Application Note

High Accuracy Current Sensing at Low Output Currents using TI Automotive Smart eFuses

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ABSTRACT

Texas Instruments' (TI) automotive smart eFuses, such as TPS2HCS08-Q1, feature a very high current sense accuracy that enables precise I2T protection, load diagnostics, and power calculations. However, as current sense accuracy decreases proportionally to load current, a high peak current sense accuracy alone is not enough to distinguish between different load states. For example, such as if the load circuitry is intentionally shut off versus if the load is disconnected due to an open load fault. To enhance diagnostic performance at low currents, automotive smart eFuse devices provide a number of features to improve current sense accuracy at lower currents, including open-load scaling and ADC scaling. This application note introduces those features and provides a design reference with test methodology and results showcasing how to use them in designs.

Table of Contents

List of Figures

List of Tables

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1 Introduction

In recent years, the increasing demand for enhanced performance, power efficiency, and advanced safety features have led to the incorporation of sophisticated electronics into modern vehicles. A key component of this shift is the rise of zonal controllers, which segment the vehicle's electrical system into smaller regions or *zones* to enable more precise control over power distribution and consumption. However, this increased complexity has also introduced new technical challenges, particularly with regards to diagnosis and fault detection.

To address these requirements, automotive systems are switching from using legacy mechanical fuse boxes to power distribution boards featuring eFuses, which feature remarkable wire and system safety schemes like I2T protection. Using the wide array of enhanced diagnostic capabilities of an eFuse, diagnosing between a zonal controller or other subsystem normal operation and fault states is made simple. A prime example of this is the ability to distinguish between a zonal controller in shutdown mode versus an actual open-load fault condition, enabling more accurate diagnostic outputs and faster troubleshooting for service technicians.

A typical high-level zonal controller architecture is shown in Figure 1-1, where eFuses on the Power Distribution Board provide power directly to each zonal controller.

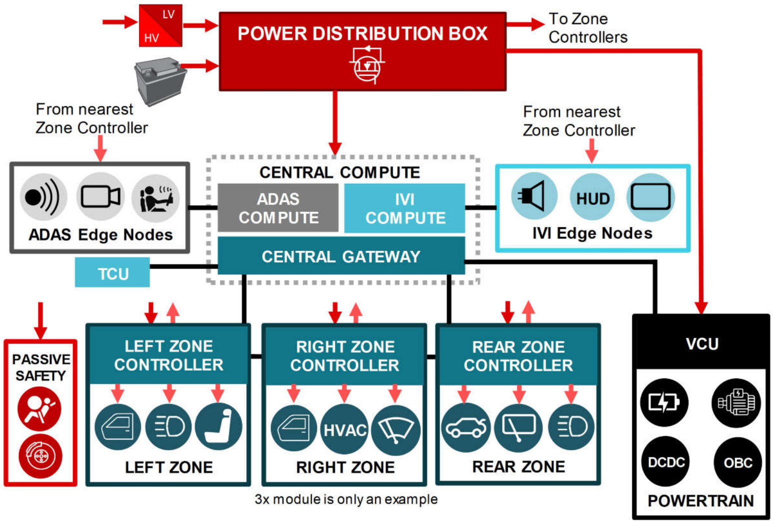

Figure 1-1. Zonal Controller Architecture

2 High Side Switch Current Sense and Open Load Detection

2.1 Current Sense in High-side Switches

When driving a load, especially one that can have a variety of load types connected or enabled downstream, having real-time diagnostic feedback about the load current magnitude is useful. External current sensing implementations used in discrete systems are costly in terms of price, current consumption, and board area. TI's high-side switches integrate this functionality by including a dedicated current sense output, which scales down the load current, which can be read as an analog voltage across an external resistor. For more information about TI's high-side switches and high-accuracy current sense, refer to the High Accuracy Current Sense of Smart High Side Switches application note.

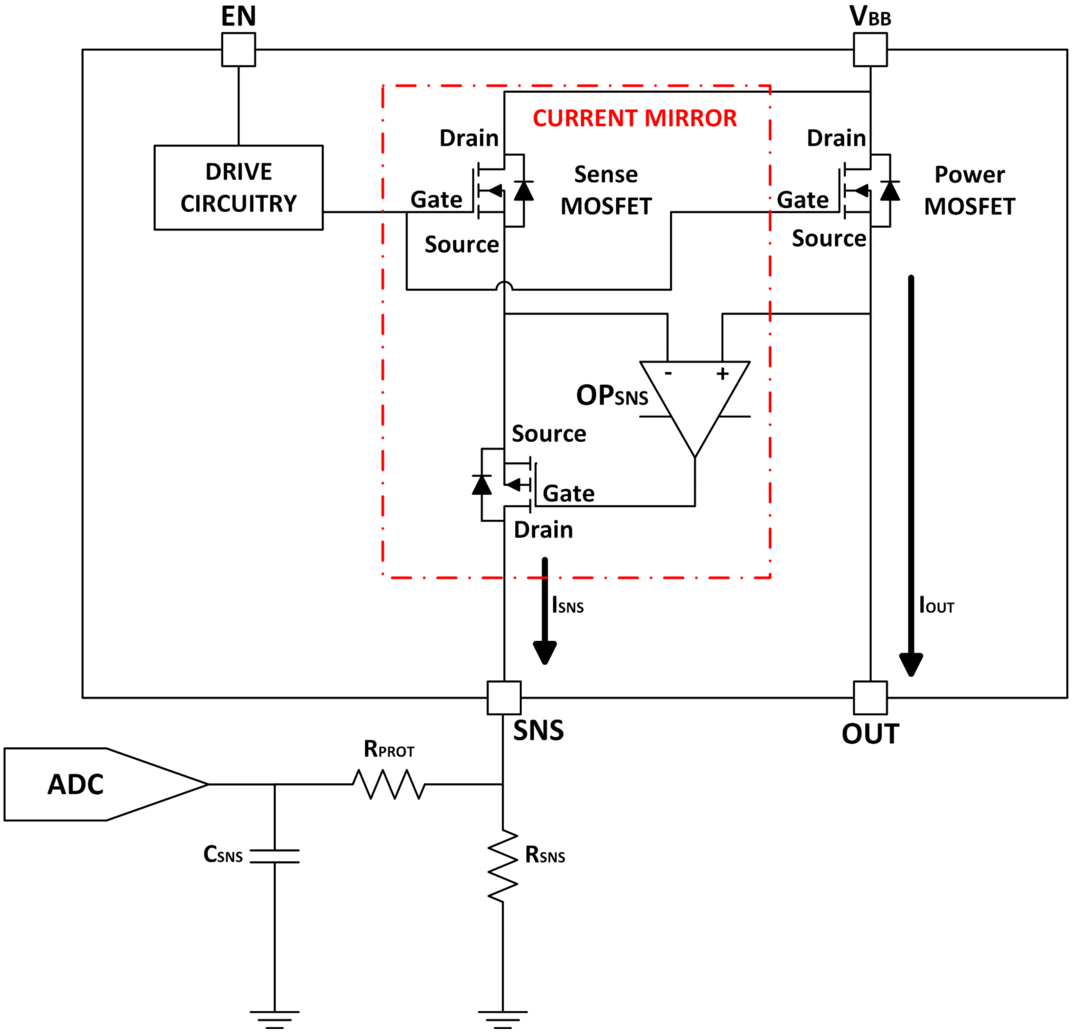

Figure 2-1. High Side Switch Current Sense Architecture

TI's smart eFuses take this feature one step further, utilizing the integrated ADCs to read provide current diagnostic information by using Serial Peripheral Interface (SPI), along with input and output voltages and FET junction temperature. This additional integration eliminates the need for an external microcontroller (MCU) or discrete ADC and allows for high-accuracy, low power consumption I2T protection, greatly reducing system cost and complexity.

2.2 Open-Load Detection in High-side Switches

Another feature that designers can find useful is the ability to detect an open load or broken wire on the high side switch output. Doing this when the device is disabled is straightforward. Place a weak pullup from VBB to VOUT and measure the voltage drop over the pullup using an integrated comparator. If that voltage drop is less than 2V (that is, VBB – VOUT < 2V), then the device determines that there is an open-load fault. All TI high-side switches and eFuses have integrated open load detection using the scheme presented above.

However, this task becomes more difficult when trying to measure an open load when the device is enabled. Using the same circuit as the off-state open load detection is not an option because VOUT needs to always be close to VBB when the device is enabled. Instead, the load current can be measured, and if this is below a certain threshold, then the device can report an open load fault. A couple TI high-side switches employ this method, but this presents two issues. First, the current that is considered an open load is dictated by the application. In a typical application, the nominal load current is greater than 1A, and an output current of <20mA is considered an open load. However, if the nominal load current is less than 20mA, then the device is always reporting an open load fault, which is unacceptable. Second, accurately measuring low currents becomes exponentially more difficult as the FET ON resistance decreases. Thus, for open load detection when the device is enabled, the current sense functionality is used such that the designer can determine an open load current threshold and recognize a fault depending on the device current sense feedback.

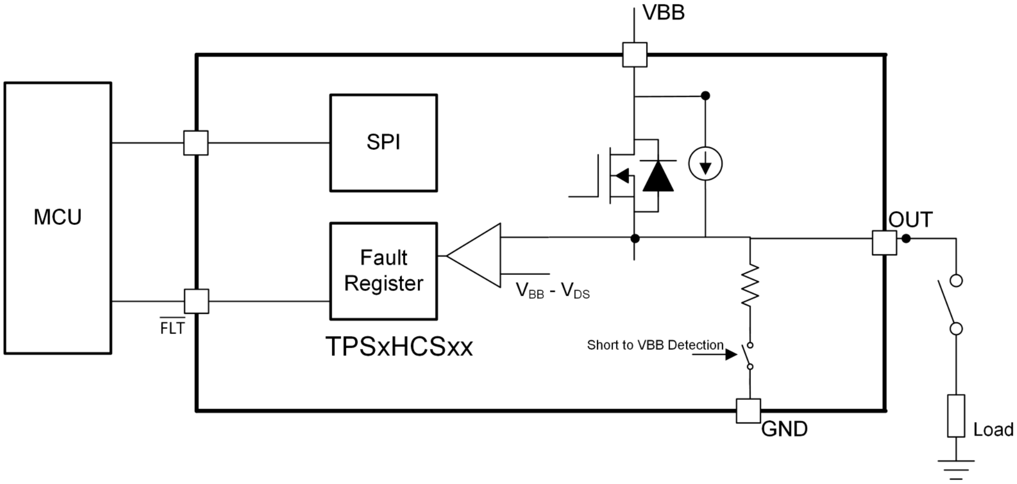

Figure 2-2. High Side Switch Open Load OFF Detection Architecture

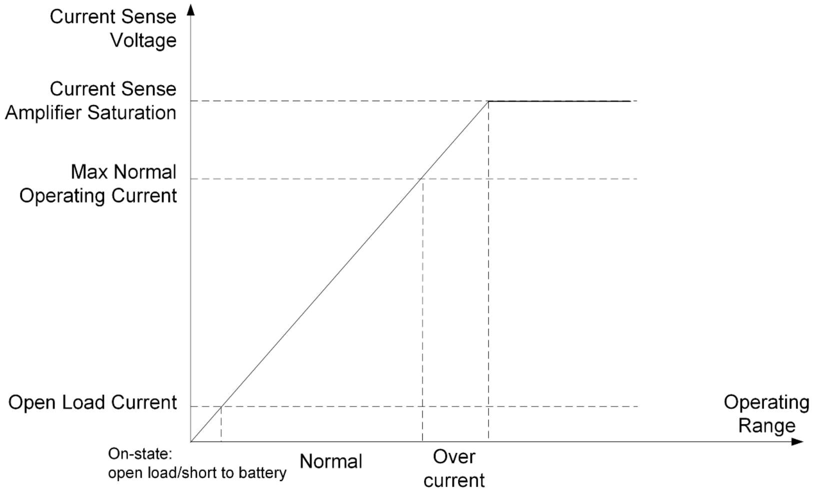

Figure 2-3. High Side Switch Current Sense Range Classification

3 Smart eFuse Current Sense and Open Load Detection

3.1 Open Load Detection in eFuses

Whereas standard high-side switches are typically used to drive a single load, smart eFuses are typically used to distribute power to zonal controllers or other systems that include multiple programmable loads. Given this safety-critical task, smart eFuses must be able to detect a detailed array of fault conditions in the system, including an open load. The open-load-while-enabled scheme presented above works to some extent. However, because the eFuse ON resistances are so low and zonal controllers' power consumption is minimal when the module is disabled, this can be difficult to distinguish between when the zonal controller is disabled and when there is a true open load fault. To address this condition, TI's smart eFuses introduce two more degrees of flexibility to distinguish between low-current operating states: open-load current sense scaling and ADC input scaling.

3.2 Open-Load Current Sense Scaling

As an example, TPS2HCS08-Q1's default current sense scaling factor is K_{SNS} = 5000A/A – that is, I_{SNS} = I_{OUT} / 5000. During load currents above 10A, this K_{SNS1} accuracy is exceptional at +/- 4%. However, as the load current decreases, the accuracy gets worse due to the nature of the circuit, and the K_{SNS1} accuracy at 100mA is +/- 18%. At lower currents, this accuracy gets exponentially worse.

To improve accuracy at low currents, TI Smart eFuses implement an OL_ON mode. In this mode, taking TPS2HCS08-Q1 as an example, the K_{SNS} value is reduced from 5000A/A to 1400A/A (K_{SNS2}), and the FET ON resistance is increased from 8.7mΩ to 27mΩ, allowing for a much higher current sense accuracy at low currents. In this case, the K_{SNS2} accuracy at 100mA is +/- 10%, and currents can be read reliably down to 10mA via SPI.

3.3 ADC Input Scaling

TI eFuses also offer the option to amplify the current sense voltage as seen by the ADC by 8x, increasing the ADC accuracy by operating at a higher input voltage and resulting in an 8x scaled I_{SNS} value. This can be used in conjunction with OL_ON mode for the highest possible total current sense accuracy.

3.4 OL_ON and ADC Input Scaling Programming Procedure

OL_ON mode can be enabled by setting the relevant OL_ON_EN_CHx bit high in the respective CHx_CONFIG register. For the device to accept the command and enter OL_ON mode, the output current must be below the $I_{ENTRY\_OL\_ON}$ threshold. If the output current is not, then the device does not enter OL_ON mode and OL_ON_EN_CHx stays low. If the output current is below $I_{ENTRY\_OL\_ON}$ and OL_ON_EN_CHx is set high, then K_{SNS} decreases and FET ON resistance increases as specified above until OL_ON_EN_CHx is set low or the output current exceeds $I_{EXIT\_OL\_ON}$.

To enable the 8x ADC input scaling, set the ISNS_SCALE_CHx bit and the respective CHx_CONFIG register high. There is no other requirement to enable ADC input scaling.

During OL_ON mode and ADC input scaling operation, TI recommends that the MCU periodically check OL_ON_EN_CHx to make sure the device is still in OL_ON mode. When reading the respective channel current sense, the ISNS_SCALE_EFF_CHx bit is included in the ADC_RESULT_CHx_I current sense result register to notify the MCU of what multiplier to use to read the current sense result. This bit directly shows whether a 1x or 8x ADC scaling factor is used.

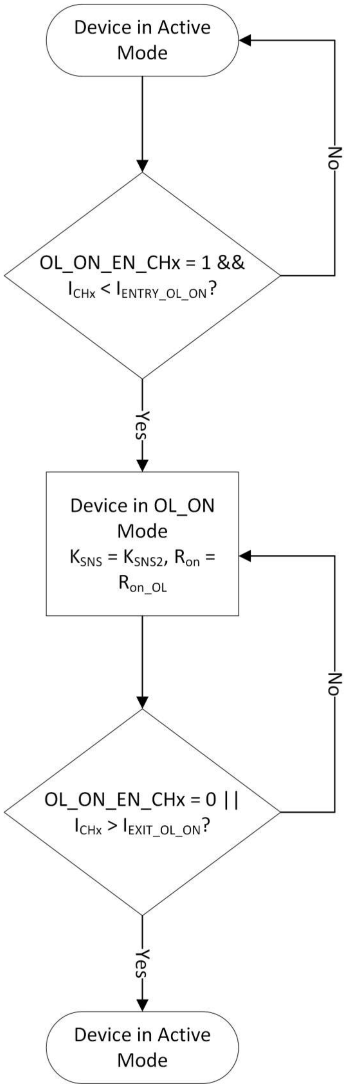

Figure 3-1. OL_ON Enable Flowchart

4 Normal vs. Open-Load Scaling Test Results

Below is an example system where TPS2HCS08-Q1 supplies power to a variable load, such as a zonal controller that has multiple output rails and low power modes. The nominal full-power current sense accuracy is recorded, then the default current sense accuracy is compared to the current sense accuracies using K_{SNS2} and K_{SNS2} with an 8x ADC scaling, respectively, are compared.

This test uses the data sheet-recommended R_{SNS} value of 698Ω. The equation to calculate the output current from the resulting ADC code is as follows:

$$IOUT = [KSNS*VADCREFHI/[1023*RSNS*ISNS_{SCALE}]]*ADC\_RESULT \text{ (Equation 1)} \quad (1)$$

Where:

K_{SNS} = 5000 for K_{SNS1}; 1400 for K_{SNS2}

ISNS_SCALE = 1 for no ADC Scaling; 8 for ADC Scaling

$V_{ADCREFHI}$ = 2.81V typ.

R_{SNS} = 698Ω

Table 4-1 through Table 4-3 detail the current sense accuracy at 10A, 100mA, 10mA, and 0mA with each K_{SNS} and ADC scaling factor applied. Table 4-1 shows the results in terms of ADC codes, Table 4-2 in terms of calculated output current, and Table 4-3 in terms of accuracy.

Table 4-1. Current Sense ADC Codes

	K_{SNS1}	K_{SNS2}	K_{SNS2} and ADC Scaling
10A	506	N/A	N/A
100mA	4	11	8E
10mA	0	1	9
0mA	0	0	6

Table 4-2. Current Sense Output

	K_{SNS1}	K_{SNS2}	K_{SNS2} and ADC Scaling
10A	9.956A	N/A	N/A
100mA	78.8mA	93.7mA	97.8mA
10mA	0mA	0.689mA	6.2mA
0mA	0mA	0mA	4.1mA

Table 4-3. Current Sense Accuracy

	K_{SNS1}	K_{SNS2}	K_{SNS2} and ADC Scaling
10A	0.44%	N/A	N/A
100mA	21.2%	6.3%	2.2%
10mA	N/A	93.11%	38%
0mA	0%	0%	N/A

Overall, there are two main trends that require the use of OL_ON mode and ADC scaling. The first is that the accuracy is significantly improved at lower currents using these two features. The second is that, at 100mA and below, the 10-bit ADC's resolution using K_{SNS1} is 19.7mA. However, using K_{SNS2} with 8x ADC scaling, the ADC's resolution becomes 0.688mA, allowing for a much smaller differentiation between low currents.

5 Design Considerations

When designing with TI eFuses, especially in power distribution systems, discretize required operating current ranges using min and max analyses to differentiate between downstream system normal operation, shutdown mode, fault state, and open load state. Then, determine what eFuse current sense thresholds needs to correspond to each operating region and when to use OL_ON mode and ADC input scaling.

TI recommends that OL_ON mode and ADC input scaling only be used when I2T is disabled on the respective channel (I2T_EN_CHx = 0), because those settings directly modify the input voltage of the ADC and decreases the respective I2T thresholds accordingly.

6 Summary

As automobile architectures become increasingly complex, the needs for verbose diagnostics and protections likewise grows, calling for more real-time feedback about system statuses and more detailed levels of control and abstraction. TI Smart eFuses address this need by introducing future-proof diagnostics including precise open load detection, which utilizes a high-accuracy, programmable, scalable current sense architecture to aid the system in detecting various downstream load states and fault modes.

7 References

1. Texas Instruments, TPS2HCS08-Q1 8.9mΩ, Automotive Dual-Channel, SPI Controlled High-Side Switch With Integrated I2T Wire Protection and Low Power Mode, data sheet
2. Texas Instruments, High Accuracy Current Sense of Smart High Side Switches, application report

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