

High Accuracy Current Sense of Smart High Side Switches

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ABSTRACT

High accuracy current sense is a feature of various devices in the high side switch family of devices from Texas Instruments. It is used as a diagnostic tool to provide high accuracy feedback to the user on the current flowing through the switch by providing a low power solution to sense large load currents.

This application report introduces the implementation and use of the function for high side switches and gives a guide on setting the sense voltages. It also provides user examples on how to leverage this feature for different application scenarios such as detecting small changes in load currents without the need for prior calibration.

The accuracy of these devices is pre-trimmed and does not require any further calibration by the user. This allows high side switches to be used in applications where external calibration circuitry is not feasible either due to increased system level costs or limited packaging space.

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1 Introduction

High-side switches from Texas Instruments are robust devices that can be used in industrial, automotive, and other power applications. They are rated at 40 V and have a wide range of on-resistance and multi-channel configurations to meet the user's needs. The high accuracy current sense enables full diagnostics including current limiting and various other protective features.

High accuracy current sensing allows for immediate feedback to the user on the status of the system. As a diagnostic tool, it allows the user to monitor the current flowing into the load while maintaining the efficiency of the system, especially in large load applications by providing a low power solution to monitor high load currents. The current sense output can also be used in an analog circuit or can be parsed with the help of an ADC and microcontroller to implement digital logic.

2 Function Description

2.1 TPSxHxxx Current Sense Circuit Description

A current mirror is a circuit that is specially designed to copy the current flowing through an active device. Using two MOSFETs, the primary FET current is mirrored in the secondary FET. The primary current and the copied current are related to each other by a fixed current gain ratio. This ratio is dependent on physical characteristics of the device and cannot be changed by the user.

Figure 1 describes the construction of the current sense circuitry.

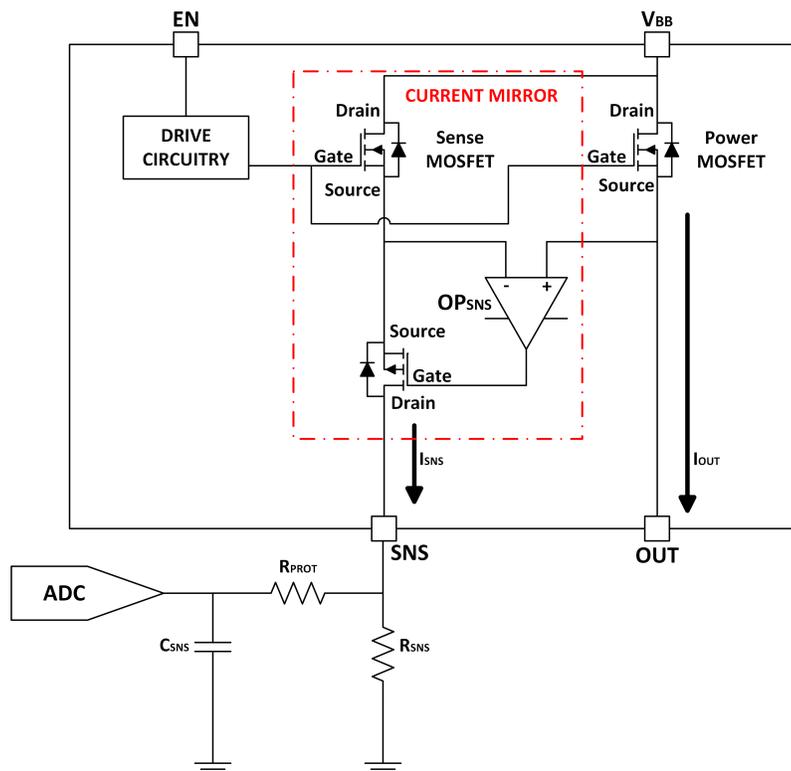


Figure 1. TPSxHxxx Current Sense Circuit

A current mirror is integrated in TPSxHxxx devices using a MOSFET-based topology. This circuit is shared between multiple channels and in this situation, the select pins (SELx) choose which channel is mirrored through the sense circuitry. The use of a current mirror topology allows for immediate feedback to be provided to the user without affecting the operation and the efficiency of the high power system. The sense circuitry has low current flowing through it. This allows the use of a low power solution to sense high load currents. The load current and the sense current are related to each other by a fixed gain factor K_{CS} or K_{SNS} , which is referred to as the "Current Sense Ratio" in the device data sheet.

Accurate current sensing can be used as a diagnostic tool in circuit design. The goal of the current sense circuit is to translate the load current into a voltage value that can be measured by sourcing a sense current through an external sense resistor. In the case of a fault, there exists a feedback loop that sources a steady fault current or pulls up to a fault voltage depending on which device is used. Therefore, the switch is able to delineate between fault operation and normal operation. Given the best-in-class accuracy with TI's high-side switch portfolio, further calibration of the sense circuitry is not needed, saving expensive production line test costs and complexity.

2.2 Choosing R_{SNS}

An external resistor must be connected to the CS pin or the SNS pin of the high-side switch. Using the chosen resistor, the user is able to get voltage values in a range that can be parsed depending on the allowed voltages of the ADC or MCU. This voltage value is directly proportional to the amount of load current flowing through the switch and can be used to implement an off chip fault controller or feedback circuitry in the form of a current meter.

A resistance value has to be chosen so that the entire load current range can be sensed by the MCU. A larger resistor has the potential to have greater accuracy since the voltage range gained is larger but the designer has to note that the fault condition can cause the sense voltage to reach levels that damage the MCU. To mitigate this, a clamping circuit with a zener diode or a voltage divider circuit can be used if necessary.

$$R_{SNS} = V_{SNS} \div I_{SNS} = (V_{SNS} \times K_{SNS}) \div I_{OUT} \quad (1)$$

[Equation 1](#) describes the calculations that are performed to choose R_{SNS} . Here, V_{SNS} is the nominal voltage value chosen by the user for the ADC. This resistor is placed between the SNS pin or CS pin and system ground.

To achieve the most accurate current sense value, it is recommended to apply filtering to the SNS output. There are two methods of filtering:

- Low-Pass RC filter between the SNS pin and the ADC input. [Figure 1](#) illustrates this filter. The typical range for the capacitor C_{SNS} is 100 pF to 10 nF. The typical value for the protection resistor R_{PROT} is 15 k Ω . The designer must select a C_{SNS} capacitor value based on system requirements. A larger value provides improved filtering while a smaller value allows for faster transient response.
- The ADC and MCU can also be used for filtering. It is recommended that the ADC collects several measurements of the SNS output. The median value of this data set must be considered as the most accurate result. By performing this median calculation, the MCU is able to filter out any noise or outlier data.

For example, if a 3.3 V ADC is used and the nominal load current of the system is 1 A, [Equation 2](#) describes the calculation for R_{SNS} on the TPS1H100-Q1. A 3 V linear range is chosen to get good current sense resolution.

$$R_{SNS} = (3 \times 500) \div 1 = 1.5 \text{ k}\Omega \quad (2)$$

The fault current for the TPS1H100-Q1 is 10 mA. With the chosen resistance, the fault voltage is 15 V. Thus, a zener clamp of 3.3 V and adequate power rating is used to set the fault voltage at 3.3 V, which is within specification for the ADC.

3 Effect of Load Current on Sense Accuracy

3.1 Sense Accuracy Trend Over Load Current

As load currents are decreased, the accuracy of the current mirror in the sense circuitry decreases. Even though certain devices are trimmed to different load current ranges, this trend is present in all TPSxHxxx devices. The accuracy for different load current ranges is documented in the data sheet and tends to be lower for low I_{OUT} . Figure 2 broadly describes the accuracy loss at lower load currents. The load current and accuracy range are device specific and are stated on the data sheet of every high-side switch.

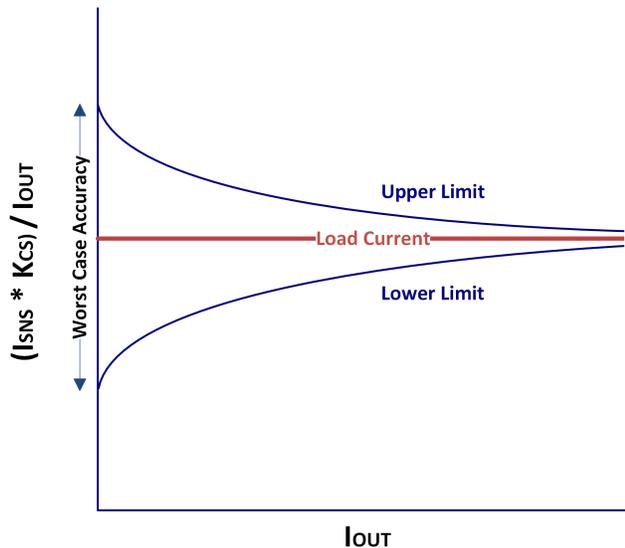


Figure 2. Current Sense Accuracy Characteristic

When running the device at lower load currents, concessions need to be made due to the lower sense accuracy. The sense pin on these devices act as fault indicators when a fault is triggered. The pin sources a fault current, I_{SNSFH} , which help differentiate between normal device operation and fault operation. Some issues that can arise due to the loss of accuracy include incorrect I_{SNSFH} sourcing and a current limit overshoot. As such, it is recommended that the designer chooses the high-side switch that is both capable of driving the desired I_{OUT} and also meets the current accuracy requirements of the system. Table 1 summarizes the current sense accuracy range of TI high-side switches at various current loads. Detailed accuracy information is given in the respective data sheets.

Table 1. TPSxHxxx Current Sense Accuracy Summary

DEVICE	LOAD CURRENT	CURRENT SENSE ACCURACY
TPS1H100-Q1	$I_{OUT} \geq 5 \text{ mA}$	$\pm 80\%$
	$I_{OUT} \geq 50 \text{ mA}$	$\pm 7\%$
	$I_{OUT} \geq 1 \text{ A}$	$\pm 3\%$
TPS2H160-Q1	$I_{OUT} \geq 5 \text{ mA}$	$\pm 85\%$
	$I_{OUT} \geq 50 \text{ mA}$	$\pm 8\%$
	$I_{OUT} \geq 0.5 \text{ A}$	$\pm 3\%$
TPS4H160-Q1	$I_{OUT} \geq 5 \text{ mA}$	$\pm 65\%$
	$I_{OUT} \geq 50 \text{ mA}$	$\pm 8\%$
	$I_{OUT} \geq 0.5 \text{ A}$	$\pm 3\%$
TPS2H000-Q1	$I_{OUT} \geq 1 \text{ mA}$	$\pm 50\%$
	$I_{OUT} \geq 5 \text{ mA}$	$\pm 10\%$
	$I_{OUT} \geq 100 \text{ mA}$	$\pm 2.5\%$

Table 1. TPSxHxxx Current Sense Accuracy Summary (continued)

DEVICE	LOAD CURRENT	CURRENT SENSE ACCURACY
TPS4H000-Q1	$I_{OUT} \geq 1 \text{ mA}$	$\pm 70\%$
	$I_{OUT} \geq 5 \text{ mA}$	$\pm 15\%$
	$I_{OUT} \geq 100 \text{ mA}$	$\pm 3\%$

Table 2. TPSxHBxx Current Sense Accuracy Summary

3.2 Sense Ratio Variance

As seen in Section 3.1, the load current flowing through the device has a direct effect on the current sense accuracy. Texas Instruments specs and trims a K_{CS} value for all high-side switches at a fixed load current. In addition to this specification, there is also a I_{SNSI} specification that describes the sense current under various load current values. This can be found under Current Sense Characteristics in the Electrical Characteristics table of the data sheet. Table 3 describes the sense current variation (I_{SNSI}) for TPS2HB08-Q1. The nominal K_{SNS} specified for this device is 5000, which is specified at 1 A of load current.

Table 3. TPS2HB08-Q1 Current Sense Ratio Variance

LOAD CURRENT	SENSE CURRENT	EFFECTIVE K_{SNS}
$I_{OUT} = 10 \text{ A}$	$I_{SNSI} = 2.020 \text{ mA}$	4950
$I_{OUT} = 3 \text{ A}$	$I_{SNSI} = 0.606 \text{ mA}$	4950
$I_{OUT} = 1 \text{ A}$	$I_{SNSI} = 0.200 \text{ mA}$	5000
$I_{OUT} = 300 \text{ mA}$	$I_{SNSI} = 0.059 \text{ mA}$	5085
$I_{OUT} = 100 \text{ mA}$	$I_{SNSI} = 0.0185 \text{ mA}$	5405
$I_{OUT} = 50 \text{ mA}$	$I_{SNSI} = 0.0084 \text{ mA}$	5952

To calculate the sense ratio at a load current that has not been specified in the data sheet, linear interpolation can be used. A straight line can be drawn between the two closest specified current loads that bound the application load current. Figure 3 describes the linear interpolation between specified load currents for TPS2HB08-Q1.

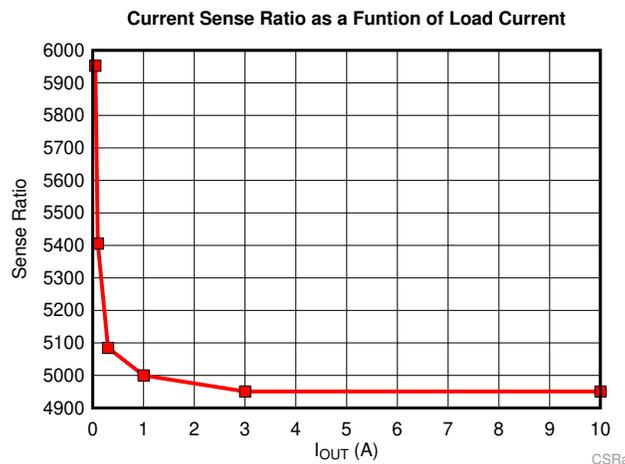


Figure 3. Current Sense Ratio as a Function of Load Current for TPS2HB08-Q1

For a load current of $x = 2 \text{ A}$, a straight line between the data at 1 A and 3 A can be drawn. Using Equation 3, the current sense ratio can be found.

$$(y - y_1) = ((y_2 - y_1)/(x_2 - x_1)) * (x - x_1) \tag{3}$$

$$(y - 5000) = ((4950 - 5000)/(3 - 1)) * (2 - 1) \tag{4}$$

$$y = K_{\text{SNS}} = 4975 \quad (5)$$

4 Fault Indication and the SNS Mux

TPSxHBxx high-side switches are a subfamily of TPSxHxxx devices. While they provide similar benefits and protection, they are built with a different architecture. The main difference between TPSxHBxx devices and the rest of the TPSxHxxx family is the range of on-resistance offered as well as the implementation of the external current limiting circuit. TPSxHxxx devices also report a fault on the SNS pin with an internal pullup that pulls the voltage to $V_{\text{CS(H)}}$. This differs from TPSxHBxx devices that output a fixed current during fault operation.

The SNS pin outputs all the necessary diagnostic information depending on how the SNS Mux is configured with the SELx pins. The following faults are communicated via the SNS output:

- Switch shutdown, due to:
 - Thermal shutdown
 - Current limit
- Active current limiting
- Open-load/ V_{OUT} shorted-to-battery

Open-load and short-to-battery faults are also indicated when the switch is off and DIAG_EN is high. There is an integrated comparator that checks the voltage on the out pin against an internal open-load detection threshold, V_{OL} .

- If $V_{\text{OL}} > V_{\text{OUT}}$, then there is no fault.
- If $V_{\text{OL}} < V_{\text{OUT}}$, then SNS reports a fault.

The SNS pin only reports a fault on the selected channel with the SNS Mux. Irrespective of the nature of the fault, it is reported by sourcing a fault current, I_{SNSFH} from the SNS pin. Table 4 describes the outputs of the SNS Mux of the TPS2HB08-Q1 high-side switch. Refer to the device-specific data sheet for other TPSxHBxx devices for their respective SNS Mux outputs. Version B TPSxHxxx devices do not have dedicated status and diagnostic pins. They report faults through the CS pin in a similar method to TPSxHBxx devices.

Table 4. TPS2HB08 SNS Mux Outputs

INPUTS				OUTPUTS
DIA_EN	SEL1	SEL2	FAULT DETECT	SNS
0	X	X	X	High-Z
1	0	0	0	CH1 Current
1	0	1	0	CH2 Current
1	1	0	0	Device Temperature
1	1	1	0	N/A
1	0	0	1	I_{SNSFH}
1	0	1	1	I_{SNSFH}
1	1	0	1	Device Temperature
1	1	1	1	N / A

Figure 4 and Figure 5 describes the fault reporting of the TPS1H100-Q1 and the TPS2HB50, respectively. These graphs describe the fault current loop that the device uses to report a fault. It is recommended to view the device data sheet to confirm the range of the parameters. Considerations such as zener diode clamps must be used if these voltages reach values that are too high for any external circuitry or microcontroller.

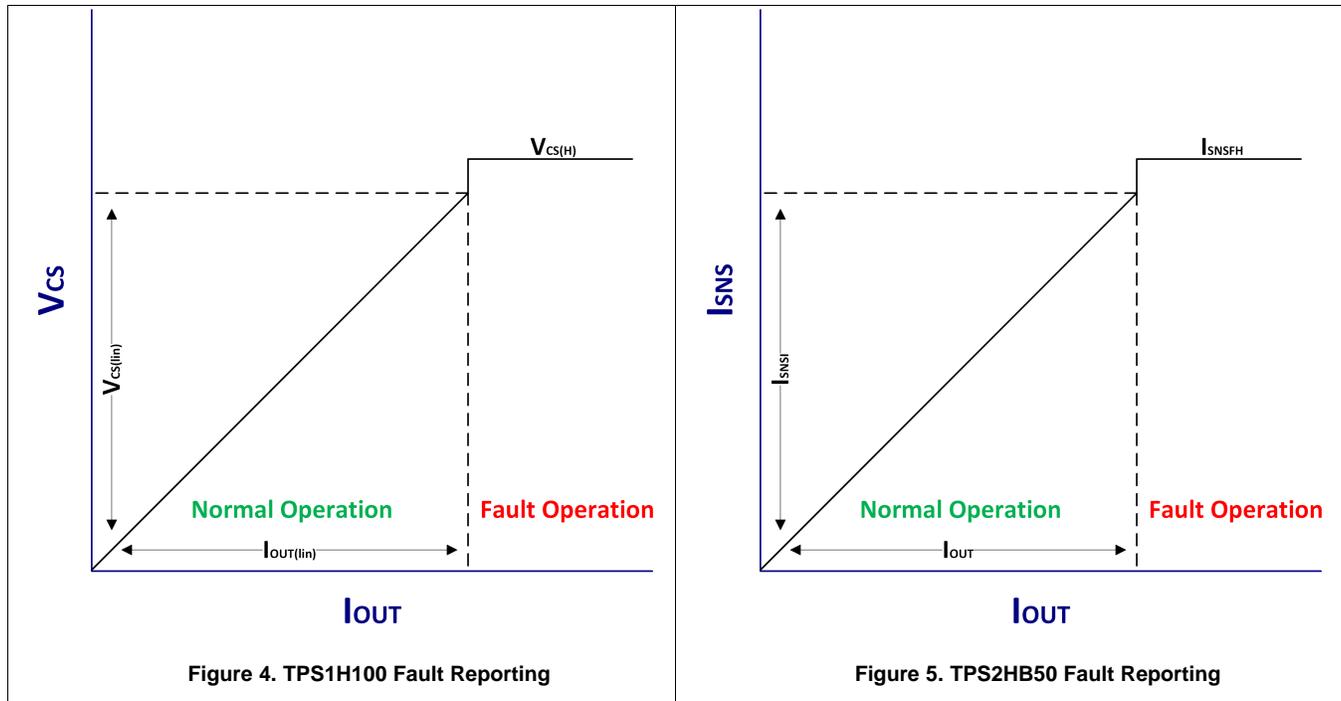


Figure 4. TPS1H100 Fault Reporting

Figure 5. TPS2HB50 Fault Reporting

5 Application Example

5.1 LED Driver Accuracy

Modern lighting solutions are trending toward more LED use. These low power devices have similar luminosity to that of conventional lighting solutions but consume significantly less power. Industrial and automotive sectors are also moving toward replacing incandescent and halogen lamps with LEDs. Since LEDs require very low currents to function, current sense accuracy becomes paramount in being able to accurately sense and protect from fault and open load events.

The high side driver topology is popular in the market since it has short to ground and can drive parallel loads. Hence, Texas Instruments offers high-side switches that combine these benefits with high accuracy current sense in devices that have a range of on-resistance and output channel configurations. This versatility allows the designer to choose the switch that best fits for the application.

A common application for high-side switches in the automotive and industrial sector is to drive a bank of LEDs connected in parallel. The high current sense accuracy allows the system to recognize a fault of one LED in a large bank, hence, the system can recognize small load current changes. Devices such as the TPS4H160 and TPS4H000 can be used to drive LED banks. Figure 6 shows an example using the TPS4H160.

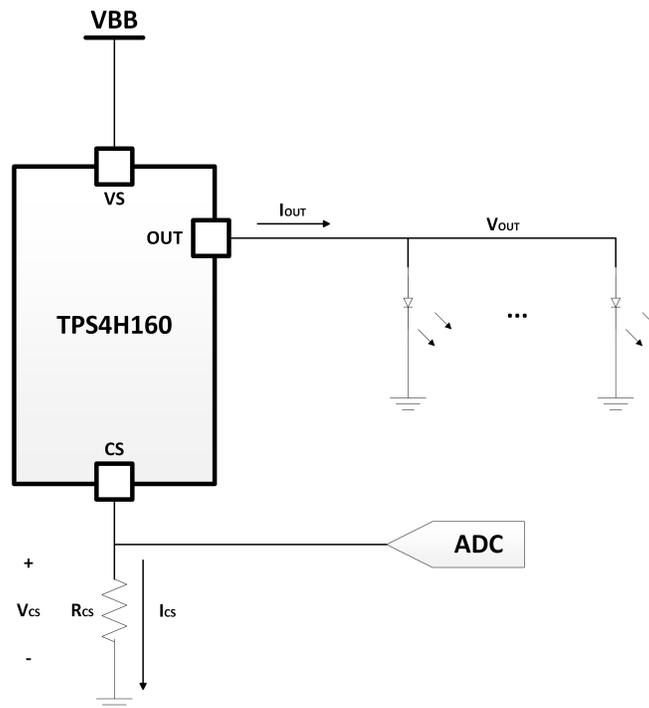


Figure 6. TPS4H160 LED Bank Load Circuit Diagram

The accuracy of the current sense feature is dependent on the current pulled by the load and is bounded by the value stated in the data sheet. This bound describes the largest current sense inaccuracy of the switch. I_{CS} then passes through a chosen resistor, R_{CS} , and V_{CS} is parsed through an ADC. Table 5 describes the system constants.

Table 5. LED Bank Load Circuit Parameters

INPUTS	VALUE
ADC_{supply}	5 V
R_{CS}	2000 Ω
$R_{variance}$	3 %
K_{CS}	300
$ADC_{variance}$	2%
$ADC_{leakage}$	3.5 μA
$ADC_{LSB, tolerance}$	4 LSB
$I_{nominal, 1 LED}$	60 mA

Using this bound, the load current sense can be calculated by Equation 6.

$$I_{OUT} = I_{nominal} \times (1 - K_{CS, tolerance} \div 100) \tag{6}$$

The voltage present on the CS pin is also dependant on the accuracy of the resistor used. When this voltage is parsed by the ADC, the value read is further affected by its inaccuracy range and the leakage current of the ADC. Equation 7 describes the calculation of the voltage read by the ADC.

$$V_{CS, read} = (I_{OUT} \div (K_{CS} \times (R_{CS} \times (1 - R_{variance} \div 100)))) - (ADC_{leakage} \div (1000 \times (R_{CS} \times (1 - R_{variance} \div 100)))) \tag{7}$$

The voltage difference between normal operation and fault operation needs to be large enough for the ADC to recognize. The difference must result in an LSB drop greater than the LSB tolerance of the ADC. The resolution of the ADC is given by Equation 8.

$$ADC_{resolution} = (ADC_{supply} \times (1 + (ADC_{variance} \div 100))) \div (2^{10} - 1) \times 1000 = 4.99 \text{ mV/step} \tag{8}$$

Table 6 summarizes these calculation for various LED loads in parallel.

Table 6. Calculated Sense Voltage from LED Bank Loads

$K_{CS, TOLERANCE}$	LED LOAD	$I_{NOMINAL}$	I_{REAL}	$V_{CS, READ}$	$\Delta V_{CS, READ}$	LSB DROP
8%	1 LED	60 mA	55.2 mA	350 mV	357 mV	71 LSBs
	2 LEDs	120 mA	110.4 mA	707 mV		
4%	5 LEDs	300 mA	288 mA	1.856 V	372 mV	74 LSBs
	6 LEDs	360 mA	345.6 mA	2.228 V		

Hence, high side switches from Texas Instruments have the current sense accuracy to distinguish small changes in the load current flowing through the circuit and this change can be correctly reported by a standard ADC.

5.2 Sense Resistor Sharing

In an effort to reduce BOM costs, a microcontroller can be used to run more than one load. This reduces the number of passive components required in the system, thereby reducing package space as well. The microcontroller may not have enough ADC terminals to support a current sense report on every load.

Multiple high side switches can use the same sense resistor as shown in [Figure 7](#).

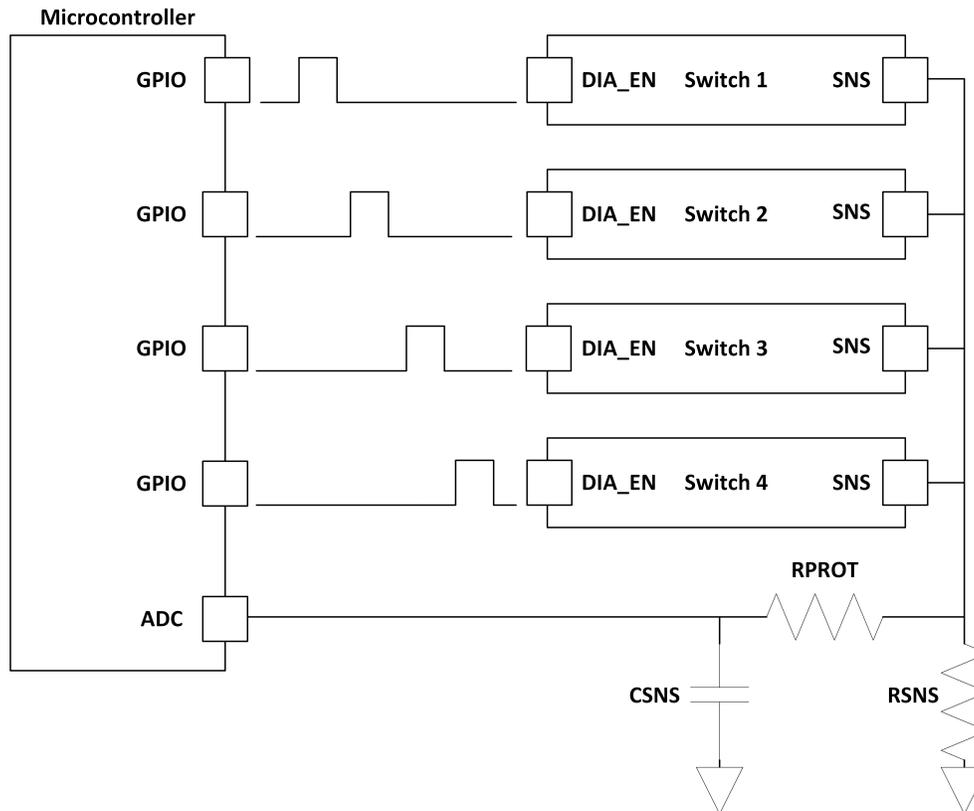


Figure 7. Resistor Sharing Network Among Multiple Devices

Certain considerations need to be taken if sense resistor sharing is used. Different load currents per channel result in different ADC ranges during current sense. Larger load currents on one channel can result in voltages that are unsafe for the ADC terminal. It is recommended that the sense resistor be chosen for the largest expected load current in the shared network.

5.3 Low Duty, High Frequency Switching

Some high power applications can require high frequency switching of the high side switch with a low duty cycle PWM signal. The benefit of using a PWM input allows high power loads to dissipate energy and provides precise control of the circuit. These applications require a fast settling of the SNS output to be read accurately by an ADC. All TPSxHxxx devices have the sense circuitry settling time defined in their respective data sheets.

Figure 8 describes a 250 Hz, 5% duty cycle PWM. This signal results in an on-time of only 200 μ s. The ADC can sample the SNS output after the defined settling time, t_{settle} .

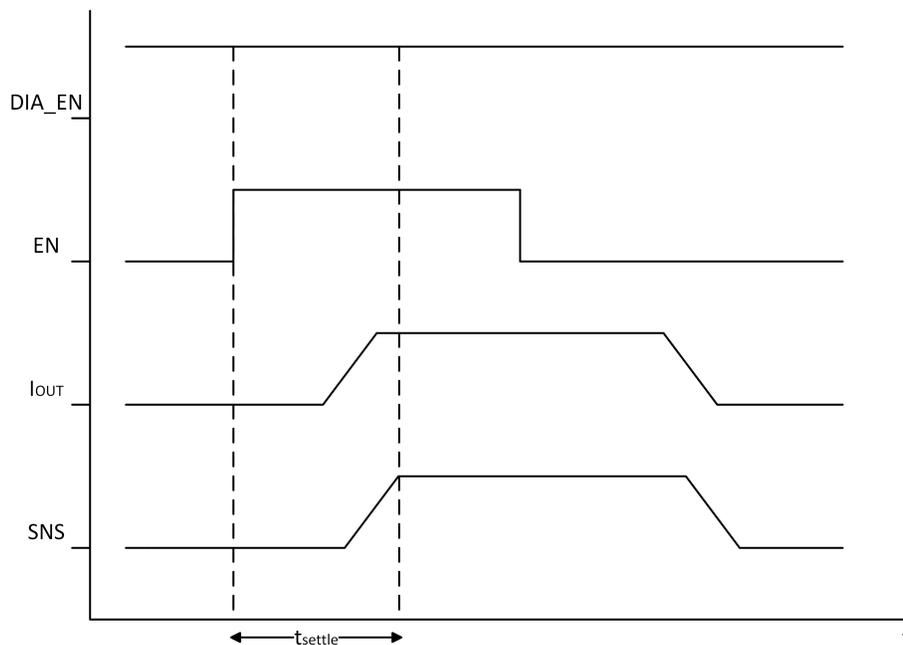


Figure 8. Current Sensing in Low Duty, High Frequency Applications

6 Summary

Texas Instruments offers high-side switches with accurate current sensing abilities that can be used as a protective and diagnostic feature. These devices allow the user to customize the voltage output with the help of an external sense resistor.

Current sensing is useful for designers in power applications since it can provide immediate feedback to the designer about the workings of the circuit. As such, this feature benefits designers by eliminating the need of an external sense circuitry by integrating it into the switch. The current sense circuitry is pre-trimmed and calibrated to a high accuracy, allowing easy integration into user designs.

7 References

- Texas Instruments, [Adjustable Current Limit of Smart Power Switches Application Report](#)

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