Application Note

Basics of High-Side Switches and Controllers

Samuel Skranak, Olivia Brandel, Patrick Shalton

ABSTRACT

Texas Instruments (TI) high-side power switches are power management devices with integrated protections and diagnostics, designed to drive resistive, capacitive and inductive loads. This portfolio includes high-side switches (integrated-FET), high-side switch controllers (external-FET) and smart eFuse high-side switches (integrated- or external-FET designs with I^2T-based wire harness protection). TI offers 12V, 24V and 48V portfolios, tailored to support automotive zone, body and battery management systems, as well as industrial automation and robotics.

Basics of High-Side Switches and Controllers walks through the TI high-side portfolio, outlines comparisons to other power switch designs and explains architectural and application differences. This document also provides an overview of many protection and diagnostic features. Altogether, this document provides a foundational understanding of TI high-side switches, high-side switch controllers and smart eFuse high-side switches.

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1 Introduction

At foundational levels, high-side switches and high-side switch controllers (commonly referred to as high-side gate drivers) are power management devices that drive resistive, capacitive and inductive loads. TI's portfolio of high-side power switches also provides intelligent control through diagnostics and protection mechanisms. A high-side switch integrates a MOSFET into the same package, whereas a controller provides the gate drive for external MOSFETs. The most decisive factor when selecting between an integrated or external FET solution is the current requirement. Thermal and die size constraints limit the maximum load current of a high-side switch. So, high-side switch controllers are the alternative for higher-current applications that cannot use a high-side switch. High-side switches and controllers come with different channel counts to reduce the number of devices per module, which reduces system size and cost. Furthermore, high-side switches offer a variety of MOSFET on-resistances to tailor the device to the current that the device must drive.

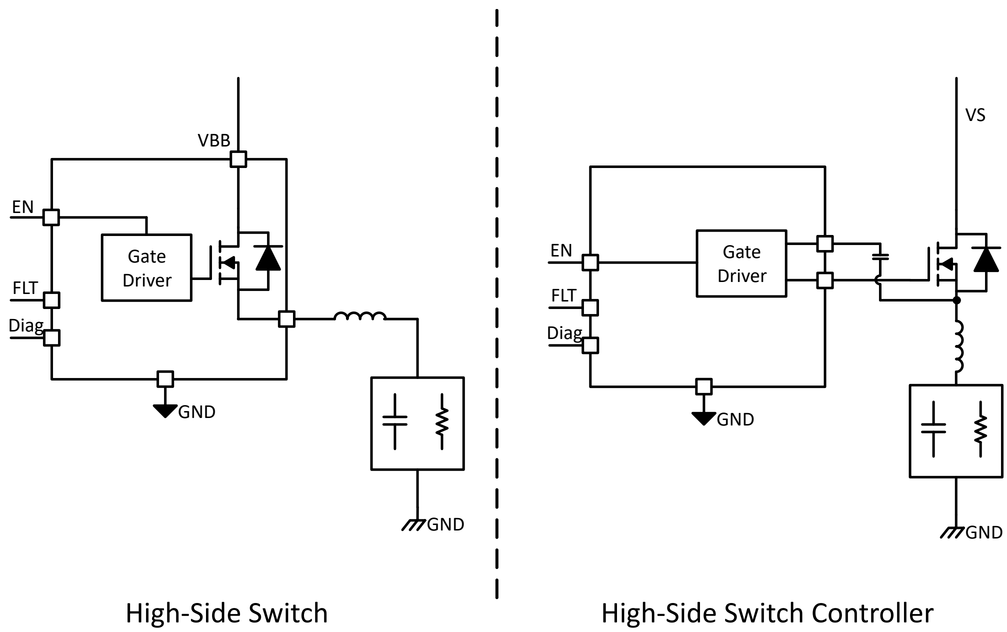

Figure 1-1. Basic Diagrams of a High-Side Switch with Integrated FET (Left) and High-Side Switch Controller with External FET (Right)

1.1 High-Side Switches Compared to Other Power Switch ICs

Switching an electrical connection between a voltage source and a load can be implemented with discrete or integrated solutions. Section 1.1.1 outlines three ways to implement a high-side switch using discrete components. The subsequent sections describe TI high-side switches versus other TI high-side ICs (load switches, hot-swap controllers, eFuses (integrated hot swaps) and motor drivers). Additionally, later subsections of Section 1 clarify TI terminology and naming conventions for power switch ICs. Figure 1-2 shows an example system block diagram featuring high-side switches and controllers in addition to other power switch ICs.

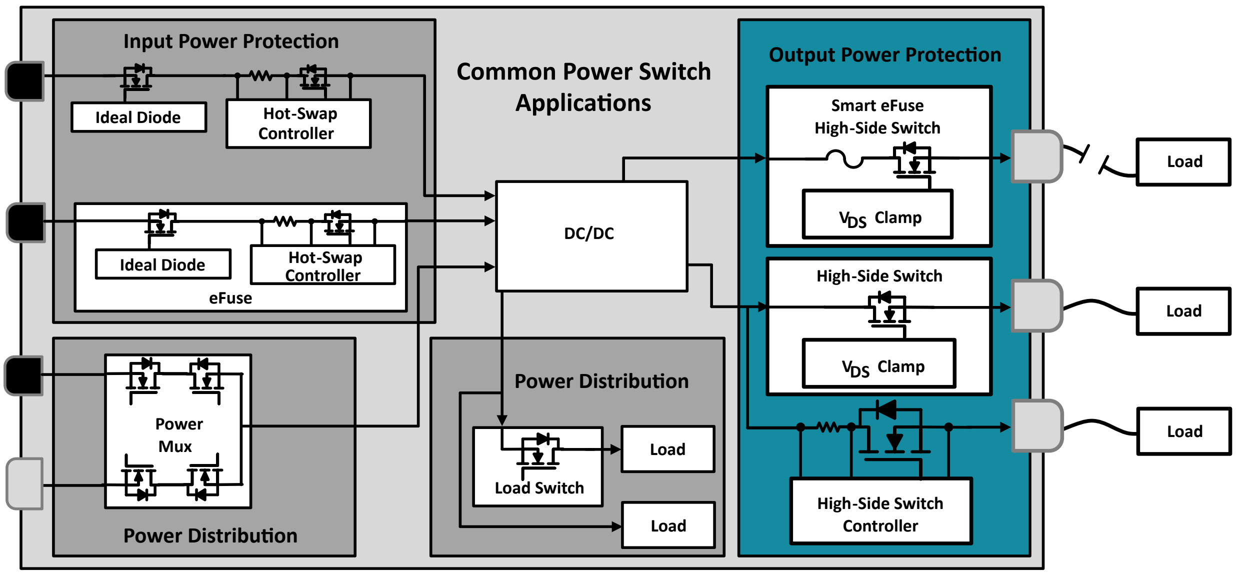

Figure 1-2. Simplified System Block Diagram Highlighting the Typical Use Cases of High-Side Switches, High-Side Switch Controllers and Smart eFuse High-Side Switches

1.1.1 Discrete High-Side Implementations

High-side switching can be implemented with a MOSFET and discrete control circuitry. To compare the solution complexity of discrete and integrated circuits, Section 1 reviews three levels of discrete implementation of a high-side switch, from simplest to most complex.

Table 1-1. Comparison of Discrete High-Side Implementations

	Level One: NFET-Controlled PFET	Level Two: NFET with a Step-Up Converter	Level Three: NFET, Step-Up Converter, Discrete Protections	High-Side Switch
Implementation	Discrete	Discrete	Discrete	Integrated
Summary	Poor thermal performance Large FET size High power dissipation	Average thermal performance High power dissipation	Large design size Complex design	Compact design size Thermally efficient packaging Integrated protections with minimal external components

1.1.1.1 Level One: NFET-Controlled PFET

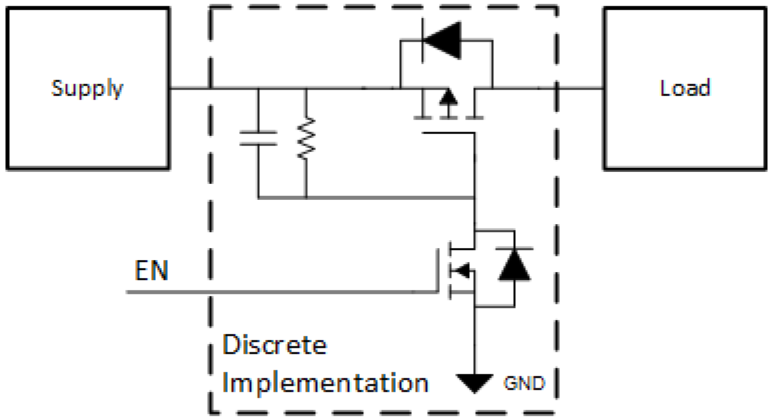

Figure 1-3. Discrete Implementation Level One: NFET-controlled PFET

The simplest discrete high-side switch implementation is a PFET pass FET which is enabled by an NFET. At the source of the PFET, there is a resistor and capacitor connected to its gate to provide slew rate control. A TVS diode can be added between the gate and the source of the PFET to keep the gate-source voltage (V_{GS}) within the PFET's absolute maximum V_{GS} limits.

This discrete circuit is highly unoptimized. First, it will have poor thermal performance as PFETs have a higher on-resistance per unit area than NFETs, making the PFET solution larger and less thermally efficient at a given load current. Moreover, the PFET may never achieve the gate-source voltage required for minimum on-resistance, which increases the necessary size of the FET at a given load current. Lastly, an enabled NFET will constantly draw current and the TVS diode will short when activated, dissipating power and leaking current at unnecessarily high levels.

1.1.1.2 Level Two: NFET with a Step-Up Converter

One way to improve the level one implementation is to use an NFET in place of the PFET and to operate it in the deep linear region. To achieve this, a step-up converter is needed to increase the gate voltage higher than the drain. While a boost converter can be used, a gate driver is more cost-, performance-, and noise-optimized. The main advantage of the level two implementation over the level one implementation is that the level two implementation has a much lower on-resistance per unit area and is more thermally efficient, so a smaller transistor can be used for the power MOSFET.

1.1.1.3 Level Three: NFET, Step-Up Converter and Discretely Implemented Protections and Diagnostics

In the final discrete implementation, there is an N-channel MOSFET and a gate driver like implementation level two, but this design includes additional circuitry around the MOSFET to provide different protections. Inductive clamping is achieved with an external TVS or flyback diode on the output. Both the current limit and the current sense are implemented with a sense resistor and amplifier. The current limit can be implemented either with an MCU ADC, which measures the current against a programmable threshold, or with a comparator with the output OR'd with the EN signal to control the EN pin. Overtemperature protection can be implemented with a temperature sense IC or a BJT placed near the pass FET.

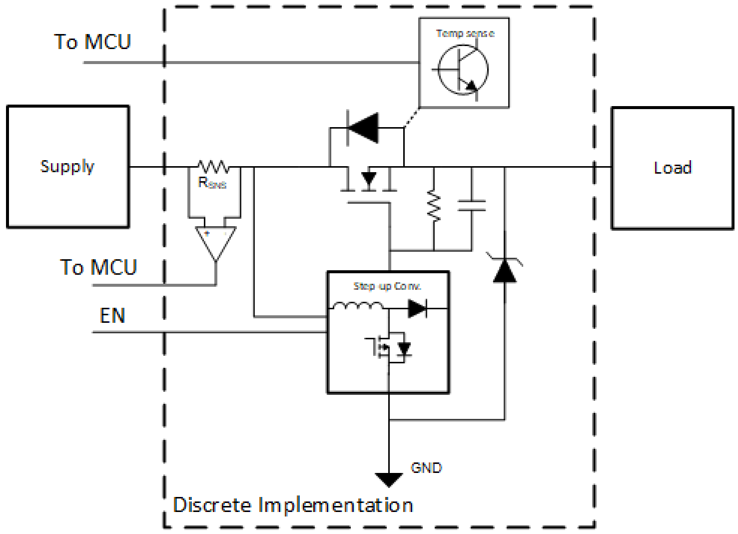

Figure 1-4. Discrete Implementation Level Three: NFET, Step-up Converter and Discretely Implemented Protection

While a discrete design is feasible, the cost and size of all the physical components significantly surpass that of an integrated design. In addition, there is higher engineering costs since the design requires more engineering effort than an integrated circuit.

1.1.2 Comparison to Load Switches

TI's load switches and high-side switches are both integrated high-side power switch integrated circuits (ICs) that connect a voltage source to an electrical load. Both have an integrated MOSFET and charge pump. Since the basic concept is the same, it is common to see other manufacturers use these names interchangeably. In TI's portfolio, the switches have different names because they offer different baseline specifications and feature sets, each tailored to the target use case. Load switches are low-voltage switches, designed to drive on-board loads in 3.3V, 5V or 12V systems. On-board loads are in a more controlled environment, so the load switch can meet system requirements with minimal protection features. Common protection features include slew rate control, thermal protection and quick output discharge. Some devices may also offer features like short circuit protection, reverse current protection or current monitoring.

In contrast, the high-side switch is a fully protected, feature-rich device optimized for driving off-board loads in 12V, 24V or 48V systems. The devices must withstand tougher voltage and current transients on unregulated rails. High-side switches are designed to drive all types of electrical loads, enduring capacitive inrush currents and kickback from inductive loads. Often supplied by off-board sources and driving off-board loads, the high-side switch needs to have more extensive protection features and diagnostic capabilities. Section 3 and Section 4 discuss these features in more detail. Table 1-2 provides a comparison between high-side switches and load switches and lists the extensive protection and diagnostic features of high-side switches.

Table 1-2. Comparison of High-Side Switches and Load Switches

	High-Side Switch	Load Switch
FET Configuration	Internal	Internal
Typical Input Voltages Supported	12V, 24V, 48V	3.3V, 5V
Typical Output Current Capability	750mA–10A	200mA–15A
Typical Use Case	*Off-board* load driving and power distribution	*On-board* load driving and power distribution
Protection Features	Adjustable current limit Overvoltage protection * Reverse current blocking* Undervoltage lockout (UVLO) Absolute thermal shutdown Relative thermal shutdown Loss-of-GND, loss-of-supply protection Reverse battery protection Inductive discharge clamp	Current limit* Overvoltage protection* Reverse current blocking* UVLO Thermal shutdown
Other Features	Fault output Analog current sensing ON and OFF state open-load and short-to-battery detection Overload and short-to-ground detection UL recognition1	Quick output discharge Power good pin Slew rate control
Interface	GPIO or SPI	GPIO
AEC-Q100 Qualification Available	Yes	Yes

1. *Available only in select devices.

1.1.3 Comparison to Hot-Swap Controllers and eFuses (Integrated Hot Swaps)

In the industrial and enterprise markets, the name *eFuse* or *integrated hot swap* typically describes an integrated-FET input power protection IC (for example, TPS2663). eFuses (integrated hot swaps) provide voltage and current protection during fault events like short-circuit, overcurrent, overvoltage, undervoltage and overtemperature events that might otherwise damage downstream loads. eFuses typically protect the input of a system, preventing damage to on-board loads. In contrast, high-side switches typically perform output power protection, preventing off-board load damage during similar fault events.

However, at a basic level, both are high-side internal-FET power switches. For example, in a PLC analog input module, an engineer may select an eFuse (integrated hot swap) to protect against miswiring at an output power port for field transmitters. A high-side switch can also provide simple current limiting at the input of a system, especially where overvoltage is not a concern. While load switches, eFuses (integrated hot swaps) or high-side

switches may work for the same application (depending on the voltage and current requirements), these devices often have tailored feature sets for either input or output protection.

eFuses (integrated hot swaps) for industrial applications often offer overvoltage protection, integrated back-to-back FETs for reverse current blocking and UL 2367 recognition. Reverse current blocking also allows eFuses (integrated hot swaps) and load switches to support input power multiplexing (or power muxing). Read more on this topic in *Power Multiplexing Using Load Switches and eFuses*. To learn more about eFuses (integrated hot swaps), see *Basics of eFuses*.

For output power protection, high-side switches integrate features like inductive discharge clamps, load dump compatibility and open-load or wire-break detection. Some high-side switches, such asTPS274C65, have the capability to drive an external FET for reverse current blocking. This feature is useful for applications like PLC digital output modules, which may encounter miswiring conditions at the output ports.

External-FET designs such as high-side switch controllers and hot-swap controllers have a similar relationship to the corresponding integrated-FET solutions. Hot-swap controllers, designed to protect a system input, provide current limiting and input transient handling during hot-swap or hot-plug events. Hot-swap controllers typically have lower overall gate drive because their primary purpose is inrush current control. High-side switch controllers, designed for both output protection (for high-current off-board load driving) and input protection, offer strong overall gate drive and transient handling for both output and input. High-side switch controllers also have bi-directional functionality. For example, TPS1212-Q1, with bidirectional current capability, is advantageous in applications that wish to protect the input power source but occasionally allow current to flow back to the source (say, to charge a battery). Another distinguishing behavior between high-side switch controllers and hot-swap controllers is the overcurrent response. High-side switch controllers do not clamp current in the typical current-limiting fashion of a hot-swap controller. Instead, they provide a circuit breaker functionality or emulate a melting fuse. An emerging programmable fuse profile in the automotive industry is I^2T, where I is current and T is time.

The automotive market typically refers to a high-side switch or controller with I^2T protection as an *eFuse* or *smart fuse*. This document refers to high-side switches or controllers with I^2T as “smart eFuse high-side switches” to distinguish them from TI eFuses (integrated hot swaps). Section 4.5 discusses the features, protections and use cases of TI’s smart eFuse high-side switches in greater depth.

Table 1-3 lists a comparison between high-side switches, high-side switch controllers, smart eFuse high-side switches, hot-swap controllers and eFuses (integrated hot swaps). Section 3.1.1 further describes the distinct overcurrent behaviors of high-side switches and high-side switch controllers.

Table 1-3. Comparison of High-Side Switches and Hot-Swap Controllers and eFuses (Integrated Hot Swaps)

Features [1] and Configurations	High-Side Switch	High-Side Switch Controller	Smart eFuse High-Side Switch	eFuses (Integrated Hot Swap)	Hot-Swap Controller
FET Configuration	Internal	External	Internal or External	Internal	External
Reverse Current Blocking (in ON and OFF state)	Yes [2]	No [3]	No	Yes [2]	Yes [2]
Input Reverse Polarity Protection	No	Yes	Yes [4]	Yes [2]	No
Output Reverse Polarity Protection	No	Yes [2]	Yes [4]	No	No
Overcurrent Protection (OCP) Behavior [5]	Current Limit	Circuit Breaker	Regulated Current (Based on I^2T fuse profile)	Circuit Breaker, Current Limit, or Power Limit	Circuit Breaker, Current Limit, or Power Limit
Overvoltage Protection	Yes [2]	Yes [2]	No	Yes	Yes
Inductive discharge clamp	Yes	No	Yes	No	No
Bidirectional current capability available	No	Yes [2,6]	Yes [4]	Yes [2,7]	No
Automotive load dump compatibility	Yes	Yes	Yes	No	No
UL Recognition	Yes [2]	No	No	Yes	No
Interface	GPIO or SPI	GPIO	GPIO or SPI	GPIO or PMBus	GPIO or PMBus
AEC-Q100 Qualification	Yes	Yes	Yes	Yes [2]	Yes [2]

1. A *yes* indicates that a feature is commonly available for that product family.
2. Available in only select devices.
3. In on-state, high-side switch controllers can detect reverse current and signal the MCU to act, but they do not have an integrated protection scheme
4. Applies to external-FET devices only.
5. Current limiting clamps the output current at a specific value; the value can be programmable or fixed. I^2T protection turns off the output current according to a specific current-time profile.
6. Bidirectional current monitoring only
7. Bidirectional power delivery in steady-state to support USB OTG or DRP operation

1.1.4 Comparison to Motor Drivers and Gate Drivers

This document specifically focuses on high-side switches and high-side switch controllers, which integrate a charge pump to enable always-on operation. These are distinct from TI's portfolio of half-bridge gate drivers, which require bootstrap circuitry or external biasing. Additionally, the high-side switch and high-side switch controller portfolios contain high-side channels only and are not configurable as half-bridge or low-side switches. High-side switches and controllers are designed to drive a broad range of possible loads (resistive, capacitive, or inductive). While high-side switches can drive motors in a single direction, like a fan, they are not targeted for motors requiring more advanced control, like BLDC or stepper motors. For more information on these other product portfolios, see *Selecting the right level of integration to meet motor design requirements* or the view the overview pages for *Gate Drivers* or *Motor Drivers*.

1.1.5 Summary

Section 1.1 outlined the terminology and use cases for high-side switches and controllers as compared to other power switches and similar ICs. Table 1-4 summarizes the use cases and key differentiating features of these ICs.

Table 1-4. Common Use Cases and Key Differentiators of Power Switch ICs

IC Type	Most Common Use Case	Key Differentiators
High-Side Switch	Off-board load driving Output power protection (12V–48V) 12V–48V power distribution	Integrated inductive discharge clamp Overcurrent protection Load diagnostics
High-Side Switch Controllers	High-current off-board load driving High-current 12V–48V power distribution Output power protection (12V–48V) Circuit breaking / battery disconnect	Circuit-breaker overcurrent protection Bidirectional current monitoring
eFuses and Hot-Swap Controllers	Input power protection (5V–48V) Hot-swapping or hot-plugging	Overcurrent and overvoltage protection
Load Switches	On-board load driving (3.3V–5V) Power sequencing for processors	Quick output discharge Slew rate control Compact packaging
Motor Drivers	Motor driving and control	Integrated motor control circuitry Specialized features by motor type (brushed, brushless, stepper, and so on.)
Gate Drivers	High-frequency switching	Requires bootstrap circuitry or external biasing

1.2 Common Automotive and Industrial Standards

1.2.1 Typical Automotive Voltage Ranges

Up until the 1950s, most cars used 6V. However, when engines increased in size and power, the engines needed more power to start, and thus the automotive industry adopted 12V as the standard battery voltage.

Since then, 12V has been ubiquitous in cars, trucks and two-wheelers, giving rise to a rich ecosystem of batteries, electronic components and wire selections optimized for using a 12V supply. It is at this system voltage where TI has a broad portfolio of high-side switches, high-side switch controllers and smart eFuse high-side switches. The 12V portfolio's supply voltages are minimally rated for 18V nominal maximum and 28V operating maximum, along with 35V load dump.

To optimize cabling and power distribution, reduce vehicle cost and weight and improve efficiency, automakers are adopting a 48V battery and power architecture for high-power loads. This voltage can deliver more power with a given cable gauge. Since 48V is new to the road, battery technology and power architecture require further honing and optimization.

TI has portfolios of high side-switches, high-side switch controllers and smart eFuse high-side switches intended for 48V systems. The 48V portfolio's supply voltages are minimally rated for 58V nominal maximum and 65V absolute maximum, while some have up to 70V absolute maximum. Transient voltage ratings can also be higher, around 80V. TI's 48V portfolio can also accommodate automotive 24V battery systems. Figure 1-5 summarizes the voltage thresholds for typical automotive systems.

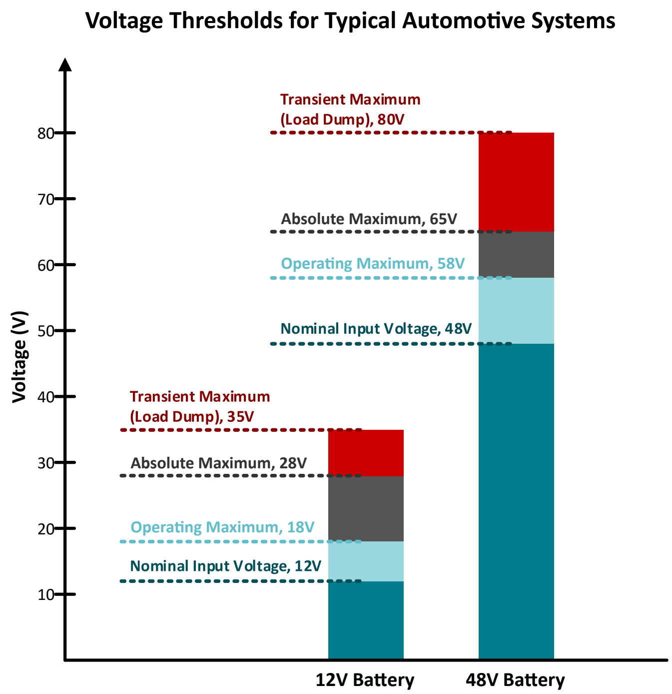

Figure 1-5. Voltage Thresholds for Typical Automotive Systems

1.2.2 Typical Industrial Voltage Ranges

For decades, factory equipment and industrial control systems have used a 24V supply, which provides high output power and noise immunity with minimal supply dips due to load transients while being safe to touch with bare skin. This standard operating voltage has evolved into different standards over time.

All TI catalog (industrial) high-side switches support 24V operation, with minimum operating voltage ratings of 36V operating maximum and 40V absolute maximum. Some earlier generations of TI automotive high-side switches (such as TPS27S100) are rated for 40V recommended maximum and 48V absolute maximum, making these devices preferred for industrial 24V systems. Some safety-critical industrial systems implement Safety Extra-Low Voltage (SELV) circuits, which require a higher high-side switch voltage tolerance of 60V. Section

1.2.4 discusses SELV requirements in more detail. Figure 1-6 summarizes the voltage thresholds for typical industrial automation systems.

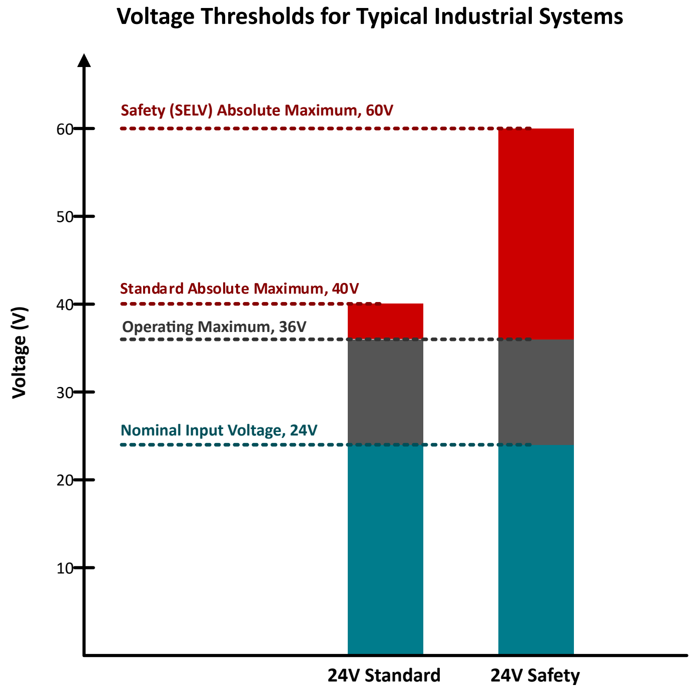

Figure 1-6. Voltage Thresholds for Typical Industrial Systems

1.2.3 Automotive Qualifications and Standards

The Automotive Electronics Council's AEC-Q100 qualification is a thorough set of quality requirements and stress tests that verify integrated circuits can perform reliably over the lifetime of automotive applications. These tests cover wire bond stresses, ESD immunity, latch-up immunity, non-volatile memory functionality, fault and early failure considerations, short circuit reliability and more. Additionally, AEC-Q100 sets standardized operating temperature ranges, required quality documents, devices characterization and testing guidelines to maximize quality control. All TI automotive-rated devices are AEC-Q100 qualified.

The International Organization for Standardization's (ISO) ISO7637 standard characterizes conducted supply and output transients commonly seen in automotive systems and provides background and test procedures for evaluating an IC's robustness towards these transients. If an IC cannot withstand the required level of energy dissipation for these pulses, external protections must be implemented at the application level. TI's automotive high-side switches are rated for ISO7637-2 pulse tolerance.

The ISO16750 standard details environmental stresses on automotive electrical, mechanical, climate and chemical systems. For example, ISO16750-2 (for electrical systems and loads) includes one test known as load dump, a long voltage transient that occurs when the battery stops providing power to a load or the battery is disconnected while the alternator is still charging the battery. All of TI's automotive high-side switches, controllers and smart eFuse high-side switches meet the load dump requirements for the respective voltage domains.

Another automotive ISO standard is ISO26262, which details automotive Functional Safety. This standard defines a rigorous methodology focused on minimizing the frequency and severity of danger to human lives. Read more about this topic on TI's Functional Safety homepage.

Other standards include the International Automotive Task Force's (IATF) IATF16949, which standardizes the assessment and certification methodology used by automotive systems and components, and the International Electrotechnical Commission's (IEC) CISPR25, a widespread vehicle EMI requirement which details test limits for conductive emissions and immunity.

1.2.4 Industrial Qualifications and Standards

The IEC61000-4 group of standards test IC immunity to different voltage transient events, including electrostatic discharge (ESD) (IEC61000-4-2), electrical fast transients (EFT) (IEC61000-4-4) and surge (IEC61000-4-5). Many TI catalog high-side switches are tested in accordance with IEC61000-4.

The IEC also defines SELV systems which are commonly used in safety-critical factory systems. A criterion of SELV power supplies is that, if this fails, the output must never exceed 60V DC. SELV verifies that no high-voltage conductors can be contacted by humans, no current return path is available for a high-voltage contact point and no live conductors are connected to earth ground. TPS281C30 and TPS281C100 are rated for >60V absolute maximum voltage to be used in SELV systems such as safety PLCs.

Underwriters Laboratories UL2637 is a certification for switches that are used for current-limiting applications, showing that the ICs can perform reliably while protecting downstream components.

TI's TPS272C45 has UL2637 certification to help simplify design cycles and enable fast time to market.

Similar to automotive applications, industrial applications also have EMI standards. A common one is CISPR32, a widespread standard that details test limits for radiated and conducted emissions and immunity.

2 Architectural and Application Differences of High-Side Switches and Controllers

2.1 Architecture Differences

The main difference between high-side switches and high-side switch controllers is the integration of the main FET (as shown in Figure 1-1). This fundamental difference allows for high-side switches to be optimized around low cost and solution size, whereas high-side switch controllers excel at configurability and very high current driving. Section 2.1 describes these differences in more detail, beginning with a summary in Table 2-1.

Table 2-1. High-Side Switch and Controller Architecture Differences

	High-Side Switch	High-Side Switch Controller
FET Configuration	Internal	External
Gate Control	Internal	External [1]
Maximum Current	Internally limited	Limited by external FET choice
Overcurrent Behavior	Current limiting	Circuit breaker
Current Sense Implementation	Fully internal, with the exception of the externally set resistors	External current sense shunt resistor or MOSFET on-resistance sensing
Directionality	Unidirectional	Bidirectional [2]
Inductive Discharging	Integrated inductive clamp	None
FET Temperature Sensing	Integrated monitoring	Remote monitoring (using BJT or NTC)

1. External gate control allows arbitrary slew rate manipulation, fast pulse-width modulation (PWM) and driving multiple MOSFET gates in parallel.
2. Back-to-back MOSFET drive enables reverse current blocking, bi-directional current monitoring and pre-charging large capacitances.

In high-side switches, since the FET is internal, the gate and gate driver are also completely internal for maximum performance and reliability. The high-side switch's turn-on and turn-off slew rates are determined by internal circuitry as a result. In high-side switch controllers, the gate driver output is inherently exposed, allowing for arbitrary slew rate manipulation, fast pulse-width modulation (PWM) and driving multiple MOSFET gates in parallel.

Since the high-side switch's maximum current is largely determined by the internal FET, the current limit and current sense architectures can be fully internal, with the exception of the externally set resistors. This allows for a relatively high level of programmability while maintaining overall design simplicity. In contrast, high-side switch controllers are developed for arbitrary current driving and do not conduct load current themselves, so the current limit and current sense architectures must be arbitrarily programmable as well. This can be accomplished two ways: using a current sense shunt resistor or the MOSFET on-resistance sensing. The current sense resistor or MOSFET voltage drop is sensed, then converted to a current, which is then converted back to a voltage via an external resistor. The voltage is then compared to an internal threshold for current limiting and read by an external ADC for current sensing. This allows for multiple points of flexibility—the current sense resistor can be chosen to minimize input voltage drop and cost, while the higher-value current limit resistor can be chosen for precise threshold control, enabling currents to be accurately sensed from under 1A to kA.

High-side switches are designed to unidirectionally provide power to a downstream load. In contrast, high-side switch controllers can control back-to-back MOSFETs, enabling important abilities such as reverse current blocking, bidirectional current control and pre-charge for large output capacitances. High-side switches cannot block reverse current with only one power FET, but the high-side switches can charge large load capacitances through the constant current capacitive charging feature. (Note: TPS274C65 has an integrated driver for an external blocking FET). Additionally, high-side switch controllers cannot inherently discharge inductive loads or regulate a constant current like high-side switches can.

The FET and controller temperatures of a high-side switch can be easily monitored because the FET is internal. High-side switch controllers must monitor the FET temperature remotely via a BJT or negative temperature coefficient (NTC) thermistor.

2.2 Application Differences

High-side switches and controllers are generally used to power off-board loads or loads that are nonlocal to the module with the high-side driving device. High-side switch controllers can also be used as an input protection device as well. Section 2.2 reviews the factors at play when deciding between power switch devices in load driving and input protection applications, beginning with a summary in Table 2-2.

Table 2-2. Application Differences of High-Side Switches and Controllers

	Typical Applications	Key Differentiators
High-Side Switch	<15A load driving	Integrated FET Adjustable current limiting OCP Load diagnostics
High-Side Switch Controller	>15A load driving (or lower-current loads with high inrush current demands) Battery disconnection DC/DC converter disconnection	External FET Circuit breaker OCP Back-to-back FET driving capability Bi-directional current monitoring Reverse polarity protection

2.2.1 Load Driving

For off-board load driving, the decision between a high-side switch or high-side switch controller is fairly simple. Both feature sets overlap to a high enough degree that the decision is based on load current. Wherever possible, it is recommended to use a high-side switch for the simplest design. Additionally, an integrated-FET design is usually more cost-competitive than an external FET solution. However, quite often, such as in automotive power distribution boxes, loads require a nominal current too high for any integrated solution. In this case, as well as parallel-FET cases, a high-side switch controller is more appropriate. There are also edge cases where a nominal load current can be controlled through a high-side switch, but the inrush demands are too high. In these cases, a high-side switch controller is also a good fit.

2.2.2 Input Protection and Circuit Breaking

Two functions unique to the high-side switch controllers are input protection and circuit breaking. For high-current input protection, high-side switch controllers sit at the output of a DC/DC converter or battery. Here, high-side switch controllers provide inrush current control and either short circuit protection (in the forward direction) or reverse current blocking, depending on the configuration. In the short circuit protection configuration, the overcurrent response type is latch-off and requires MCU intervention to turn the device back on. If a system requires both reverse current blocking *and* reverse short-circuit protection, one can combine a high-side switch controller and an ideal diode controller. Or, alternatively, use an ideal diode controller which has both features integrated. Both ideal diode controllers and high-side switch controllers are common choices for automotive input power protection because they offer high current capability and automotive AEC-Q100 qualification. Devices designed for input protection, like ideal diode controllers and hot-swap controllers, prioritize a stronger sink current to enable fast turn-off. High-side switch controllers often feature both strong source current and strong sink current, enabling their use for both input protection and output protection. For lower-current input protection applications, especially in industrial or enterprise applications, eFuses (integrated hot swaps) are more common solutions due to their compact size and power density advantage.

Table 2-3 summarizes the key differences between a high-side switch controller and ideal diode controller. To learn more about ideal diode controllers, see *Basics of Ideal Diodes*. Similar to the input protection function, high-side switch controllers can also perform circuit breaker functionality. For a DC/DC circuit breaker application, one can use two back-to-back FET high-side switch controllers on either side of the DC/DC converter. In this configuration, the high-side switch controllers control inrush current, manage overvoltage conditions and block current both upstream and downstream from the DC/DC converter.

Due to the bi-directional nature of this application, high-side switch controllers with bi-directional current monitoring and I^2T-based short-circuit protection offer optimal protection. For circuit breaker functionality in a battery management system (BMS), one can use a high-side switch controller on the positive battery rail. A high-side switch controller with back-to-back FETs allows independent control of the charge and discharge paths. Additionally, in this BMS disconnect switch configuration, high-side switch controllers offer low quiescent current, reverse polarity protection (input and output) and current sensing. Automotive DC/DC and BMS circuit breaker applications are typically high-current (around 150A with 1kA peak) and thus require external-FET designs.

Table 2-3. High-Side Switch Controller and Ideal Diode Controller Comparison

	High-Side Switch Controller	Ideal Diode Controller
FET Configuration	External (single or back-to-back)	External (single or back-to-back)
Typical Source Current	0.5A–3.7A	0.011A–0.06A
Typical Sink Current	2A–4A	1.5A–2.7A
Reverse Current Blocking (in ON and OFF state)	No [1]	Yes
Input Reverse Polarity Protection	Yes	Yes
Output Reverse Polarity Protection	Yes [2]	No
OCP Behavior [3]	Circuit Breaker	Circuit Breaker [2]
Overvoltage Protection	Yes [2]	Yes [2]
Automotive load dump compatibility	Yes	Yes

1. In on-state, high-side switch controllers can detect reverse current and signal the MCU to act, but they do not have an integrated protection scheme.
2. Available only in select devices
3. Current limiting clamps the output current at a specific value; the value can be programmable or fixed. I^2T protection turns off the output current according to a specific current-time profile

2.3 Summary and Product Family Selection Matrix

To select among TI's high-side switch and controller portfolio, focus on the primary application of the device. For low- to mid-current load driving and power distribution, look to the highly integrated high-side switches. For high-current load driving and disconnect switching, leverage the flexibility of external-FET high-side switch controllers. When seeking to emulate a traditional melting fuse or optimize wire harnesses, utilize the integrated I^2T -based overcurrent protection of smart eFuse high-side switches.

If unsure about using a high-side switch or controller versus another power switch product family, consider the system design and these four key factors:

1. **Location of the power switch** (output power protection or input power protection)
2. **System input voltage** (for example, 12V or 48V battery)
3. **Desired overcurrent behavior** (to limit current, break the circuit, or emulate a melting fuse)
4. **Output current** (determines internal or external FET)

Determining the location of the power switch and the desired overcurrent behavior (if any) focuses the selection on product families with optimal feature sets. The required output current steers the selection toward internal- or external-FET product families. This is no fixed threshold for what output current necessitates an internal- versus external-FET product. TI releases new devices regularly, so check product selection tables to see the maximum output current available at a given time. If not high enough, consider an external-FET device instead. Lastly, considering the system input voltage narrows down the selection to product families that typically support that voltage range. Similar to the output current, this can change over time as TI releases new products, so check the product selection tables for the latest options available.

Table 2-4 summarizes this methodology visually as a product family selection matrix. Once the product family is selected, find a specific device by utilizing the product selection tables on TI.com to filter parameters, features, package types and package sizes.

Table 2-4. Product Family Selection Matrix for High-Side Power Switches

<table>
<tr><th rowspan="2">Voltage</th><th colspan="3">Output Protection</th><th colspan="5">Input Protection</th></tr>
<tr><th>OCP: Current limit</th><th>OCP: Circuit breaker</th><th>OCP: I^2T</th><th>OCP: Current limit</th><th>OCP: Circuit breaker</th><th>OCP + Reverse Current Blocking</th><th>Reverse Current Blocking</th><th>Reverse Current Monitoring</th></tr>
<tr><td>3V–5V</td><td>Load switch</td><td>X</td><td>X</td><td>eFuse (integrated hot swap)</td><td>eFuse (integrated hot swap)</td><td>eFuse (integrated hot swap)</td><td rowspan="4">Ideal diode/ ORing controller</td><td>X</td></tr>
<tr><td>12V</td><td rowspan="3">High-side switch</td><td rowspan="3">High-side switch controller</td><td rowspan="3">Internal FET: Smart eFuse high-side switch External FET: Smart eFuse high-side switch</td><td rowspan="2">Internal FET: eFuse (integrated hot-swap) External FET: Hot-swap controller</td><td rowspan="3">Internal FET: eFuse (integrated hot-swap) External FET: Hot-swap controller or high-side switch controller</td><td>Internal FET: eFuse (integrated hot swap) External FET: Hot-swap controller or select ideal diode controllers</td><td rowspan="3">High-side switch controller</td></tr>
<tr><td>24V</td><td rowspan="2">Internal FET: eFuse (integrated hot swap) External FET: Select ideal diode controllers</td></tr>
<tr><td>48V</td><td>eFuse (integrated hot swap)</td></tr>
</table>

3 Core Features of High-Side Switches and Controllers

Typical features of high-side switches and controllers fall into two categories: protection features and diagnostic features. Protection features act during fault conditions. In contrast, diagnostic features only identify and report fault conditions. Since both types of features are centered on load and fault status, detection and protection mechanisms are integrated together. Section 3 explores core protection and diagnostic features that are common in most TI high-side switches and controllers (summarized in Table 3-1).

Table 3-1. Core Features of High-Side Switches and Controllers

Protection Features	Diagnostic Features
Overcurrent protection (OCP)	Current sensing
Thermal shutdown (absolute and relative)	Voltage sensing
Undervoltage lockout (UVLO)	Open-load detection
Overvoltage lockout (OVLO)	Short-to-battery detection
Inductive load handling	Junction temperature sensing
Reverse polarity protection	

3.1 Protection Features

3.1.1 Overcurrent Protection

The most typical form of overcurrent protection in high-side switches is the *current limiting* response. The integrated MOSFET modulates the output current to a safe level during a fault condition. Traditional high-side switches have an internally fixed current limit that is set very high to accommodate broad load requirements. Many of TI high-side switches offer an adjustable current-limit range that is lower than traditional fixed current limits. A lower current limit setting can greatly reduce the fault energy and output current during a short-circuit or a partial load short (soft short). By lowering fault energy and current, the overall system improves through:

- Reduced size and cost (in current carrying components such as PCB traces and module connectors)
- Less disturbance at the power supply (VS pin) during a short circuit event
- Less additional budget for the power supply to account for overload currents in one channel or more
- Improved protection of the downstream load

In most TI high-side switches, the current limit is adjustable with an external resistor. In devices with telemetry, this current limit is programmable. For further reading on this topic, see *Adjustable Current Limit of Smart Power Switches*.

In recent generations of high-side switches, there are additional methods of current limitation. While clamping current at a set level is still the primary response in the TI portfolio, there is a variation of clamping where the current limit is dynamically controlled to limit the difference between the controller of the device and FET temperatures and prevent the device from entering relative thermal shutdown. This dynamic clamping feature is called thermal regulation, and it enables the device to charge larger capacitive loads and charge the same capacitive load for longer before shutdown.

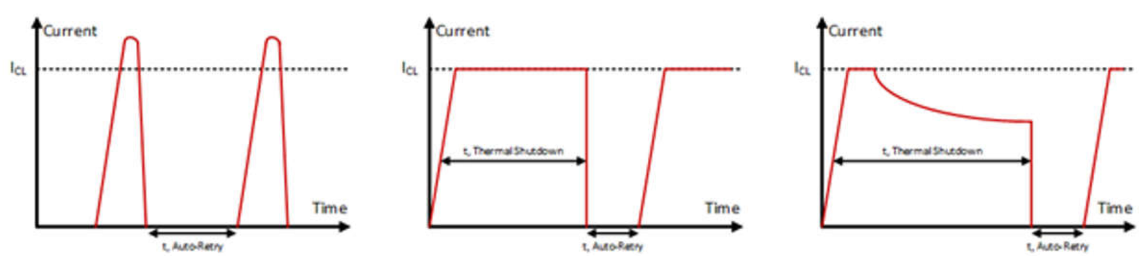

Figure 3-1. Current vs Time Graphs for Three Different Current Limit Responses: Immediate Shutdown (Circuit Breaker) (Left), Current Clamping (Middle), and Current Clamping with Thermal Regulation (Right)

3.1.2 Thermal Shutdown

3.1.2.1 Absolute Thermal Shutdown

Overtemperature conditions can happen in high-side switches for an array of reasons: sustained overcurrent, high power dissipation due to current clamping, environmental factors, PCB heating due to nearby components and more. In order to prevent permanent damage during overtemperature events, high-side switches and high-side switch controllers must be able to detect overtemperature conditions and turn the main FET off when they occur. High-side switches and controllers do this in two different ways.

High-side switches have a temperature sensor on the device controller. When the controller temperature reaches a certain level, typically above 150°C, the device detects it and shuts off the FET within microseconds. Repeated occurrences of thermal shutdown do not jeopardize the reliability of TI high-side switches.

High-side switch controllers do not need to monitor their temperature because the devices themselves do not dissipate a significant amount of power. Instead, high-side switch controllers need to monitor the external FET's temperature, which they do via a BJT or NTC thermistor placed next to the FETs. Similarly, if the FET temperature rises above 150°C, the device immediately shuts off.

3.1.2.2 Relative Thermal Shutdown

In the case of high-side switches, as heat takes time to travel from the FET to the controller, TI high-side switches implement a second type of thermal shutdown: relative thermal shutdown. This implementation uses a second temperature sensor on the FET and compares the FET temperature to the controller temperature. If the temperature difference exceeds a certain amount, typically around 60°C, the device shuts off and reenables when the temperature difference decreases. Relative thermal shutdown only happens when there is a very fast and large load current increase, and thus relative thermal shutdown acts with the current limit to provide short-to-ground protection.

3.1.2.3 Undervoltage Lockout and Overvoltage Lockout (UVLO and OVLO)

Most modern integrated circuits, including TI high-side switches, include an undervoltage lockout circuit to ensure the device is powered down into a known and safe state below a certain input voltage. TI high-side switches feature a low UVLO threshold that allows for high performance during common industry events, such as automotive cold crank.

Some TI high-side switches and controllers also include overvoltage lockout, where the output will be turned off when the input voltage is above a certain value (for example, TPS281C30 and TPS4811-Q1). OVLO requirements are typically driven by industrial SELV standards and automotive 48V operating ranges.

3.1.2.4 Inductive Clamping

Inductors resist changes in current when an external voltage is applied. Driving inductive loads results in two important behaviors: slower current slew rates during turn-on and output pull-down during inductive turn-off. During turn-on, a slower current slew rate allows for more time for the device to detect overcurrent events, so inductance does not present an issue.

However, when a high-side switch is turned off while driving an inductive load, the inductor will resist the decrease in current. In an ideal case, when the high-side switch is turned off, the current will instantaneously go to 0A. Using Equation 1, we can evaluate what the inductor voltage will be when this happens.

$$V_{inductor} = L_{inductor} \times \frac{dI}{dt}_{inductor} \quad (1)$$

When the current immediately decreases from a nonzero value to 0, $dI/dt_{inductor}$ is negative infinity, and thus $V_{inductor}$ is negative infinity volts. Since ground is a stable reference, the output node of the high-side switch will be pulled to negative infinity volts and cause component and system damage. In reality, all nodes have some amount of parasitic capacitance. Good analog design dictates using decoupling and ESD capacitors, but these capacitances are small and can only reduce the current slew rate by a marginal amount. Thus, when an inductive load is turned off by a high-side switch, the positive node of the load is pulled quickly to a highly negative value. To protect the high-side switch and surrounding circuitry, TI high-side switches implement a dynamic drain-source clamp called the VDS clamp. This circuitry partially turns on the FET when the FET source reaches a certain voltage below the drain—typically around 40V—limiting the drain-source voltage to the VDS clamp voltage and quickly discharging the energy stored in the inductor.

The VDS clamp feature provides an elegant, integrated design for quickly dissipating inductive energy in an inductive load. However, when the VDS clamp activates, it causes high power dissipation in the FET which can damage the device if activated for too long, and thus the VDS clamp can only safely dissipate a certain amount of inductive energy. If the maximum inductive energy of the load exceeds the discharge rating of the high-side switch, an external design such as a flyback diode or TVS clamp must be used.

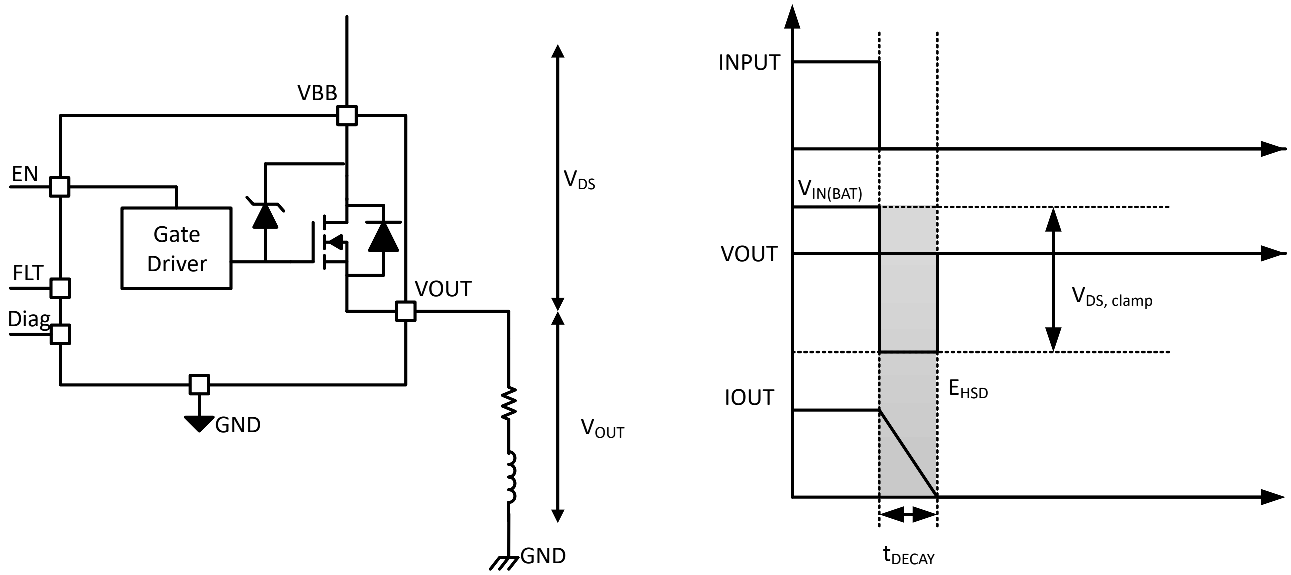

Figure 3-2. Simplified Schematic (left) and Timing Diagram (right) of a High-Side Switch Driving an Inductive Load

3.1.3 Reverse Polarity Protection

Reverse polarity conditions can occur at the input or output of a system. For input reverse polarity protection, a PFET, discrete diode or input protection IC is placed in series with the system input. When a reverse polarity event occurs at the input, such as when an automotive battery is mis-wired, the input blocking device becomes high-impedance and prevents all current flow, protecting the devices on the board. TI reverse polarity protectors (such as LM74500-Q1) or ideal diode controllers (such as LM74700-Q1) are recommended for input reverse polarity protection. TI high-side switches and controllers implement features for output reverse polarity protection.

3.1.3.1 Ground Networks

In addition to input reverse polarity protection, ground networks are another way to protect high-side switches from input reverse polarity conditions. Ground networks utilize a resistor and diode in parallel to connect the high-side switch IC ground to system ground. This limits the current into the device GND pin during reverse polarity conditions but allows for normal operation when the input is connected properly.

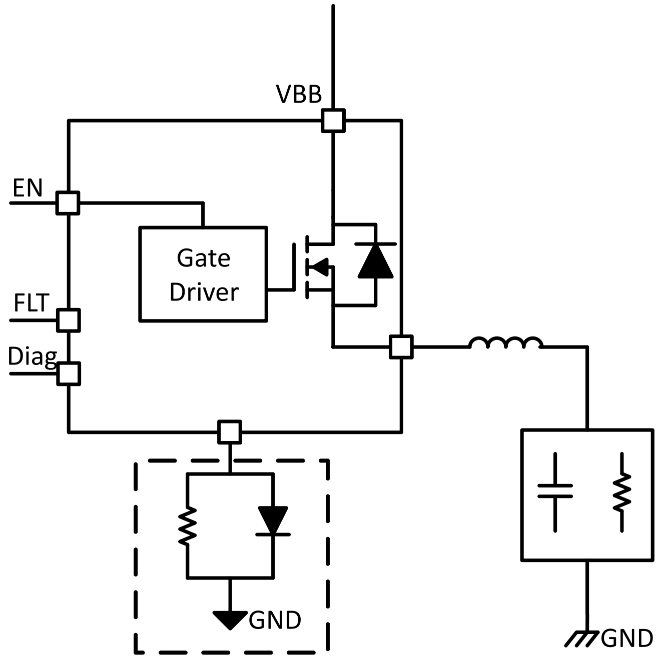

Figure 3-3. Simplified Schematic of a High-Side Switch with a Ground Network

This ground network only protects the device's GND pin. Since the FET source is ultimately connected to the system ground, not the IC GND, current can flow from the FET source to the drain during a reverse polarity condition. This current is limited by the load. To prevent current flowing through the FET body diode and thus causing high power dissipation in the device, the FET is turned on during a reverse polarity condition. The ground network components can be shared between multiple high-side switches.

3.1.3.2 Reverse Polarity and Reverse Current Protection in High-Side Switch Controllers

Unlike the high-side switches, some high-side switch controllers include a second gate drive. One of the main purposes of the second gate drive is to control a back-to-back FET which provides reverse current blocking and reverse polarity protection. In contrast, an integrated high-side switch turns on the pass FET to dissipate power for protection. With a back-to-back FET, the high-side switch controller can block reverse current in the off state, multiplex power and be used at the inputs or outputs of DC/DC converters where bidirectional transients are expected. With this capability, high-side switch controllers have broader use cases than high-side switches.

Additionally, high-side switch controllers have integrated reverse polarity protection that protects the IC during a reverse input polarity condition without external components.

3.2 Diagnostic Features

3.2.1 Analog Current Sense

One of the most important diagnostic features of high-side switches and controllers is the ability to sense, amplify and report current. In high-side switches, the analog current sense uses a current mirror to source $1/K_{SNS}$ of the load current, where K_{SNS} is the ratio of the output current to the sense current. This current is driven out of the sense pin (SNS or CS) through a sense resistor (R_{SNS}) to ground, creating an analog voltage that can be read by an ADC. The R_{SNS} resistor can be manipulated to some degree to maximize the range of currents that can be read. For many of the high-side switches, faults are also reported on the SNS pin in the form of a logic high. For these devices, the upper limit of the R_{SNS} value must leave margin for the logic high output, known as the headroom voltage.

For the high-side switch controllers, the current is similarly measured and reported through the analog current monitoring output (IMON). Differently from the high-side switches, the high-side switch controllers read from an external current sense resistor (R_{SNS}) placed in series with the pass FET. The terminals of this resistor serve as the inputs to a comparator that modulates the current onto another external monitoring resistor (R_{IMON}). By reading the voltage on R_{IMON}, an external ADC can determine the load current . The voltage range for this current monitoring scheme is bounded at the upper end by an internal clamp on the IMON pin. At the lower end, it is bounded by the source voltage (VS).

Another interesting feature of some of the high-side switch controllers is the ability to measure current in both directions. This is helpful in applications with two power sources. For example, in some electric vehicles, there is a DC/DC converter stepping down voltage from the high-voltage battery to power electronics or a secondary battery. The switch on the secondary battery rail will see current flow in both directions as it is both charged and discharged to power loads. A high-side switch controller can indicate the magnitude of the current on RIMON and report the direction of that current with a high or low signal on the I_DIR pin.

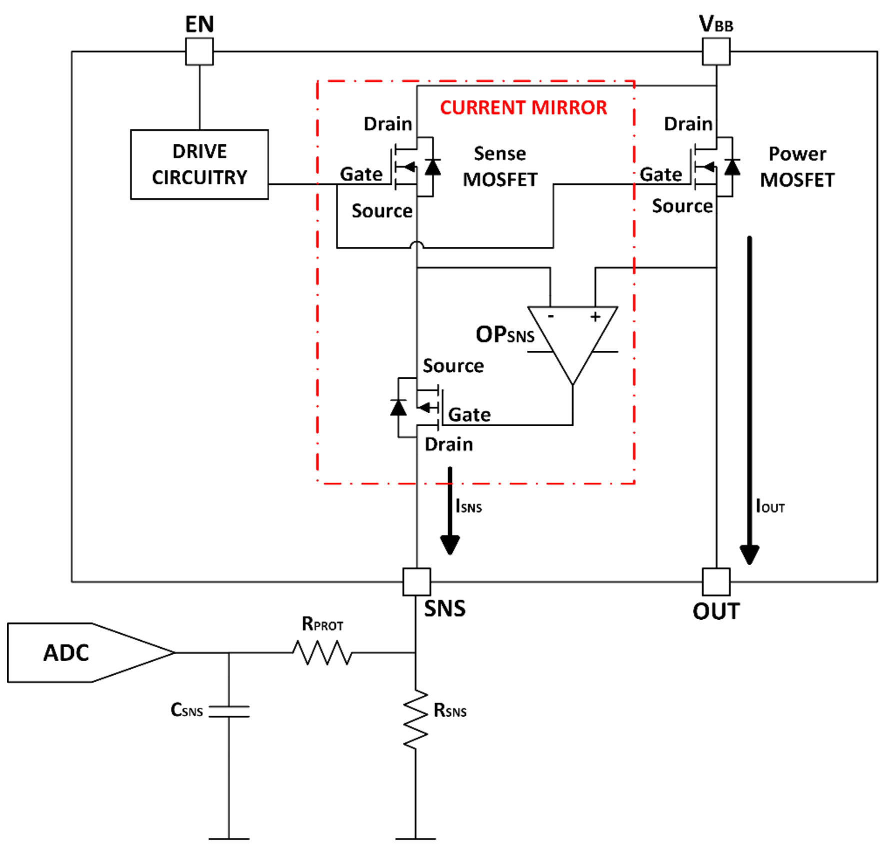

Figure 3-4. Basic High-Side Switch Current Sense Implementation

3.2.2 Open Load and Short-to-Battery Detection

When driving off-board loads, an open-load fault can result from a wire break, a gap in the solder or any other physical disconnection in the conduction path between the switch and the load (or the load and ground). To pass system reliability tests, these failures must occur at very low rates. Despite this, it is common for the high-side switches to detect open-loads when they occur. A short to battery is a fault that occurs when the input of the switch and the output of the switch are shorted together. Open load and short-to-battery faults exhibit the same signature when the fault occurs, so the detection and reporting mechanisms are the same.

To detect an open-load or short to battery in the off state, a weak drain-to-source pullup is activated and the drain-to-source voltage is measured. If this difference is less than the open-load detection threshold for the device, then it is effectively the same and the device determines that the output is not discharging to ground. Therefore, either the terminals of the switch are shorted, as in a short-to-battery fault, or there is some break in the conduction path. The FLT pin then goes low and the SNS reports this with a logic high.

To detect these faults in the on-state, some additional intelligence is required. These faults occur when the switch is on, but little to no current flows through it. To detect this, an MCU compares the low, ADC-reported sense current against the current levels expected during normal conditions. Then by cross-checking that the EN signal is high, the MCU can know that there is an open load or short to battery.

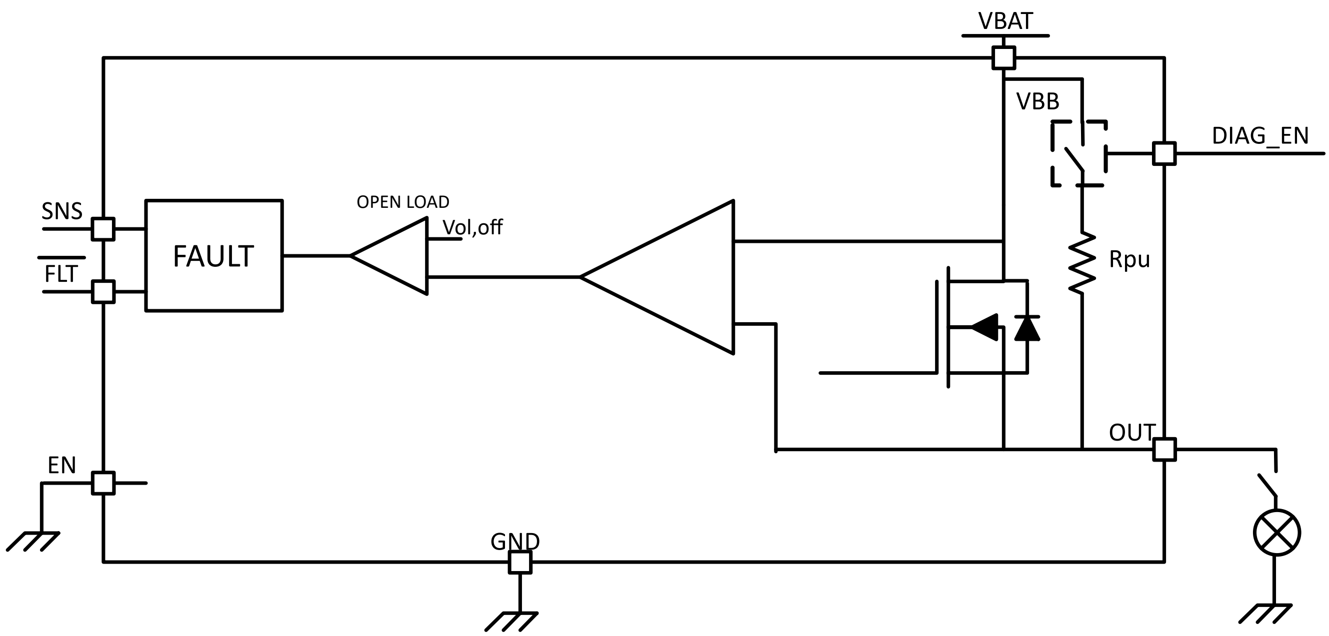

Figure 3-5. Typical Open-Load Detection Scheme Integrated Within the High-Side Switch

With integrated ADCs and pull-up networks, SPI-controlled high-side switches and smart eFuse high-side switches have the ability to detect these faults in the on and off states and differentiate between them.

3.2.3 Junction Temperature Sensing

Some of the standard high-side switch devices, along with smart eFuse high-side switches, can read out the junction temperature of the integrated FET. In the devices with a GPIO interface, this is achieved through an internal temperature sense circuit that is multiplexed onto a SNS pin and read by an ADC. For the SPI high-side switches, the integrated ADC sends the temperature information over the SPI interface.

For the high-side switch controllers with a GPIO interface, a temperature sense pin near the power FET reads the voltage through an NTC thermistor. Once this voltage reaches a high enough level, the voltage can be read as an analog of the FET temperature. The controllers offer the ability to program a temperature threshold which, if exceeded, signals the controller to shut off the FET to protect the controller.

3.2.4 Input and Output Voltage Sensing

Input and output voltage sensing is a feature of both the high-side switches and the controllers. This feature simply reads the drain and source voltage of the FET to provide protection and communicate diagnostic data. In the high-side switch controllers, the VDS sense is one of two ways to read current, as the current sense pins can be connected to the drain and the source of the FET, rather than connected to the terminals of a current-sense resistor. For the high-side switches, an internal sense current can specifically read the supply voltage and output this value onto a sense pin for an MCU ADC to read.

In the SPI-controlled high-side switches and smart eFuse high-side switches, input and output voltages can be read individually and stored in a readable register for the MCU to extract. Along with the current and temperature data extracted by the internal ADCs, a complete thermal and electrical picture of the FET status can be captured at any given time.

4 Specialized Features

Beyond the typical protection and diagnostic features, select high-side switches and controllers have specialized features. These specialized features often cater a device to a specific end application, like how smart eFuse high-side switches have features designed for wire harness protection. Section 4 explores these specialized features in more detail (summarized below).

- Capacitive charging features
- Serial communication and corresponding features
- Enhanced EFT
- Reverse current blocking
- LED driving
- Integrated watchdog timer
- Cyclic redundancy check (CRC)
- Steady-state programmable PWM switching
- Programmable time-current characteristics (I^2T)
- Low-power mode (LPM)
- Memory retention after power cycling (NVM or EEPROM)

4.1 Capacitive Charging Features

Capacitive load charging for standard high-side switches is achieved through a clamping current limit. As discussed previously, the current limit in some devices can be programmed to hold the overcurrent at a steady level until the load is charged or the device hits the thermal limits. The main goal of this scheme is to avoid the large and potentially damaging inrush currents that come with capacitive load initialization. In the high-side switch controllers, large capacitive charging can be achieved through a secondary, smaller FET in parallel with the main power FET or by placing an RC delay on the main FET gate. The secondary path operates as a passive-resistive based pre-charge scheme.

The SPI-controlled high-side switches (and select GPIO-controlled devices such as the TPS272C45) implement a configurable dual-stage current limit approach. The first stage, or the inrush stage, can have length and current limit programmed. The current limit in this stage clamps the current to control the inrush. The datasheets specify the different time periods and current limit values that are available in this stage. The second stage, or the steady-state stage, has a current limit independently programmed of the inrush stage. This dual stage scheme can be used for more than just capacitive loads. This can also be configured for any load with a unique inrush profile, such as a motor stall current or bulb lamps. The SPI interface controllers offer a linear charging method, where the current is clamped a specific level either through the path of the main FET or the secondary FET. There are two variants available: a variant with the secondary path integrated and a variant with the pins to control an external secondary path. They also offer a PWM charging method, where the gate of the main path is triggered with a PWM signal of adjustable duty cycle and frequency. Lastly, there is a short-circuit-protection-based approach where the main FET is turned on until the short-circuit protection is triggered. The FET disables for protection and after the auto-retry period expires, the FET turns back on until the short-circuit protection is triggered again. This repeats until the capacitive load is fully charged.

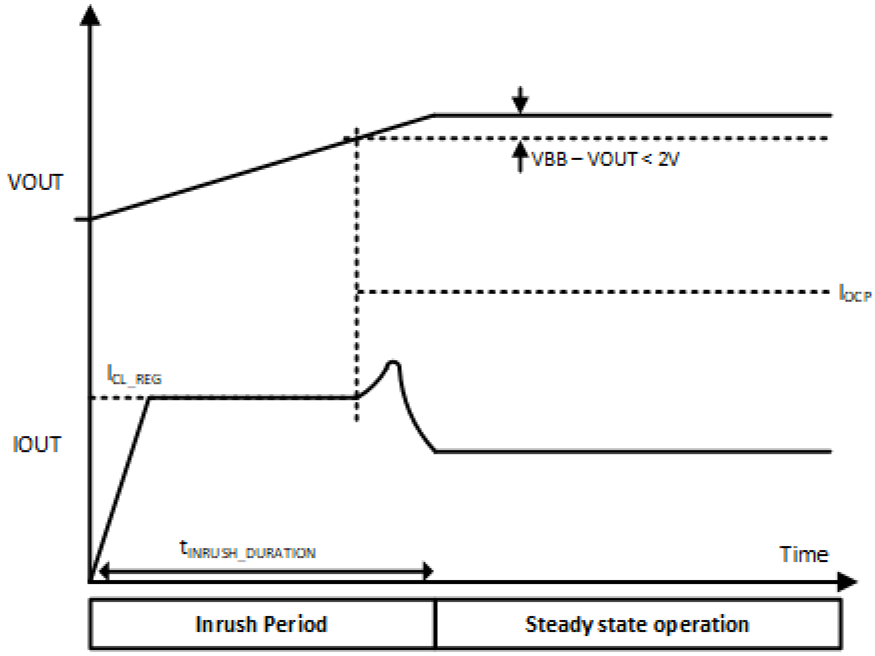

Figure 4-1. Timing Diagram Showing High-Side Switch Behavior During the Inrush and Steady-State Periods of a Capacitive Charging Scheme

4.2 Serial Communication and Corresponding Features

There are two methods of controlling high-side switches: with simple GPIO pins or with serial communication protocols like Serial Peripheral Interface (SPI). SPI capability in a high-side switch enables greater customization and control, allowing users to control functions such as:

- Enabling and disabling the switches
- Enabling and disabling diagnostics
- Selecting and enabling voltage, current, and temperature measurements
- Managing faults
- Configuring the current limit and inrush current time
- Configuring the I^2T fuse curve
- Configuring low-power and capacitive charging modes

High-side switches can have either addressable or daisy-chain SPI modes. With daisy-chain SPI, devices are connected serially and data transfers sequentially from one device to the next. This method is slower, as delays are introduced at each transfer, but allows for more units to be controlled with the same SPI bus. Addressable SPI allows devices connected serially or in parallel. Each device has a unique address, allowing direct communication and eliminating the cascading delays of daisy-chain.

High-side switches with SPI often integrate an analog-to-digital converter (ADC) as well. The integrated ADC helps to simplify current sensing in a system by allowing the high-side switch to transfer the current sense information back to the MCU through SPI. Figure 4-2 shows an example of this in a PLC digital output module. In this case, integrating the current-sense circuitry, ADC and SPI into TPS274C65 enables transfer of current-sense data over isolation barriers and reduce the routing of ADC channels since the routing occurs inside the high-side switch.

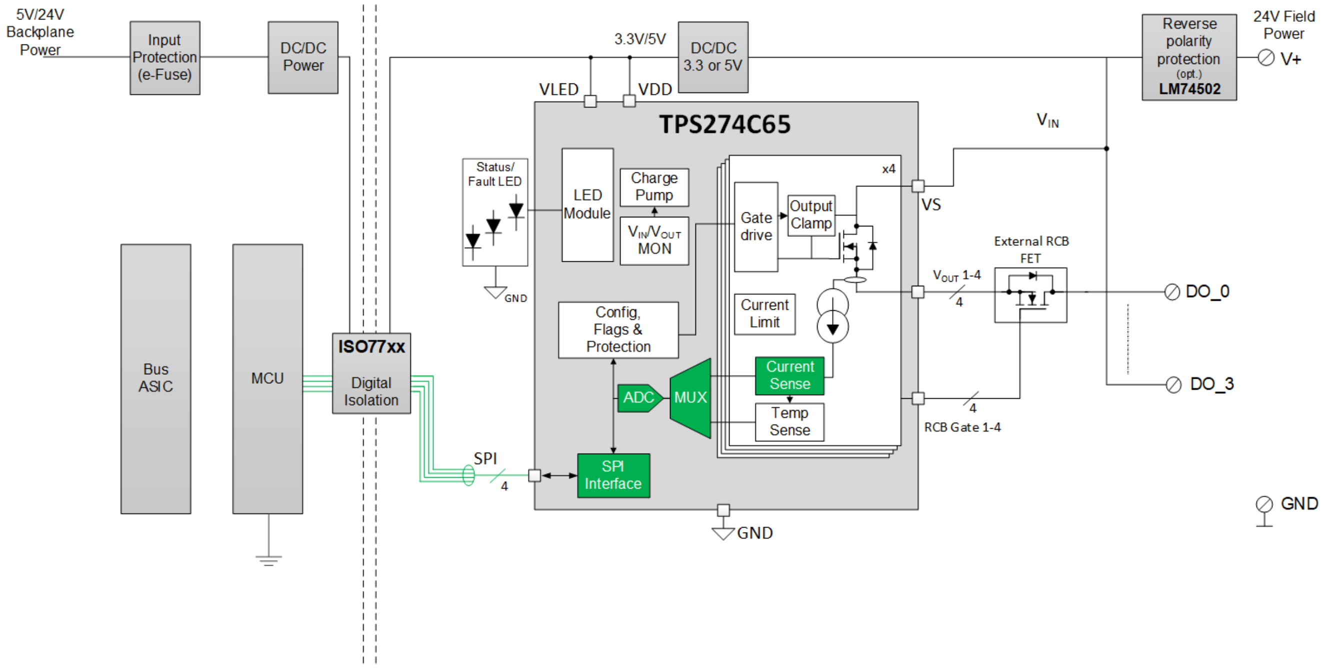

Figure 4-2. Simplified Block Diagram of TPS274C65 in a PLC Digital Output Module

In addition to current sensing, SPI and integrated ADCs also facilitate the measurement and reporting of other signals such as temperature, supply voltage and output voltage. Altogether, this diagnostic and reporting capability is helpful for on-site and remote monitoring of digital output loads. The high-side switch can report current-sense data and fault information via SPI, helping systems and technicians identify problems quickly and eliminate potential root causes. Diagnostic data that shows how a system was operating before it failed enables the establishment of a predictive resolution procedure to prevent similar failures in the future.

4.3 Features for Industrial Systems: Enhanced EFT, Reverse Current Blocking, LED Driving

A unique element of PLCs and industrial control systems is that the load is often unknown. These digital output ports must be robust enough to support the wide range of loads that may be connected in the field (and a subsequent wide range of fault events). For this reason, high-side switches may offer UL recognition or testing in accordance with industrial standards from IEC (International Electrotechnical Commission). Section 1.2.4 discusses several of the common industrial standards. For example, TPS272C45 is UL 2367 recognized (a standard for solid-state overcurrent protection devices).

TPS281C30E provides an enhanced layer of robustness against repetitive electrical fast transients (EFT) (per IEC 61000-4-4), helping to improve system robustness against undesired coupling. The device stays off with up to a 2.5kV EFT pulse applied at VS or VOUT, with appropriate output and coupling capacitors (see device data sheet for details).

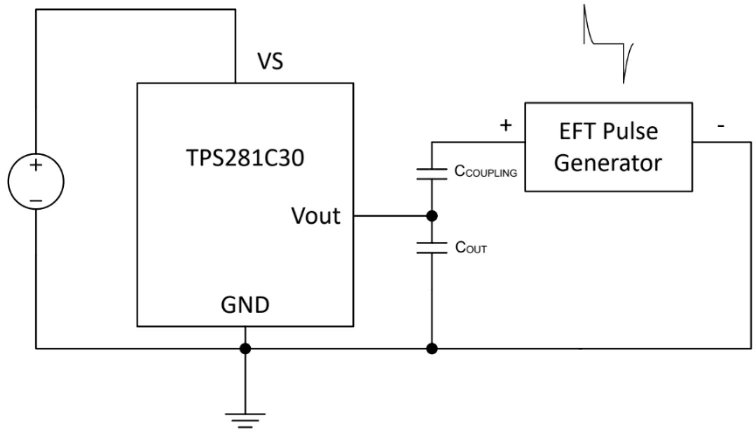

Figure 4-3. Simplified Diagram Showing how TPS281C30 is Tested Against Electrical Fast Transient Pulses

Devices with Enhanced EFT implement a stronger gate pulldown than other high-side switches. In the off state, this helps the device to stay off, even in the event of an EFT pulse. The maximum EFT voltage level V_{EFT} depends on the components used in the test circuit. The larger the output capacitor and the smaller the coupling capacitor, the higher the EFT voltage tolerance.

Reverse current can occur in industrial systems due to miswiring at the output when the input power supply is not available. Another common cause can be large capacitive loads. For example, if there is a significant amount of load capacitance and the supply voltage node has a transient droop, the output voltage can be greater than the supply voltage. Inrush currents from other loads can cause a supply voltage droop. TPS274C65 monitors the supply and output voltages to provide true reverse current blocking during a reverse current or input power failure condition. TPS274C65 implements reverse current blocking with an integrated gate driver for driving an external blocking MOSFET.

TPS274C65 also includes SPI communication and an internal ADC as discussed in Section 4.2. Integrating the current-sense circuitry and ADC in the TPS274C65 enables it to transfer current-sense data over isolation barriers in digital output modules and reduce the routing of ADC channels, since the routing occurs inside the high-side switch. TPS274C65 also includes one additional feature for PLC modules: an LED driver (drives eight LEDs). This allows TPS274C65 to drive the common configuration of one on and off status LED and one fault LED for each of the four channels.

4.4 Additional Specialized Features

4.4.1 Integrated Watchdog Timer

In safety-critical systems, processors and microcontrollers must be monitored to verify functionality at all times. One way to accomplish this is by using an external watchdog timer (an external component must receive a regular signal from the controlling component). If a certain amount of time elapses before the controlling component sends a signal to the watchdog, the watchdog signals a fault.

TI offers multiple high-side switches with integrated watchdog timers, both on GPIO-controlled and SPI-controlled devices. On SPI-controlled devices, this watchdog timer is programmable.

4.4.2 Cyclic Redundancy Check (CRC)

Similarly, TI SPI-controlled high-side switches feature optional cyclic redundancy check (CRC). This generates a checksum based on the SPI transmission. During write procedures, the SPI controller calculates this checksum and appends the checksum to the SPI frame. If the appended checksum is different than what the high-side switch calculates, the high-side switch signals a fault. During read procedures, the high-side switch appends the checksum to the SPI frame for the SPI controller to compare against the calculated value.

4.4.3 Steady-State Programmable PWM Switching

An advanced feature common to the SPI-controlled high-side switches and controllers is the programmable PWM switching mode. In this mode, the device can be programmed to turn on the FET, external or internal, at a specific duty cycle and frequency while at steady state. While in this mode, the programmed current limits, thermal protections and other protections are all still active. For the switches, the fastest frequency programmable is 1770Hz. The upper switching frequency limit on the controllers depends on the size and number of FETs that have been selected for driving the load.

4.5 Smart eFuse High-Side Switch Protection Features

In the automotive industry, there is an architectural shift underway. The move from the legacy domain architecture to zone-based architecture is fueled by the need for further material and power optimization. The domain architecture is the dominant mode of electrical organization in vehicles today. Domain architecture is an organization of electrical systems and loads by function. Thus, there is the body and lighting domain for body loads and lighting and the infotainment domain for cluster, center displays and speakers. Conversely, the zone architecture is the organization of the car by location. Zones can be demarcated by locales of a vehicle (such as front, rear, left and right) or by areas of higher load concentration (such as a seat or roof zone). Zone architecture promises to optimize materials by cable reduction and optimize power through higher intelligence electronics.

4.5.1 Energy Management with Programmable Time-Current Characteristics (I^2T)

One way to aid in both power and material optimization is with a programmable I^2T curve—current squared multiplied by time. This value is representative of the energy in a component based on the current that flows through the component. In melting fuses, it is the energy associated with the thermal threshold at which the fuse melts. When replicated and implemented digitally in an IC, fuse protection is available to any automotive electronic control unit (ECU) regardless of physical accessibility.

The benefit of an I^2T semiconductor design is therefore not one-dimensional. Smart eFuse high-side switches offer a much higher degree of configurability, allowing a designer to tailor a protection profile to match a melting fuse, a wire-tolerance curve or custom load protection scheme. Since this protection is completely configured through software, this also opens the door to hardware reuse.

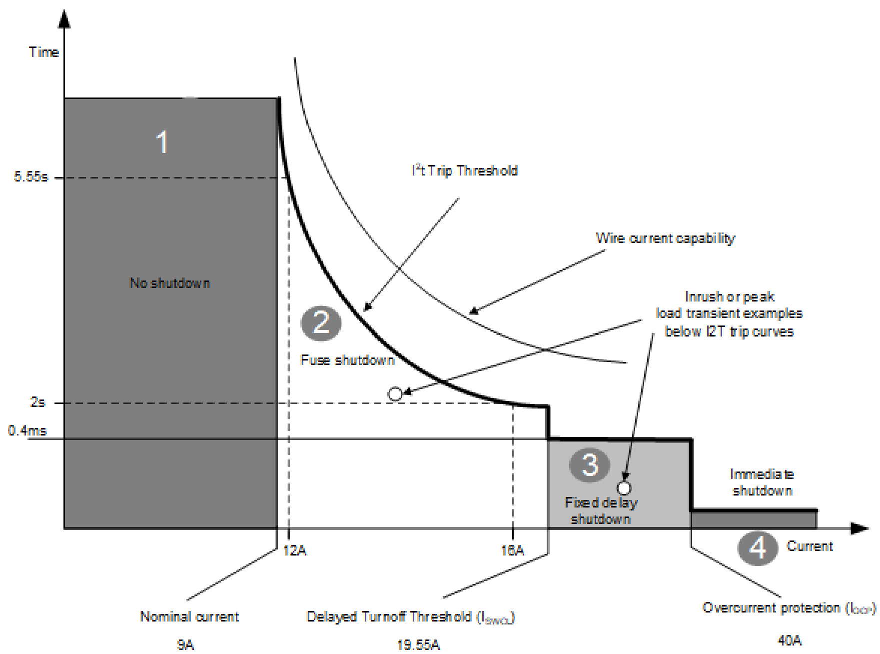

Figure 4-4. Current vs Time Plot of the I^2T Curve with Four Sections Highlighted: Normal Operation, Fuse Shutdown, Fixed-Delay Shutdown and Immediate Shutdown

4.5.2 Power Optimization Through Low-Power Mode

As electrical demands increase with each generation of automobile, so grows the need for higher energy efficiency across power systems in the vehicle. A feature of the smart eFuse high-side switch solves this issue by introducing a low-power mode that still offers protection but at a much lower current draw. Low-power mode is intended for loads which require small amounts of current in the key-off state of the vehicle. The smart eFuse high-side switch can independently monitor the load while consuming little power itself, letting the MCU sleep. When the currents rise and cause an exit of the low-power mode, the smart eFuse high-side switch will notify the MCU with a wake signal. TI smart eFuse high-side switches feature a programmable low power mode exit current threshold. Low power mode is a way to further optimize power distribution in vehicles, making them more efficient and versatile in response to more demanding system requirements. This feature is implemented in two ways, either through the main pass FET in the device, shown in blue in Figure 4-5, or through a secondary, smaller internal FET shown in green.

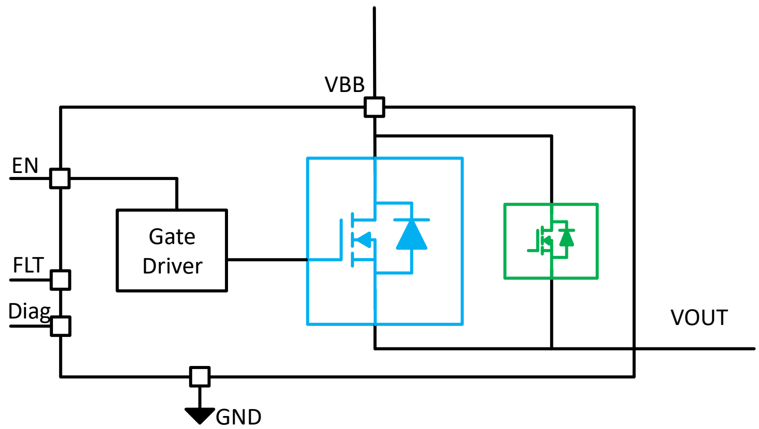

Figure 4-5. Low-Power Mode Implementation for Integrated-FET Devices (Using Either the Main or a Secondary Integrated FET)

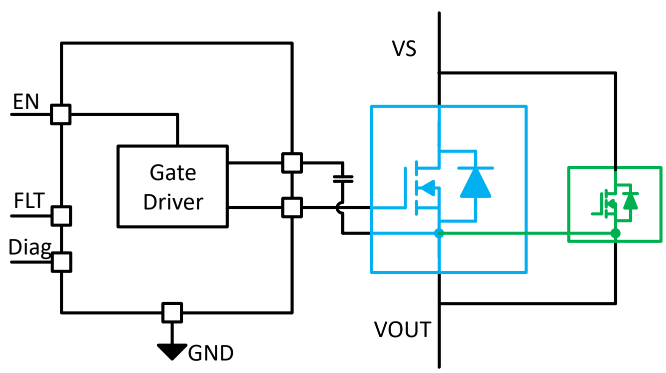

Figure 4-6. Low-Power Mode Implementation for External-FET Devices (Using a Secondary Gate Drive for a Smaller Power FET)

The external-FET smart eFuse high-side switches implement low-power mode in a slightly different way. Some variants have a secondary, integrated FET through which the low-power mode current is passed. However, most other variants have a second gate drive to control a secondary external FET. The secondary FET is intended to be sized smaller and pass a smaller current. The device can automatically switch from low-power mode to steady state on its own, but manual control for low-power mode exit and entry is still available.

Demand for low-power mode is growing in automotive power distribution and there are also many places where the demand is becoming a requirement on standard loads. Because of this, TI has released high-side switches with low-power mode as a base feature. For these devices, such as TPS4HC120-Q1 and TPS2HC120-Q1, the low-power mode is basic and completely automatic, requiring very little additional control and supporting circuitry but enabling additional power optimization.

4.5.3 Memory Retention After Power Cycling (NVM or EEPROM)

With so much digital configuration and data-crunching, having some sort of memory backup in the smart eFuse high-side switch is important. Fault-triggered power cycling and standard power cycling (every time a car engine is stopped or started) causes a configuration reset for a device not equipped with EEPROM. Smart eFuse high-side switches have an EEPROM backup to prevent this. All configurable thresholds and functional settings are protected from power cycles, including I^2T settings, capacitive charging, current limiting, and open-load settings.

5 Summary

TI offers a wide range of high-side power switching solutions for automotive power distribution units, PLC digital output modules, battery management systems and much more. When searching for the optimal device, first consider the system's voltage and current requirements. Next, consider the role of the high-side power switch (to limit current or break the circuit). Then, determine the necessary protections and diagnostics.

For low- to mid-current load driving and power distribution, look to the highly integrated high-side switches. For high-current load driving and disconnect switching, leverage the flexibility of external-FET high-side switch controllers. When seeking to emulate a traditional melting fuse or optimize wire harnesses, utilize the integrated I^2T -based overcurrent protection of smart eFuse high-side switches. To narrow down to the exact device, use the product selection tables on TI.com to filter the required parameters and features to meet system requirements.

6 References

1. Texas Instruments, *Power Multiplexing Using Load Switches and eFuses*, application note.
2. Texas Instruments, *Basics of eFuses*, application note.
3. Texas Instruments, *Selecting the right level of integration to meet motor design requirements* , technical article.
4. Texas Instruments, TI Functional Safety homepage, webpage.
5. Texas Instruments, *Basics of Ideal Diodes*, application note.
6. Texas Instruments, *Adjustable Current Limit of Smart Power Switches*, application note.

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