Application Note

Fault and Normal Diagnostic Considerations for Smart High Side Switches

ABSTRACT

The operation of a high side switch becomes smoother, smarter, and enhanced when adding features such as diagnostics and fault reporting. Diagnostics and fault reporting are key features in high side switches to protect power supplies and loads such as LEDs or motors safe while keeping the switch intact. The following application report goes over the diagnostics and fault reporting that are provided in TI's Smart High Side Switch solutions in both normal and fault conditions such as accurate current sensing, short-to-GND detection, and open load detection. Using this document, designers can take advantage of each advanced function and make the most of TI's high side switch in their application.

Table of Contents

List of Figures

List of Tables

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1 Introduction

High Side Switches are used and seen most commonly in automotive and industrial applications. High side switches have applications where providing power to off-board loads are essential, providing a point of disconnect between the system, supply, and the load. High-side switches can provide diagnostics during normal operation, such as load current measurement and device temperature monitoring. With load current measurements, the system is able to take measurements of the output current by correlating it with a voltage based output. With device temperature monitoring, the system is able to monitor the internal junction temperature of the switch as it increases during operation using a voltage based output. High side switches also provide diagnostics for faults that can alert when open loads, short-to-GND, loss of battery, or thermal shutdown occur. Each fault brings efficiency to the system by allowing features that help monitor down time and ways to ensure current can continue to be drawn through the switch.

2 Normal Operation Diagnostics

Aside from simple on-off operation, most TI smart high-side switch devices come with diagnostics that help monitor regular operation. Some devices have pins that allow measuring the operating load current on the Current Sense [CS] pin. As the device is best kept operating below a certain temperature threshold, the device junction temperature may also be of interest when monitoring device operation. The following sections discuss how to configure the different operations on devices that are able to and also how to optimize current measurements. Table 2-1 lists the devices that are able to measure load current or both device temperature and load current by using their Current Sense (CS) or Sense (SNS) pins.

Table 2-1. Devices With Current Sense or Sense Pins

Feature	Devices
Current Sensing: CS or Current Sense (ISNS) Pin	TPS1H100-Q1, TPS27S100, TPS2H160-Q1, TPS4H160-Q1, TPS2H000-Q1, TPS4H000-Q1
Current and Temperature Monitoring: SNS Pin	TPS1HA08, TPS1HBxx, TPS2HBxx
No Current Sensing or Temperature Monitoring	TPS1H200A-Q1, TPS1H000A-Q1

2.1 Configuring Diagnostics With SEL/SELx Pin

For devices that have a configurable output pin for measuring either the operating load current or the device temperature, there are pins that need to be configured to the appropriate logic values to see the respective output. These are the Select High and Low pins (SEL, SHE) or the Select 1 or Select 2 pins (SELx) pins. By pulling either of these pins to the pin's high or low logic, the diagnostic output is configured to either the device temperature or the operating load current. Table 2-2 shows the different devices and their corresponding SEL/SELx pin.

Table 2-2. Devices With Select Pins

Feature	Devices
SEL and SEH pin	TPS4H160-Q1, TPS2H000-Q1, TPS4H000-Q1
SELx pins	TPS1HA08-Q1, TPS1HB16-Q1, TPS1HB35-Q1, TPS1HB50-Q1, TPS2HB16-Q1, TPS2HB50-Q1

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2.1.1 Diagnostics Select Pin: SEL1

Devices such as the TPS1HB16 have a single SEL1 pin that can be configured with a high or low signal. It acts as the diagnostics select pin. Depending on its state, one of two outputs will be measurable from the sense output pin SNS. The first is load current, which allows the SNS pin to output a voltage signal that reflects the load current that the switch is outputting. The second is the device's junction temperature. The junction temperature is the internal temperature of the switch and is important to monitor to ensure the device remains below the thermal thresholds. These different output configurations are shown in Table 2-3.

Table 2-3. SNS Pin Output Based on SEL1 Pin State

SEL1 Pin State	SNS Pin Output
Low	Load Current
High	Device Temperature

2.1.2 Diagnostics Select Pin: SELx

For devices that have multiple SEL pins such as the TPS1HA08, the device is able to be configured in three ways: device temperature, load current, or supply voltage. As with the single SEL pin devices, device temperature allows for measuring the internal junction temperature and the load current measurement allows for a proportionate voltage signal that reflects the load current. An additional setting allows for monitoring the supply voltage that is supplying power to the output, which is helpful in applications where a battery is involved such as in the automotive industry. For devices with multiple channels, additional SEL pins are used to select which channel to monitor.

Table 2-4 shows the different diagnostics that are used in the SELx pins on the TPS1HA08-Q1 and how to configure them. Table 2-5 shows the configurations that available on the SELx pins on the TPS2HB16 and the settings associated with them.

Table 2-4. SELx Configuration for the TPS1HA08-Q1

SEL1 State	SEL2 State	SNS Pin Output
Low	Low	Load Current
Low	High	No Diagnostics
High	Low	Device Temperature
High	High	Supply Voltage

Table 2-5. SELx Configuration on the TPS2HB16-Q1

SEL1 State	SEL2 State	SNS Pin Output
Low	Low	Channel 1 Load Current
Low	High	Channel 2 Load Current
High	Low	Device Temperature
High	High	N/A

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2.2 Operating Current Measurements Using the SNS/CS Pin

Many devices have an option to measure the current through the switch, through a dedicated pin such as the CS/SNS pin that has been configured to measure current by the SEL pins. Through the use of a current mirror and external resistor, the SNS pin outputs a proportional current that changes the voltage across the sense resistor that can be measured by an ADC that represents the actual load current. This is available on all devices in the TPSxHxxxB and TPSxHBxxx family of smart high side switches. The architecture of how current mirror works in the TPSxHxxxB devices is explained in *High Accuracy Current Sense of Smart High Side Switches*. The implementation and use of current sense have sensitive factors that can be leveraged to maintain accurate values on the SNS pin. These factors range from within the operating device to connections outside the device.

2.2.1 Internal/External Factor: Load Current Through Device

TI's smart high side switches implement a current mirror circuit that mimics the current going through the output and reflects it by an internal ratio and outputs a current on the CS pin.

Due to the internal current mirror, current sense can vary as a result of the current load. The current sense ratio K_{SNS} is directly affected by the sense current and becomes more accurate with increasing load current which is reflected in the Current-Sense accuracy value, *dK/K*, As a result, the output current measured from the SNS pin is affected at different load currents and operates optimally at currents closer to the maximum current the device is rated to operate at. For the TPS1H100-Q1, for example, the optimal current sense accuracy occurs when the operating load current I_{OUT} is 1A or greather. Within that range, the TPS1H100-Q1 is able to measure the load current with an accuracy of up to 3% depending on the load current.

2.2.2 External Factor: Analog-to-Digital Converter (ADC)

For each of the configuration of the SNS pin, whether it is configured for measuring load current or device temperature, the voltage needs to be interpreted by the system. This can be done by measuring with an Analog-to-Digital Converter (ADC). With a digital system, it is common to use an ADC to measure analog signals such as the one outputted on the SNS pin. As a result of being an intermediate step for reading the CS pin, the ADC becomes a limiting factor in the accuracy of reading the voltage output on the CS or SNS pin.

Ultimately, the factors that should be taken into account by an engineer regarding the ADC is the resolution and the reference voltage. These are factors that are determined by the designer and allow the user to interpret the ADC reading with their judgement. An example of the effect of the choice in a 16 versus 8 bit ADC can be seen in Table 2-6.

Table 2-6. Comparison of Accuracy in 8-Bit ADC and 16-Bit ADC With 3.3 V Reference

Number of Bits	CS or SNS Resistor [Ω]	Current [A]	Current Sense Ratio	Sense Current [A]	Sense Voltage [V]	ADC Measured Value	Measured Sense Voltage [V]
8	3.01k	1.5	1500	0.001	3.010	233	3.003
16	3.01k	1.5	1500	0.001	3.010	5977	3.009

As shown, the 16-Bit ADC can read the output voltage with the less error, due to having a tighter voltage step than the 8-bit ADC per bit, and reduce the amount of error that occurs when converting the voltage back to the current. More details and examples to configure the ADC and sense resistor can be seen in *Automotive Load Short-Circuit Reliability and Accurate Current Sensing Reference Design*. As the ADC is an external factor, it is up to the engineer on how to take advantage of the ADC.

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2.2.3 External Factor: Probe Ground Termination

With the CS or SNS pin, measuring the pin on an oscilloscope in a lab environment can help diagnose issues but also brings another external factor that can affect the measured value of the CS or SNS pin. More specifically, in a lab environment, the errors can stem from the hardware such as oscilloscope probes that will have some resistance and capacitance associated with the probe tip. With the case of oscilloscopes, the major factor is the ground termination on the probes. Oscilloscope probes have an internal capacitance that allows for compensation. Ground traces or leads can create an inductance. The result of the internal capacitor and the ground inductance, voltages seen by an oscilloscope probe can have a ringing voltage. By using a shorter ground lead or using a ground spring accessory, the inductance that would result from a long PCB ground trace can be minimized and the chances of inaccuracies reduce.

2.2.4 External Factor: Component Tolerances

To use the CS pin, an external resistor is used by the device to convert the current from the current mirror to a voltage. This voltage is proportional to the load and can be used by the ADC to measure the current. Equation 1 shows the relationship between the resistor R_{CS}, the current sense voltage V_{CS}, the current sense current I_{CS}, the current sense ratio K_{CS}, and the output current I_{OUT}.

$$R_{CS} = \frac{V_{CS}}{I_{CS}} = \frac{V_{CS}K_{CS}}{I_{OUT}} \quad (1)$$

The SNS pin requires a resistor that should be selected that allows for the largest load current that puts the voltage V_{SNS} at about 90% of the ADC's full scale value as to differentiate from a fault value on the SNS pin. Along with this requirement, the smallest load current must keep V_{SNS} from falling below 1 LSB of the ADC. Table 2-7 and the following calculation show an example of the sense resistor calculation to ensure that the max load of 1.5A meets the 95% requirement and the minimum load of 0.2A stays above the 1LSB in a 4-bit ADC

Table 2-7. Calculations of 3.01kΩ Sense Resistor

Load (A)	Sense Ratio	I_{SNS} (mA)	R_{SNS} (Ω)	V_{SNS} (V)	% of 3.3V ADC
1.5	1500	1	3.01k	3.01	91%
0.2	1500	0.133	3.01k	0.401	12%

$$3.3V/(2^{8} \text{ steps}) = 0.012 \text{ V/bit} \quad (2)$$

As the 0.012 V/bit step size is smaller than the lowest sense voltage, a standard resistor closest to 3.01k Ω will be acceptable in this application.

The tolerance of the external resistor impacts the accuracy of the current sense. With a device that works better as it gets closer to the rated operating current, the smart high side switches will be impacted by the tolerance of the current sense resistor as shown where the tolerance of the resistance is represented as a decimal P_{RTol}. The effect of the resistor Equation 3 tolerance can be seen in where R**CS** is the current sense resistor, P_{RTol} is the resistor tolerance, V_{CS} is the current sense voltage, K_{CS} is the current sense ratio, and I_{OUT} is the output current.

$$R_{CS}(1 \pm P_{RTol}) = \frac{V_{CS}K_{CS}}{I_{OUT}}$$

$$I_{OUT}(1 \pm P_{Tol}) = \frac{V_{CS}K_{CS}}{R_{CS}} \quad (3)$$

Devices that have a SNS or CS pin will already have a specified deviation for the current sense accuracy such as the TPS1HB08-Q1 with a ± 5% accuracy when the current output is 10A. For best results, a 1% tolerance or less should be used to ensure minimum error.

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2.3 Device Temperature on the Sense (SNS) Pin

The SNS pin on some devices can be configured to output the device temperature in a way that will be more accurate than measuring the device temperature externally. As the high side switch heats up due to power dissipation, a transient signal that is pulsed can be correlated with a corresponding junction-to-ambient thermal resistance $R_{\theta JA}$ that can be further used to calculate the junction temperature. As measuring the current on the CS pin becomes more accurate at higher load currents within the current rating, similarly, this transient signal becomes more reliable over time but is limited by the sampling rate of the SNS pin. The SNS pin . As it becomes reliable, it can be read to determine whether the device is close to thermal shutdown and used to correlate an increase or decrease in temperature. An example of using the SNS pin for temperature of the device is shown in Figure 2-1, which indicates that the temperature is rising within the device as when current is flowing through the device and falling when the device is disabled.

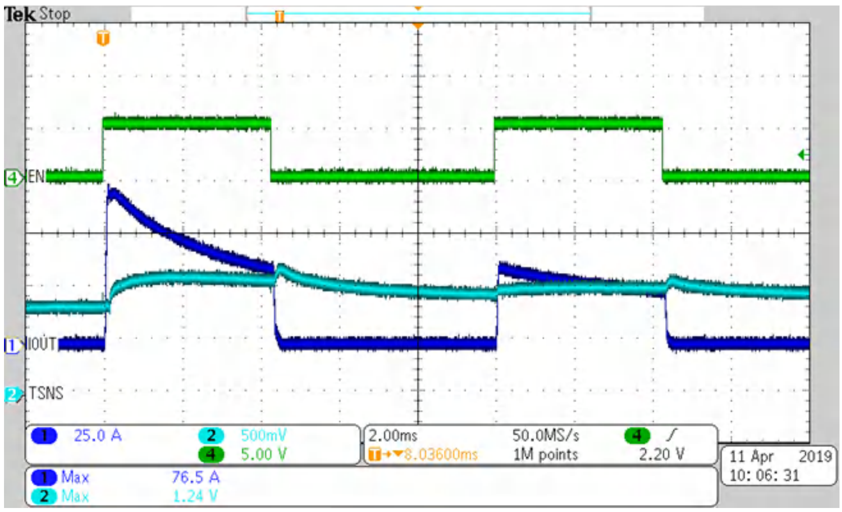

Figure 2-1. SNS Pin Waveform Showing Increasing and Decreasing Temperature Over Time

To ensure accurate sensing measurement, the sensing resistor should be connected to the same ground potential as the ADC that is used. The tolerance of the sensing resistor will keep this method of measuring the device's temperature more reliable and capable than measuring through external means.

3 Fault State Diagnostics

During normal operation, the device will monitor for fault events that can occur. These faults can include loss of battery, a disconnected load, or the output becoming shorted to ground. Using some status pins, the device can report these faults once they are detected and a procedure can be followed to distinguish, diagnose, and reset the device to ensure the fault does not continue to be a problem. These faults can be detected and distinguished by the device for the user to understand the behavior and take the appropriate measures to counteract or remove the problem that is resulting in the fault. By enabling these reports using the diagnostics enable pin DIAG_EN, the fault event will be reported either on the /ST, CS, or /FLT pins. The sections that follow will describe each fault, the conditions that cause them well as how to distinguish them.

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3.1 Fault Behavior Configurations: Latch/THER/Delay Pin

Depending on the device, the recovery behavior of the device when it detects a fault event can be configured to do a few things: turn off, latch the current, or retry. These different states help the device maintain operation and prevent unwanted behavior that can occur as a result of faults such as short to GND. This is dictated by the configuration of a single pin that varies from device to device. This is typically done through a THER, LATCH, DELAY pin.

Table 3-1 shows the different devices that have any of the three pins.

Table 3-1. Devices and Corresponding Fault Configuration Pin

Pin	Device
DELAY	TPS1H200A-Q1, TPS1H000A-Q1
THER	TPS2H000-Q1, TPS4H000-Q1, TPS2HB160-Q1
LATCH	TPSxHBxx-Q1 family, TPS1HA08-Q1

3.1.1 Latch Pin

For the devices that have a latch pin, the pin can either be set to be pulled high or low. When the LATCH pin is pulled high, the device will not try to come back on once it shuts down due to a fault. When the LATCH is pulled low, if the device disables the switch due to a fault , it will try to resume operation after a time t_{RETRY}.

If the LATCH pin is high and the fault has been cleared, the device will be able to exit the LATCH behavior. To exit either LATCH behaviors, the device must meet three conditions:

1. The LATCH pin is low
2. t_{retry} has expired
3. All faults have been cleared

3.1.2 THER Pin

Devices that have a THER pin allows for control over a specific fault that occurs: thermal shutdown faults. As with the LATCH pin, the THER pin can be pulled high or pulled low to configure different thermal shutdown behaviors, depending on what is desired. By pulling the THER pin high, the device will operate in latch mode after a thermal shutdown. When pulling the THER pin low, the device will operate in auto-retry mode. This can allow the device to recover when the device's junction temperature is below the shutdown temperature by a set amount, although limiting the current as to prevent higher power dissipation and causing a repeated thermal shutdown. It is important to maintain a device temperature below the thermal shutdown threshold that can be caused by high currents in applications such as capacitive loads, and is described in the Section 2.3.

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3.1.3 Delay Pin

The devices that have a DELAY pin can be configured three ways: pulled directly to GND, pulled to GND through a capacitor, or pulled high through an external pull up. This allows for three modes for devices that have the DELAY pin: Holding, Latch-Off, and Auto-Retry as shown in Table 3-2.

The Latch-Off and Auto-Retry operate in similar modes as the LATCH behavior. Latch-Off mode will latch off after a configured delay time by grounding the DELAY pin through a capacitor. Auto-Retry will periodically attempt to restart normal operation after some time. The Holding mode is configured by grounding the DELAY pin and sets the device to hold the current limit until the device hits thermal shutdown.

Table 3-2 shows these modes, their behavior, and how to recover from them.

Table 3-2. DELAY Pin Configuration, Current Limit Behavior and Fault Recovery

Mode	Delay Configuration	Output Current Behavior	/Fault Recovery
Holding	Connect to GND directly	When hitting a current limit, the output current holds at the set current. The device enters into thermal shutdown mode when $T_J > T_{(SD)}$	/Fault clears when IN turns low for a duration longer than $t_{/FAULT}$ OR when the current limit is removed when IN is high
Latch-Off	Connect to GND through a capacitor	When hitting a current limit, the output current holds at the set current, but latches off after a preset DELAY time (t_{dl1} + $$C_{DELAY} = \frac{I_{dl(chg)} t_{dl2}}{V_{dl(ref)}}$$ t_{dl2}) where The output stays latched off regardless of whether the current limit is removed. The output recovers when IN is toggling.	/Fault clears when IN turns low for a duration longer than $t_{/FAULT}$
Auto-Retry	External Pullup	When hitting a current limit, the output current holds at the set current, but periodically comes on for $t_{hic(on)}$ and turns off for $t_{hic(off)}$.	/Fault clears when IN turns low for a duration longer than $t_{/FAULT}$ OR when the current limit is removed for $t_{hic(on)}$

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3.2 Open Load Fault

For a high side switch to properly provide power from the supply to a load, the load needs to be connected and remain connected. In the event the load becomes disconnected, the device will detect what is known as an Open-Load fault.

For devices in the TPSxHxxxA family of smart high side switches, when the switch is enabled, the device determines an open load by first comparing the output current with a specified value $I_{OL,ON}$. If the current is less than $I_{OL,ON}$, then the device detects either a short-to-battery fault that occurs when the supply becomes shorted with the load or an open load fault. When either of these faults occur, the /Fault pin will be pulled low but to a process that requires toggling an external FET or switch to determine an open load or short-to-battery fault as shown in Figure 3-1. When the switch is disabled, all voltage drops across the pullup resistor with the load and pullup resistor present, resulting in VOUT being pulled low. If either the open-load or short to battery occurs, the output remains high, the fault signal remains, and the external FET or switch, Q_{SW} **,** comes into play. By disabling the switch, the open-load can be determined by seeing the output pulled to ground along with the fault signal disappearing.

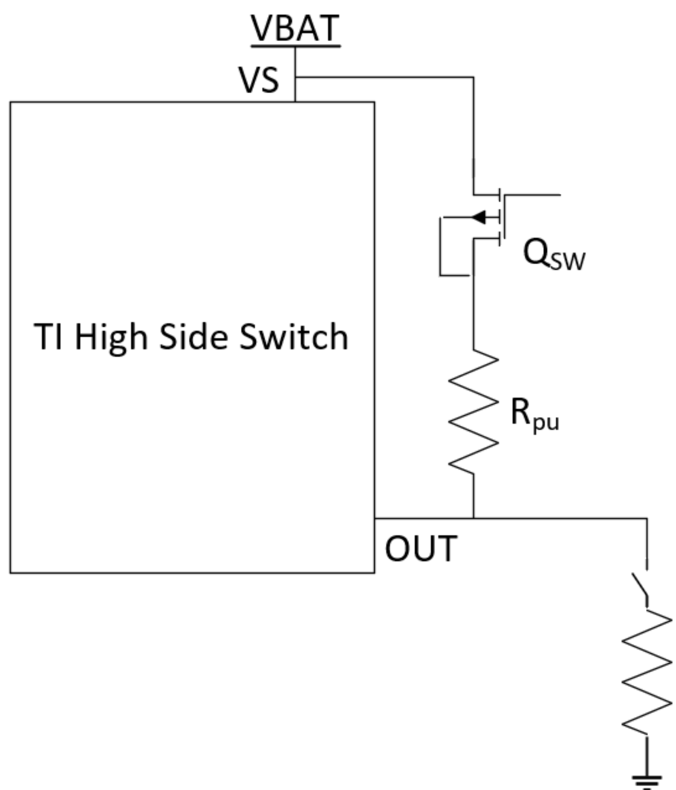

Figure 3-1. External Circuitry Used to Minimize Leakage Current and Identify Open Load

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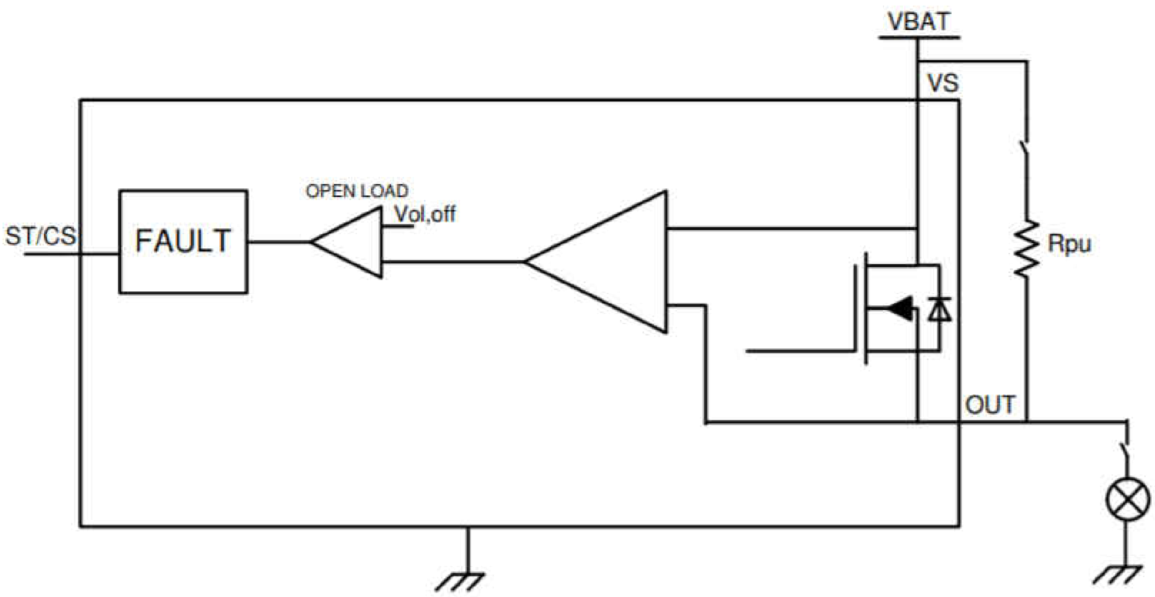
3.3 Short to Battery Fault

The short-to-battery fault follows a similar procedure as the open-load fault. A short-to-battery occurs when the output of the high side switch becomes shorted with the supply, VS. The device determines a fault has occurred by first comparing the current with a specified value $I_{OL,ON}$ and if the current is less than that value, the device detects either a short-to-battery fault or an open load fault.

To distinguish this fault, when the supply is in enabled, the output current is less than the specified device's open load current $I_{OL,ON}$. The way to determine which fault is occurring is to add a weak pull up resistor and a small switch between VS and VOUT as shown in Figure 3-2. When the switch is disabled, the pullup resistor is present and the load is present, all of the voltage should be dropped across the pullup resistor meaning that VOUT would be low. However, in a fault condition, the output could remain high. To determine if this fault is either a short to battery or an open load condition, the small switch in series with the pullup resistor should be disabled. If there is an open load condition the output will go low and the fault signal will be removed since there is nothing to pull VOUT up to VS. However, if the fault does not go away when the pullup is removed, it is safe to assume that there is a short to battery event occurring.

Figure 3-2. External Circuitry Used to Distinguish Short to Battery Fault



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3.4 Thermal Shutdown

There are two types of faults that detail the smart devices thermal behavior. As the device dissipates power, the device's junction temperature will increase. The first thermal fault could occur is absolute thermal shutdown and happens when the device's junction temperature exceeds thermal shutdown temperature, T_{ABS}. The second is known as relative thermal shutdown or thermal swing. Thermal swing occurs when the junction temperature of the main FET increases a set amount above the controller.

In both cases, the switch is disabled. The device will attempt to retry re-enable when the junction temperature is below the shutdown temperature hysteresis but also lowers the output current.

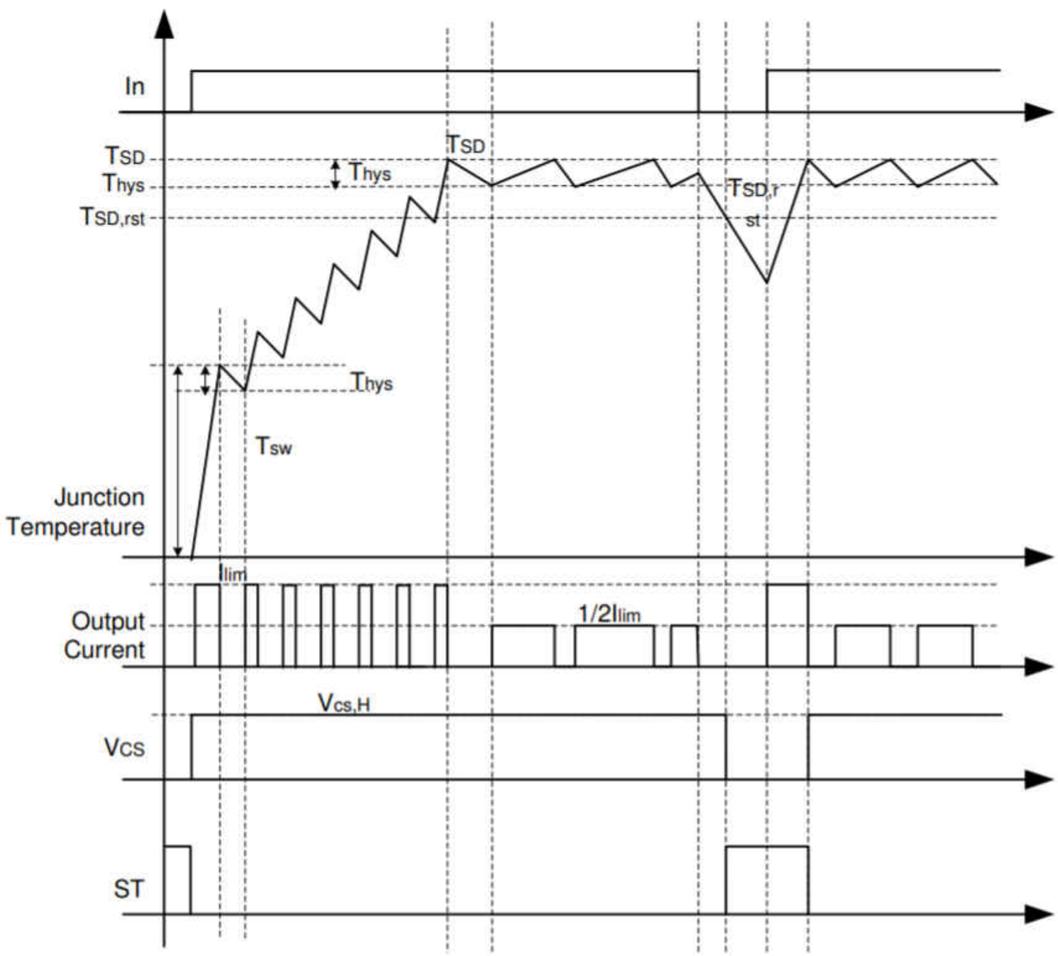

Figure 3-3. Thermal Behavior in TPS1H100-Q1

3.5 Loss of Ground or Power Supply

There are two types of loss of ground that TI's smart high side switches protect from: Device GND and Module GND. In both cases, there is a mismatch of a ground reference for the device that causes the device to turn off the output. Loss of ground is not a fault that is reported on with diagnostics enabled because there is no way to; however, the device will protect itself.

In the case of a power supply loss, loads that are resistive or capacitors in nature, there are no concerns with the device protections that require external circuitry. Since inductive loads will reverse in polarity to maintain current when turned off, external circuitry such as a GND network and/or a free-wheeling circuit may be required. For more information, see *Designing for Loss of Groudn and Loss of Battery on Texas Instruments High-Side Switches*.

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3.6 Summary

It is nice to know what is going wrong when a high side switch begins to display irregular behavior. When used in automotive and industrial applications, it is important to have operation be smooth and problems easily diagnosed. With a footprint in end equipment such as servo drive control modules, mixed I/O modules, and cockpit processing units, TI's Smart High Side Switches strive to be one step above other switches and provide features that optimize performance and the system around it. With diagnostics such as load current and device temperature measurement, high side switches can be monitored for regular operation. In a fault condition, the device can remain protected or diagnose issues such as open load, short-to-GND, loss of battery, and thermal shutdown.

4 References

- Texas Instruments: *High Accuracy Current Sense of Smart High Side Switches*
- Texas Instruments: *Automotive Load Short-Circuit Reliability and Accurate Current Sensing Reference Design*
- Texas Instruments: *Designing for Loss of Groudn and Loss of Battery on Texas Instruments High-Side Switches*

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