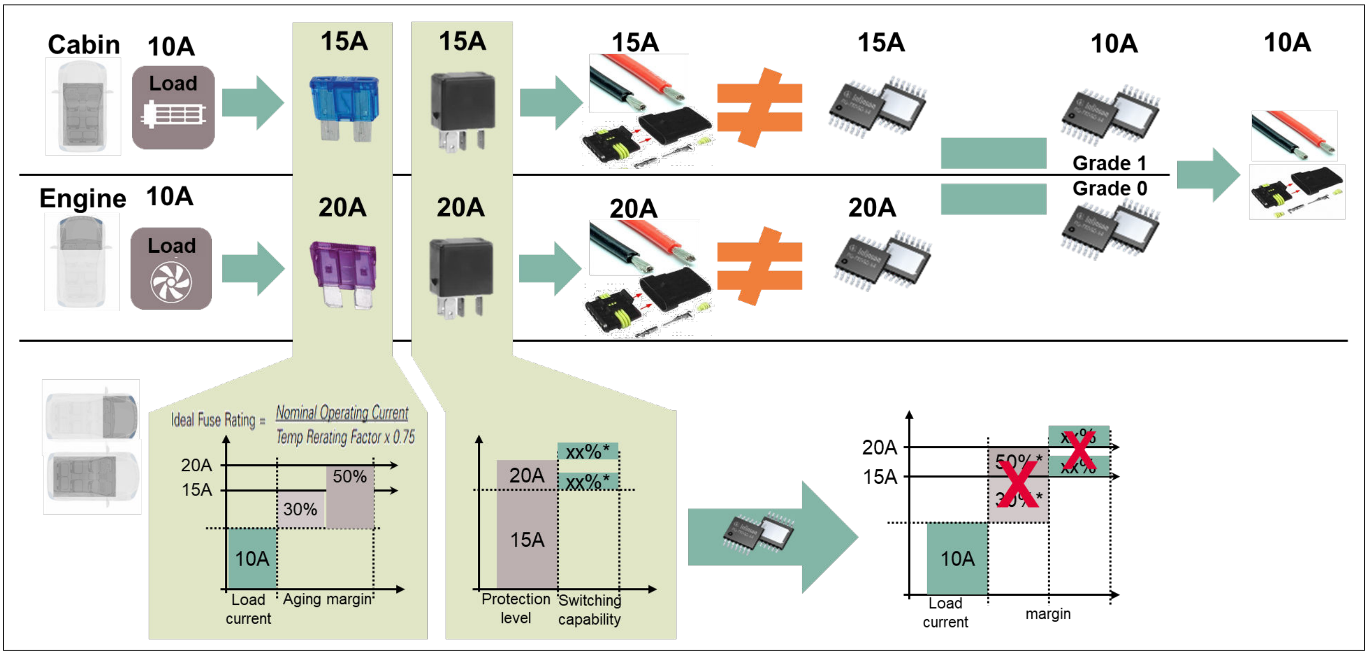

Figure 19 Wire protection use case: system considerations

For more information about relay replacement, refer to the following application notes: Relay replacement I and Relay Replacement II.

8 Conclusions

In this application note, various methodologies for implementing wire protection in low voltage automotive systems were thoroughly examined. We embarked on this exploration by focusing on traditional melting fuses, before transitioning our analysis towards semiconductor solutions, thereby examining different ways in which wire protection can be applied.

Moreover, explicit examples using Infineon products were included to provide readers with a tangible demonstration of these concepts in action. It is important to note that every technique carries its own set of advantages and disadvantages, which should be considered carefully. The selection of an appropriate method heavily depends on the specific requirements of the application in question.

The table below summarizes the type of application requirements fulfilled by each solution. It is designed to assist the reader in making an informed decision on the most suitable wire protection strategy for the specific need.

Table 5 Fulfillment of requirements for various implementations

Requirements	Melting fuses	Current sensing and microcontroller	Configurable current limitation/ tripping	I^2t and I-t methods
Featured product families	×	• Power PROFET™ +12/24/48V • PROFET™+ 24V • PROFET™+2 • SPOC™+2 • PROFET™ Load Guard 12V • PROFET™ Wire Guard 12V • EiceDRIVER™ APD 2ED2410-EM, 2ED4820-EM	• PROFET™ Load Guard 12V • PROFET™ Wire Guard 12V • EiceDRIVER™ APD 2ED2410-EM, 2ED4820-EM	• PROFET™ Wire Guard 12V • EiceDRIVER™ APD 2ED2410-EM
Protect wires from over-heating	✓	✓	✓	✓
Different wire protection for different wires	✓	✓	✓	✓
ASIL requirements for failure disconnection	×	✓	✓	✓
Accurate protection characteristics for optimizing wire diameter and reducing harness weight	×	✓	✓	✓
Protect complex load profiles	✓	✓	×	✓

(table continues...)

Table 5 (continued) Fulfillment of requirements for various implementations

Requirements	Melting fuses	Current sensing and microcontroller	Configurable current limitation/ tripping	I^2t and I-t methods
Standalone hardware protection (limp home function)	✓	✗	✓	✓
Software-configurable wire protection (such as SOTA)	✗	✓	✓	✓
Software-resettable wire protection	✗	✓	✓	✓
Module access free	✗	✓	✓	✓
Offload the microcontroller resource and effort	✓	✗	✓	✓

9 References

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2. Infineon EiceDRIVER ™APD 2ED2410-EM - 24 V evaluation MOSFET daughterboard, common drain, pre-charging; EB 2ED2410 3M, https://www.infineon.com/cms/en/product/evaluation-boards/eb-2ed2410-3m
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5. Infineon PROFET™ Wire Guard, https://www.infineon.com/cms/en/product/power/smart-power-switches/high-side-switches/profet-wire-guard-12v-automotive-smart-high-side-switch/
6. Infineon PROFET™ Load Guard, https://www.infineon.com/cms/en/product/power/smart-power-switches/high-side-switches/profet-load-guard-12v-automotive-smart-high-side-switch/
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Glossary

ADC

analog-to-digital converter (ADC)

ASIL

automotive safety integrity level (ASIL)
One of four levels to specify the item's or element's necessary ISO 26262 requirements and safety measures to apply for avoiding an unreasonable risk, with D representing the most stringent and A the least stringent level

COMP

comparator (COMP)
Compares an input voltage against a second input voltage.

CSA

current-sense amplifier (CSA)
Special-purpose amplifiers that output a voltage proportional to the current flowing in a power rail. They utilize a "current-sense resistor" to convert the load current in the power rail to a small voltage, which is then amplified by the current-sense amplifiers.

DC

direct current (DC)

One-directional flow of electric charge. An electrochemical cell is a prime example of DC power. Direct current may flow through a conductor such as a wire, but can also flow through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric current flows in a constant direction, distinguishing it from alternating current (AC).

fault

abnormal condition that can cause an element or an item to fail

SPI

serial peripheral interface (SPI)

A synchronous serial communication interface specification used for inter-chip communication, primarily in embedded systems.

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