Application Note

Replacing Melting Fuses with TI Smart eFuse High-Side Switches

ABSTRACT

Melting fuses used ubiquitously in automotive and industrial systems serve an integral purpose – overload and short circuit protection. However, the design of protection schemes using melting fuses is challenging and often limited because of fuses' inherent variability and thermal derating inaccuracies, resulting in the need to oversize wire gauge and connectors. TI's Smart eFuse High-Side Switches make overload and short circuit protection simple and richly featured with accurate rating current thresholds, I^2T thresholds, resettability and in-depth fault reporting. This document details the benefits of using TI's Smart eFuse High-Side Switches over melting fuses and includes a design example on how to replace a specified melting fuse with a TI Smart eFuse High-Side Switch.

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1 Introduction

As automobiles and their systems become increasingly complex and cloud-based, the need for comprehensive coordinated overload and short circuit protection schemes similarly grows in both complexity and importance. Zonal architectures create an elegant function and power distribution platform, but that platform and its wiring must be protected at every stage – directly off the battery, at the zone input level and at the output level – otherwise, some safety-critical functions like steer-by-wire or door locks may be compromised. Historically, melting fuses have provided this protection, but they have become a limitation in modern-day vehicles due to the need for a dedicated fuse box, limited diagnostic feedback available and overengineering of wire to account for fuses' wide tolerances. This necessitated the switch to using eFuse High-Side Switches instead of melting fuses for power tree protection. TI Smart eFuse High-Side Switches outperform melting fuses in all major functionalities, introducing on-the-fly programmability, verbose fault reporting, load switching and current limiting while featuring high-accuracy current sense and I^2T protection. These advantages greatly simplify coordinated protection schemes and enhance system safety and performance. Additionally, due to the accurate I^2T protection, wire gauge and connector size can be reduced, lowering vehicle weight and improving cost and energy efficiency.

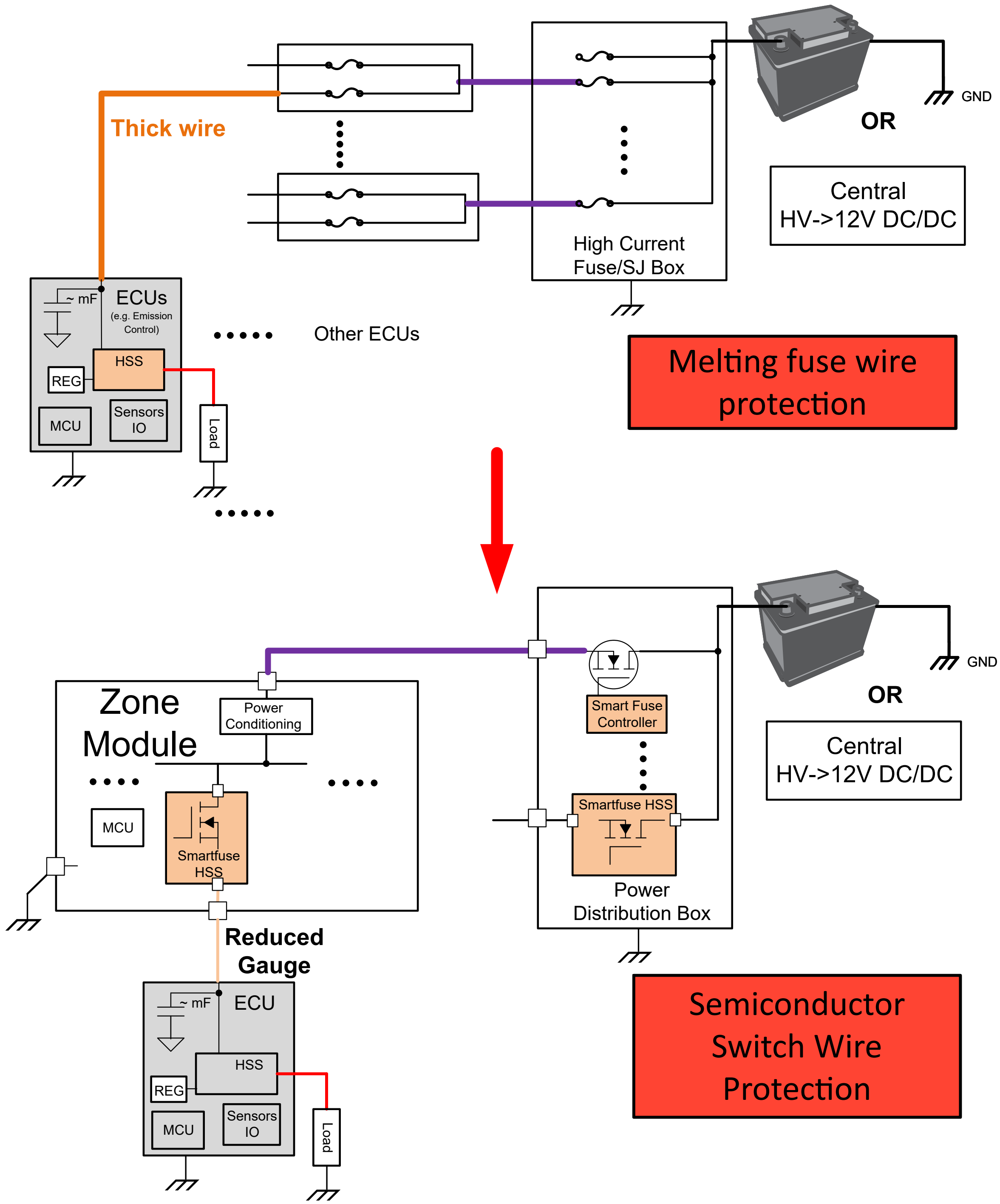

Figure 1-1. Zonal Architecture Power Distribution

2 Melting Fuse Performance

Used since the 1880s to protect telegraph cables from severe weather and short circuit conditions, melting fuses have a long and thoroughly studied history. Since melting fuses are, in theory, just a strip of wire with a low melting point, these devices are an easy, cheap and crude way to implement short circuit protection. Although melting fuses have retained the responsibility as a circuit's failsafe overcurrent protection mechanism, technical developments over the past hundred years required additional dimensions of performance and characterization from fuses. For example, a 1900's factory motor can undoubtedly handle more relative transient overcurrent before the fuse tripped than a 1980's computer processor board. Thus, fuse engineering became more refined and precise while keeping the same principle working theory – always fail open-circuit during an overcurrent or short circuit condition – resulting in the following physics-determined considerations and behaviors of fuses.

2.1 Current Rating

This is the main parameter of a fuse and represents the maximum current that a fuse can continuously carry at room temperature. Therefore, in the best case, a 10A fuse can carry 10A indefinitely without tripping. However, fuses are not precise components, and thus the rule of thumb is to derate a given fuse's current rating by 25% to avoid accidental tripping during normal operation below the current rating. Thus, a 10A fuse is not recommended for more than a 7.5A nominal current at room temperature.

2.2 Rerating Curve

Since a fuse's trip point is based on its instantaneous temperature, any ambient temperature difference from its data sheet ratings will affect the current rating. A lower ambient temperature requires a greater temperature difference (current) to melt the internal wire, and a higher ambient temperature requires a lower temperature difference (current) to melt the internal wire. Fuse data sheets typically include a current rerating curve to help designers estimate the fuse's performance at different ambient temperatures.

For example, a typical fuse rerating curve details that the rerating factor at an 85°C ambient temperature is about 91%, so the 10A fuse from would have a rated current of 6.825A at 85°C according to Equation 1.

$$\text{ReratedOperatingCurrent} = \text{CurrentRating}*0.75*\text{ReratingFactor} \tag{1}$$

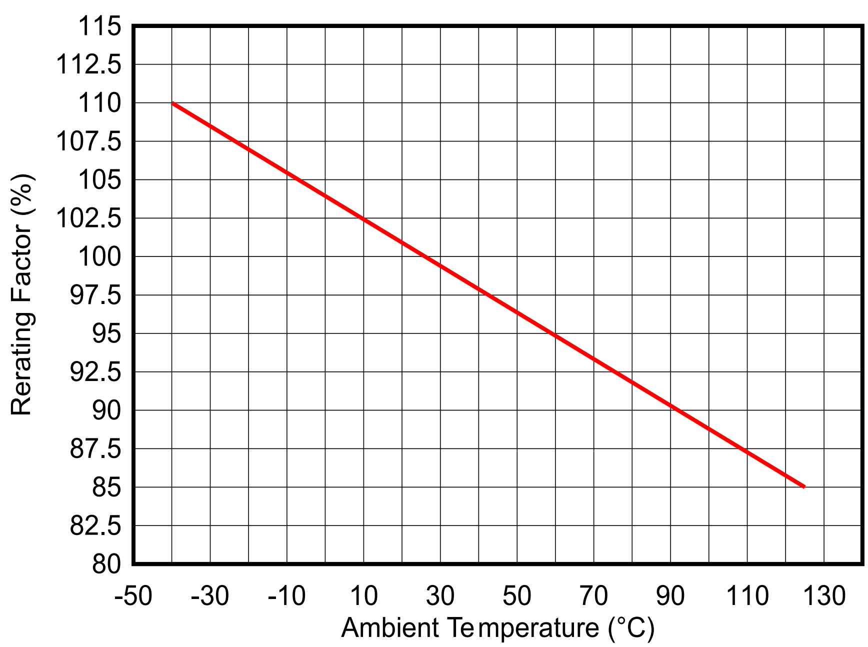

Figure 2-1. Example Melting Fuse Rerating Curve

2.3 I^2T Values

I^2T is a representation of a fuse's thermal capacity before it trips, denoted with the unit ampere-squared-seconds (A^2s). During transient overcurrent events, a fuse's trip point is estimated using an I^2T value. If a given current pulse's I^2T value is above the fuse's rating, then the fuse can be expected to blow when subjected to it.

To calculate a pulse's I^2T value, the instantaneous current-squared (I^2) value is integrated over the pulse's duration (T). This can be done simply by assuming a rectangular current pulse of 5A for 50ms. Using Equation 3, this pulse's I^2T value is $1.25A^2s$.

$$I^2TThreshold = \int I(t)^2 dt \tag{2}$$

$$I^2TThresholdforRectangularCurrentPulse = I^2 * t_{pulse} \tag{3}$$

2.3.1 Melting I^2T

Melting I^2T is the thermal energy needed to melt the fuse's internal wire. This value is used when determining if a fuse is fit for allowing a specific transient current pulse.

2.3.2 Arcing I^2T

After melting fuses' wires melt, the melted metal and ionized air inside the fuse hold a conductive path open through the fuse for a short time. This is called the arcing time and can be characterized by a respective I^2T value.

Some fuses are engineered to have a very short arcing time and low I^2T value.

2.3.3 Total Clearing I^2T

This is the total I^2T value that the load sees, and this value should be below the load's and supply's short circuit withstand capabilities and wire's I^2T threshold. As can be seen, the total I^2T value that a system's wiring sees is higher than the melting I^2T value, and thus wires are often overengineered to not be damaged by the arcing I^2T.

2.3.4 Fuse I^2T Considerations

Since fuses are not precise components, their I^2T values are multidimensionally dependent on unit-to-unit variation, ambient temperature, voltage drop, number of prior transient current pulses, and even the transient current conditions through the fuse. Thus, a fuse's I^2T parameters are not guaranteed as their values and time-current graphs are typical only, and a wide safety margin must be designed to account for fuse variation for both allowable current transients and to ensure that wires are properly protected.

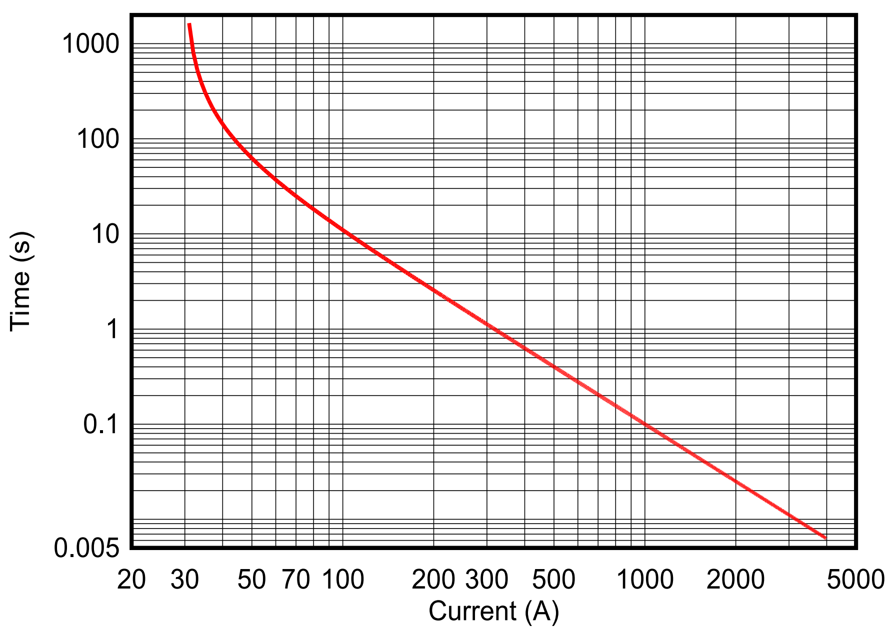

Figure 2-2. Example Melting Fuse Time-Current Graph

2.4 Opening Time

Fuses often have guaranteed opening times at different relative currents. For example, an industry-standard fuse gives opening times at different relative currents according to Table 2-1.

Table 2-1. Example Melting Fuse Opening Times

% of Current Rating	Opening Time min / max (s)
110	360000 / ∞
135	0.75 / 600
160	0.25 / 50
200	0.15 / 5
350	0.08 / 0.5
600	0 / 0.15

As can be seen, at each relative current value there is an opening time variation of two to three magnitudes and the fuse is not guaranteed to trip until about 130% of its current rating.

2.5 Voltage Rating

A fuse's voltage rating must be above the system's voltage rating to suppress the arcing that occurs after a fuse melts.

3 TI Smart eFuse High-Side Switch Performance

To meet the demanding needs of current-day wire protection systems, TI Smart eFuse High-Side Switches such as TPS2HCS08-Q1 and TPS2HCS10-Q1 feature a highly programmable, high-performance, precise fuse functionality while integrating powerful functionalities of a high-side switch. To achieve this, TI Smart eFuse High-Side Switches integrate an ADC, a sophisticated digital core and SPI communication into a high-side switch. When designing fuse functionality with TI Smart eFuse High-Side Switches, the following operating parameters are relevant.

3.1 Process/Voltage/Temperature Considerations

TI Smart eFuse High-Side Switches' internal analog circuitry is temperature-compensated, so features such as current sense, I2T thresholds and overcurrent thresholds are accurate across temperature.

For current sense-based thresholds, there are three data sheet accuracies which should be considered: K_{SNS} accuracy, $ISNS_{ADC,ACC}$ accuracy and $V_{ADCREFHI}$ accuracy.

3.1.1 Max Operating Temperature

TI Smart eFuse High-Side Switches include an overtemperature protection called thermal shutdown. When the internal temperature of the device exceeds about 180°C, the device triggers thermal shutdown and turns the outputs off.

To ensure that thermal shutdown does not occur during normal operation, the chosen device must be able to pass the maximum steady-state load current at the maximum ambient temperature without triggering thermal shutdown. This can be estimated using Equation 4.

$$T_J = T_{amb} + \left(R_{\theta}JA^*\left(I_{OUT}{}^2{}^*R_{ON,\,max}\right)\right) \quad (4)$$

3.2 I^2T Curve

TI Smart eFuse High-Side Switches use a fully programmable four-stage overcurrent protection scheme, seen in Figure 3-1 and Figure 3-2. Each threshold can be configured during startup and on-the-fly via the SPI register space. If more threshold options are required, the external current sense (SNS) resistor can be dynamically adjusted to achieve any threshold not specified in the datasheet.

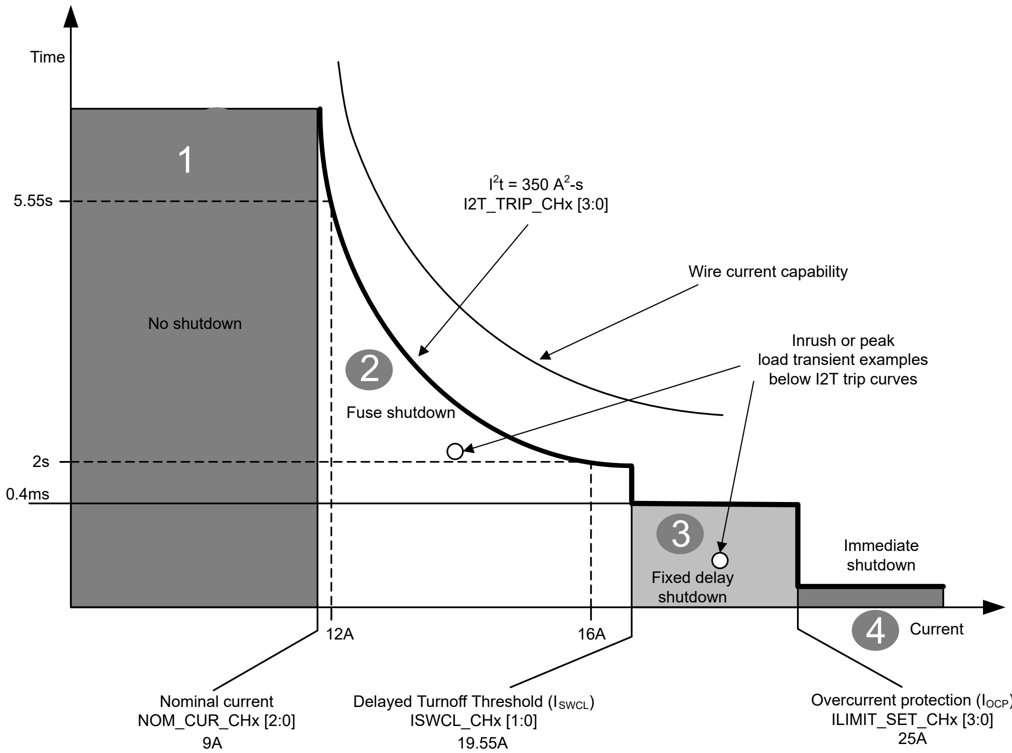

Figure 3-1. TI Smart eFuse High-Side Switch Overcurrent Protection Scheme

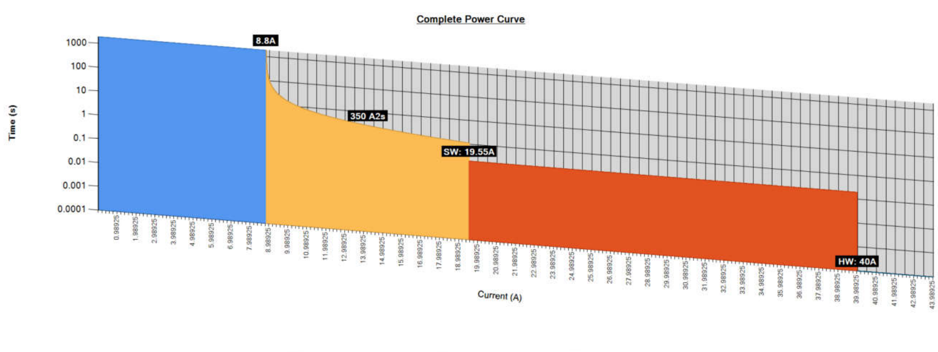

Figure 3-2. Example Overcurrent Protection Setup

3.2.1 Nominal Current Threshold (INOM)

This threshold is analogous to a fuse's current rating – below this current, the fuse will never trip due to I^2T overcurrent, and above this current, the I^2T integration will start. Since this threshold has very little variation across temperature, it does not have to be derated like in melting fuses.

3.2.2 I^2T Fuse Threshold

When the output current exceeds INOM, the device starts I^2T accumulation according to Equation 5, where dt = 50us. When the programmed I^2T threshold is met, the output shuts off and an I^2T fault is reported. If the output current decreases below INOM before the I^2T threshold is reached, the I^2T counter will decrement according to Equation 5.

Since the I^2T accuracy can quantified, an I^2T or time-current graph can be plotted with minimum and maximum curves, giving systems more control over the maximum energy that their wires and components can experience.

$$I^2T_{count} = \int_0^t (I_{out}{}^2 - INOM^2)dt \quad (5)$$

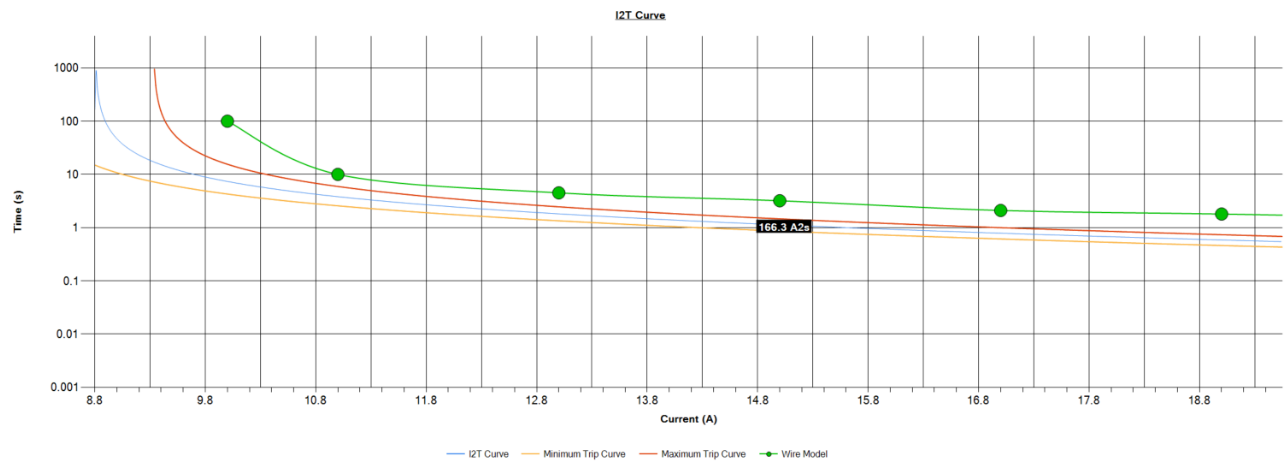

Figure 3-3. Example I2T Trip Times

3.2.3 Fixed-Delay Shutdown Threshold

If a current above this threshold persists for a short programmable time, the device shuts off. This length can allow transient overcurrent events for a very short blanking time but turns off much faster than a melting fuse can trip.

3.2.4 Immediate Overcurrent Protection Threshold (I_{OCP})

If the load current exceeds this value at any time, the output will immediately shut off within microseconds. This protection is always active and can be programmed at any time to be above the fixed-delay shutdown threshold, in the I^2T region, or below INOM.

As can be seen, this protection can turn off the output much, much more quickly than a melting fuse, which is critical for sensitive downstream electronics.

3.3 Additional Protections and Diagnostics

3.3.1 Additional Protections

3.3.1.1 Short-to-Ground Protection

TI Smart eFuse High-Side Switches achieve robust short-to-ground protection by combining two protection features: I_{OCP}, detailed above, and relative thermal shutdown. To implement relative thermal shutdown, the device monitors the temperature difference between its FETs and controller. If that difference exceeds about 60°C, the device will shut off until the temperature difference equalizes.

3.3.1.2 Capacitive Charging

Large system capacitances can be easily charged with minimum input disturbance by using the programmable constant-current-limiting capacitive charging mode.

3.3.1.3 Limp Home Mode/Watchdog/CRC

TI Smart eFuse High-Side Switches include multiple safety-critical functions that help detect and protect against system faults before they turn catastrophic. These include limp home mode detection, an integrated watchdog, and CRC, where the Smart eFuse High-Side Switch can output a fault and take action if the LHI pin's digital value is not as expected, if the attached MCU does not send a SPI frame in a given amount of time, or if the device's calculated CRC checksum does not match the MCU's appended checksum.

3.3.1.4 Reverse Battery Protection

During a reverse battery condition, the device will turn on its FETs to prevent current from going through the body diode and thus decrease the power dissipation of the device. For more information on reverse battery protection, please see the TI Smart eFuse High-Side Switches' data sheets.

3.3.1.5 Loss of Battery/Ground Protection

If VBB or GND is disconnected at any point during operation, the outputs will immediately shut off to protect the device and system during a fault condition.

3.3.1.6 Integrated Inductive Discharge

TI Smart eFuse High-Side Switches integrate a drain-source clamp feature to quickly discharge inductive loads and energy stored in wire inductance, preventing the need for a TVS or flyback diode connected to fuse outputs.

3.3.2 Additional Diagnostics

With TI Smart eFuse High-Side Switches' advanced digital core, verbose input and output faults, load currents, input and output voltage, drain-to-source voltage, FET temperature, and device states can be read via the SPI interface to provide increased system safety and information output.

4 Switching from Melting Fuse to TI Smart eFuse High-Side Switch

4.1 Melting Fuse Design

For example, consider designing a protection scheme for a 5A nominal current load. From Equation 1, it can be calculated that a 7.5A rated fuse should be selected to avoid nuisance trips. Using the data in Table 1, Table 2 can be created to evaluate the trip times for different output currents.

Table 4-1. Melting Fuse Opening Times for 5A Nominal Current Load

Current (A)	Opening Time min / max (s)
8.25	360000 / ∞
10.125	0.75 / 600
12	0.25 / 50
15	0.15 / 5
26.25	0.08 / 0.5
45	0 / 0.15

As can be seen, the melting fuse is not guaranteed to open until the fuse current is over 10A – more than double the nominal current. If the load, upstream supply, or connecting wires do not have the ability to handle 10.125A for up to 10 minutes, then there must be additional headroom engineered into the respective systems to accommodate for the melting fuse tolerances. Similarly, the load, upstream supply, and connecting wires must be able to handle 45A for up to 150ms, which can add significant complexity and overengineering to circuitry throughout the power tree.

4.2 Current Rating

Instead of a melting fuse, a TI Smart eFuse High-Side Switch such as TPS2HCS10-Q1 can be used to control, protect, and provide enhanced diagnostics on this rail. From Table 8-33 NOM_CUR_CH1 bits in the TPS2HCS10-Q1 data sheet, this device offers programmable nominal INOM thresholds from 4A to 15A with RSNS = 700Ω.

Table 4-2. TPS2HCS10-Q1 I2T_CONFIG_CH1 Register Field Descriptions

Bit	Field	Type	Reset	Description
15-14	TCLDN_CH1	R/W	0h	These bits set the cool down time (or time to retry) after an I2T shutdown for Channel 1. Note: If setting 0x0 is used, the channel will remain off after an I2T shutdown with no retry. To retry in this setting, change the bits to 0.8s, 2.0s, or 4.0s options to allow the device to retry after an I2T shutdown. 0h = indefinite cooldown 1h = 0.8s 2h = 2.0s 3h = 4.0s
13-11	RESERVED	R/W	0h	Reserved
10-9	SWCL_DLY_TMR_CH1	R/W	0h	These bits set the timer at which Channel 1 will shut down if the IOUT current continuously exceeds the ISWCL level for the configured time. 0h = 0.2ms 1h = 0.4ms 2h = 1.0ms 3h = 2.0ms

Table 4-2. TPS2HCS10-Q1 I2T_CONFIG_CH1 Register Field Descriptions (continued)

Bit	Field	Type	Reset	Description
8-7	ISWCL_CH1	R/W	0h	These bits set the delayed turn off current sense value ($I_{SWCL,700}$) for channel 1. Once the IOUT current exceeds the $I_{SWCL,700}$ value, a timer starts and will turn off the channel if the current remains above the $I_{SWCL,700}$ threshold for a duration of SWCL_DLY_TMR_CH1. The threshold should be set below the current sense saturation value ($I_{OUT\_SAT} = K_{SNS1} * I_{SNS\_SAT}$). The current threshold below assume R_{SNS} = 700Ω. To calculate the new $I_{SWCL,700}$ thresholds based on a different R_{SNS} value, the following equation can be used: $I_{SWCL,ADJ} = I_{SWCL,700} * (700 / R_{SNS})$ 0h = 19.55A 1h = 17.6A 2h = 16.05A 3h = 13.3A
6-3	I2T_TRIP_CH1	R/W	0h	These bits set the I2T trip value for Channel 1. Note: For reference the equation for the I2T trip value is: $I2T = (I_{OUT1}{}^{2} - NOM\_CUR\_CH1^{2}) * t$ The below values assume R_{SNS} = 700Ω. To calculate the new I2T trip values based on a different R_{SNS} value, the following equation can be used: $I2T_{ADJ} = I2T_{700} * (700 / R_{SNS})^2$ Note: The I2T_TRIP_CH1 value cannot be modified when the device is in the cool down time period. 0h = 8.8 A2s 1h = 13.1 A2s 2h = 26.3 A2s 3h = 39.4 A2s 4h = 52.5 A2s 5h = 65.6 A2s 6h = 78.8 A2s 7h = 91.9 A2s 8h = 109.4 A2s 9h = 126.9 A2s Ah = 144.4 A2s Bh = 166.3 A2s Ch = 192.5 A2s Dh = 218.8 A2s Eh = 262.5 A2s Fh = 350 A2s
2-0	NOM_CUR_CH1	R/W	0h	These bits set the nominal current value for channel 1 for the I2T function. If the I2T function is enabled for channel 1, above this value the device will enter the I2T accumulation mode. The nominal current values below assume R_{SNS} = 700Ω. To calculate the new I2T trip values based on a different R_{SNS} value, the following equation can be used: $NOM\_CUR\_CH1_{ADJ} = NOM\_CUR\_CH1_{700} * (700 / R_{SNS})$ Note: The NOM_CUR_CH1 value cannot be modified when the device is in the cool down time period. 0h = 4.0A 1h = 5.0A 2h = 5.7A 3h = 6.5A 4h = 7.5A 5h = 9.0A 6h = 12.0A 7h = 15.0A

When determining which INOM threshold to use, the INOM threshold accuracy must be quantitatively analyzed to find a threshold that will always be above the nominal load current. Equations 6-9 can be used to calculate the INOM threshold accuracy and minimum/maximum values.

$$INOM_{accuracy,\,min} = \left(\left(1 + K_{SNS1,\,accuracy,\,min}\right)*\left(1 + ISNS_{ADC,\,ACC,\,min}\right)/\left(1 + V_{ADCREFHI,\,accuracy,\,max}\right)\right) - 1 \quad (6)$$

$$INOM_{min} = INOM_{typ}*\left(1 + INOM_{accuracy,\,min}\right) \quad (7)$$

$$INOM_{accuracy,\,max} = \left(\left(1 + K_{SNS1,\,accuracy,\,max}\right)*\left(1 + ISNS_{ADC,\,ACC,\,max}\right)/\left(1 + V_{ADCREFHI,\,accuracy,\,min}\right)\right) - 1 \quad (8)$$

$$INOM_{max} = INOM_{typ}*\left(1 + INOM_{accuracy,\,max}\right) \quad (9)$$

Using Equations 6-9 and the relevant data sheet specifications, it can be found that the INOM threshold accuracy for INOM = 5.7A is -11.63% minimum, 11.18% maximum. Thus, the minimum INOM threshold across device variation will be 5.04A, the maximum INOM threshold will be 6.34A, and INOM = 5.7A can be reliably used without nuisance trips.

4.3 I^2T Trip Times

Equations 10-12 can be used to calculate the minimum, typical and maximum I^2T trip times.

$$I^2T_{trip,\,typ} = \frac{I2T_{TRIP}}{(IOUT)^2 - INOM_{max}^{\,2}} \quad (10)$$

$$I^2T_{trip,\,min} = \frac{I2T_{TRIP}}{\left(IOUT*\left(1 + INOM_{accuracy,\,max}\right)\right)^2 - INOM_{max}^{\,2}} \quad (11)$$

$$I^2T_{trip,\,max} = \frac{I2T_{TRIP}}{\left(IOUT*\left(1 + INOM_{accuracy,\,min}\right)\right)^2 - INOM_{min}^{\,2}} \quad (12)$$

Using Equations 10-12 and $I2T_{TRIP} = 8.8A^2s$, Table 3 can be generated to compare the minimum and maximum I^2T trip times at different relative current levels.

Table 4-3. TI Smart eFuse High-Side Switch I2T/Overcurrent Protection Trip Times for 5A Nominal Current Load

Current (A)	Opening Time min / typ / max (s)
6.27	1.043 / 1.29 / 1.65
7.695	0.266 / 0.329 / 0.422
9.12	0.140 / 0.174 / 0.222
11.4	0.0744 / 0.0903 / 0.113
19.95	.0000075 or SWCL_DLY_TMR
34.2	.0000075 or SWCL_DLY_TMR
45	.0000075 or SWCL_DLY_TMR

Reviewing Table 4-3, a few notable details stand out.

First, the TI Smart eFuse High-Side Switch minimum and maximum opening times are orders of magnitude less variable than those of the melting fuse.

Second, as the current increases, the opening time switches from being determined by the I^2T algorithm to SWCL_DLY_TMR. This is because the operating current passes into the Fixed-Delay Shutdown region, so the opening time is a software-programmable fixed time. If this behavior is not desired, the Immediate Overcurrent Protection threshold can be programmed below the Fixed-Delay Shutdown threshold or RSNS can be reduced to proportionally shift all I^2T-based thresholds, including the Fixed-Delay Shutdown threshold, higher.

Third, TI Smart eFuse High-Side Switches can open incredibly quickly (7.5us max) if the current exceeds the Immediate Overcurrent Protection threshold. This is more than four orders of magnitude faster than the melting fuse.

TPS2HCS10-Q1 features I^2T_{TRIP} thresholds from $8.8A^2s$ to $350A^2s$, allowing nearly any system-level transient current requirements to be met with one device.

5 Summary

TI Smart eFuse High-Side Switches' intuitive I^2T protection scheme, powerful functionality and enhanced feature set make switching from melting fuses simple, fast, cost-effective and inevitable for any competitive system, increasing performance and real-time feedback while improving vehicle weight, cost and efficiency.

6 References

1. *Fuseology*, littlefuse.com
2. *MICRO2 Blade Fuses - Aftermarket*, littlefuse.com