Design Guide: TIDA-00971

Automotive Load Short-Circuit Reliability and Accurate Current Sensing Reference Design

Description

This reference design addresses the design challenges of providing power to the two actuators in a variable displacement A/C compressor. In designing circuits for these two loads, design engineers not only have the challenge of managing different current levels but also have to sense the current accurately to control the actuators and protect the circuits against faults. This reference design is able to surpass all of these challenges using a singular chip. The design guide will walk through all of the key specifications for controlling the variable compressor actuators. Finally it will show the testing of the loads for each of the scenarios discussed and how TI's smart high-side switch portfolio allows robust protection of these automotive loads. The automotive loads tested in this reference design represent a subsection of all of the total loads present on a body control module board. For more information about driving different types of loads see the *How To Drive Resistive, Inductive, Capacitive, and Lighting Loads With Smart High Side Switches Application Report*.

Resources

TIDA-00971	Design Folder
TPS2HB50-Q1	Product Folder
TPS7B82-Q1	Product Folder

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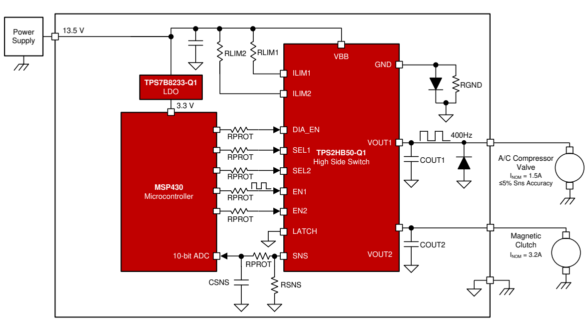
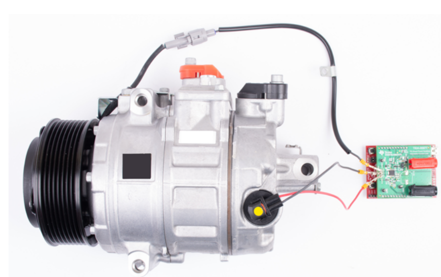
Features

- Short circuit reliability due to adjustable current limiting
- High-accuracy current sensing

Applications

- Automotive HVAC systems
- Automotive BCM loads





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1 System Description

The TIDA-00971 reference design takes a car battery input and delivers the power to two separate load with different requirements while providing equal protection and high reliability. TI's smart high-side switches feature an adjustable current limit that allows the system to detect and protect against faults quicker and safer than high-side switches with fixed current limits. Using one IC to provide power to two different loads with different current limit levels, along with high-accuracy current sensing integrated means less ICs; therefore, lower overall system cost.

In automotive load environments there are many protection challenges. The first and most obvious being a short-circuit current event. Short circuits occur when harness wires accidentally touch the chassis of the vehicle essentially causing the car battery to be shorted to ground. However, the switches currently available that are typically used in the industry have very high current limits. Such switches can be useful in applications like bulbs where inrush currents are high. However, for most other loads it is not useful and potentially harmful to have so much current flow uninhibited. For more information, see the *Improved Automotive Short Circuit Reliability Through Adjustable Current Limiting Tech Note*. This reference design goes through these challenges and shows how TI solves this issue with its adjustable current limit in the smart high-side switches.

Applications that require a high-side switch with high current-sensing accuracy, such as automotive climate control and body control modules, are the primary focus of the testing of this reference design. However, the principles can be used for many different automotive load applications.

1.1 Key System Specifications

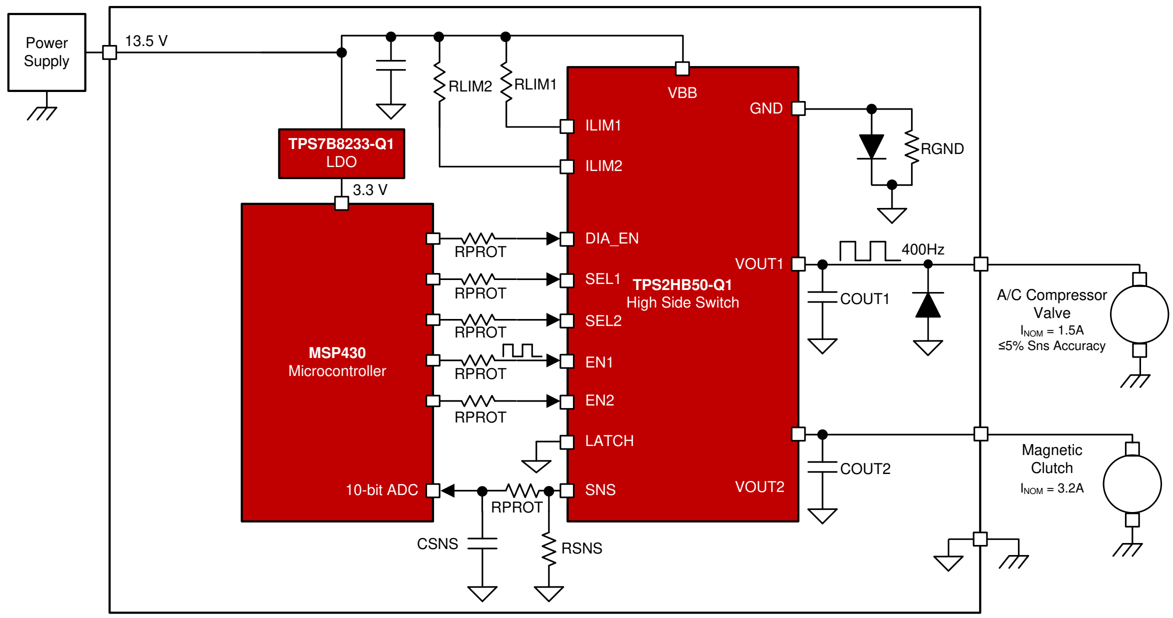
Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input voltage	VBB	3 V to 18 V
LDO output voltage	V3V3	3.3 V
Input Capacitance	C1	2.2 µF
Current sense ratio	—	5000
Current Limit for Channel 1	ILIM1	8 A
Current Limit for Channel 2	ILIM2	10 A
PWM frequency	—	200 Hz
Full-scale ADC voltage	—	3.3 V
ADC resolution	—	10 bit

2 System Overview

2.1 Block Diagram

Figure 1. TIDA-00971 Functional Block Diagram



2.2 Design Considerations

The TIDA-00971 design consists of 3 main integrated circuits: the TPS2HB50-Q1, MSP430™, and TPS7B8233-Q1. The TPS2HB50-Q1 device is used to drive two different loads and is responsible for adjustable current limiting, current sensing, and short-circuit protection with diagnostics. The MSP430 MCU is used to generate the switching pulse which is a 200-Hz pulse-width modulation (PWM) frequency. Also, the TPS2HB50-Q1 current-sensing output (SNS) is connected to the analog-to-digital converter (ADC) of the MSP430 MCU through a low-pass RC filter, which attenuates the noise above a threshold cutoff frequency. The ADC reads the load current sensing and adjusts the PWM duty cycle to change the current through the load. The TPS7B8233-Q1 device is a low-dropout regulator (LDO) which yields 3.3-V DC voltage for the MSP430 MCU. This LDO offers 5-µA quiescent current, which is good for improving the overall system efficiency.

This design can be used for many different automotive loads as all of the key features are common across all types of circuits. However, for the testing of the design, an A/C compressor valve and magnetic clutch were driven. These loads are inductive by nature and the design goes into the protection thereof. There are several system challenges that automotive designers run into when trying to distribute the car battery to the different functions of the vehicle. Firstly, the input from the battery must prevent the dropping of the voltage for the other parallel loads and be able to survive the different conditions the battery may be in such as cold crank or load dump. This is necessary not to protect the battery, but to ensure the IC connected to it can survive this transient. Secondly, a key issue is current sensing. Many loads that are pulse-width modulated need to have very accurate current sensing going to the load so that it can be fed back into the total control loop that is measuring real world events such as pressure, temperature, torque, and so forth.

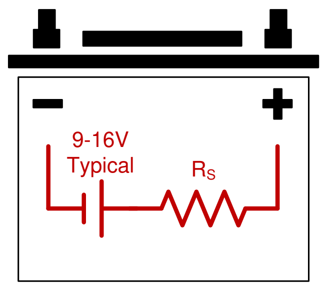
These automotive loads represent a subsection of all of the total loads present on a body control module board. Since obviously the same challenges arise for all of the other loads, this design can be scaled appropriately for many different types of loads and still carry the same amount of protection. For more information about driving different types of loads, see the *How To Drive Inductive, Capacitive, and Lighting Loads With Smart High Side Switches Application Report*.

2.2.1 Battery Input Protection

In a vehicle, the most important parameter for all of the electronics associated is the car battery voltage. In theory, a constant 12 V is provided to all components hanging on the battery line with unlimited amounts of current to power anything and everything inside of the vehicle. However the battery line voltage can change from all the way down to 3 V in cold crank operation to up to 40 V in a load dump condition. This means that any device connected to the battery line must be able to survive these conditions. Both of these conditions are characterized in the automotive standard ISO16750.

The power source can be thought of as a voltage cell with a very, very small series impedance. This is shown in Figure 2. This series impedance is important because it is so small, it would take massive amounts of current to drop any significant amount of voltage across it. However, that is exactly what cold crank does. Cold crank is when the battery provides power to the starter motor that is used to crank the engine, which will drop the voltage very low, to approximately 3 V, for several milliseconds. In newer vehicles such as those that turn off completely when stopped at red lights , this event can happen more often than just initial turn on. For safety and convenience reasons it is important for the functions to still be working. Therefore, for all new smart high-side switches, TI makes the minimum operating voltage 3 V so that it can still operate during a cold crank.

Figure 2. Vehicle Power Source Internal Image

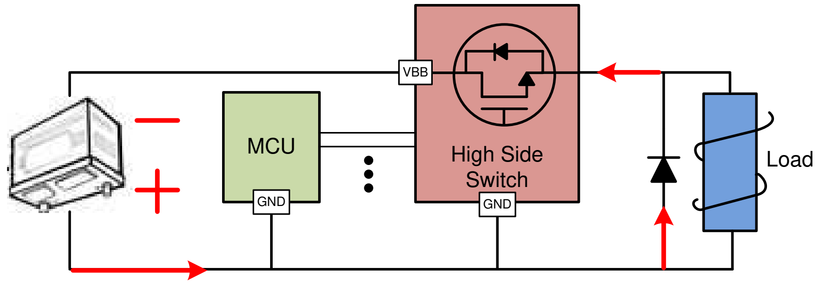


Load dump occurs when the battery is connected in the system to the alternator and then abruptly gets disconnected. This causes the voltage on the power line to increase as high as 120 V and can take up to 400 ms to decay. In most vehicles; however, the load dump pulse is suppressed by large circuitry that can clamp it down to 40 V. For this reason TI makes all of their smart high-side switches tolerant of voltages up to 40 V so that it can survive a load dump condition.

2.2.1.1 Reverse Battery Protection

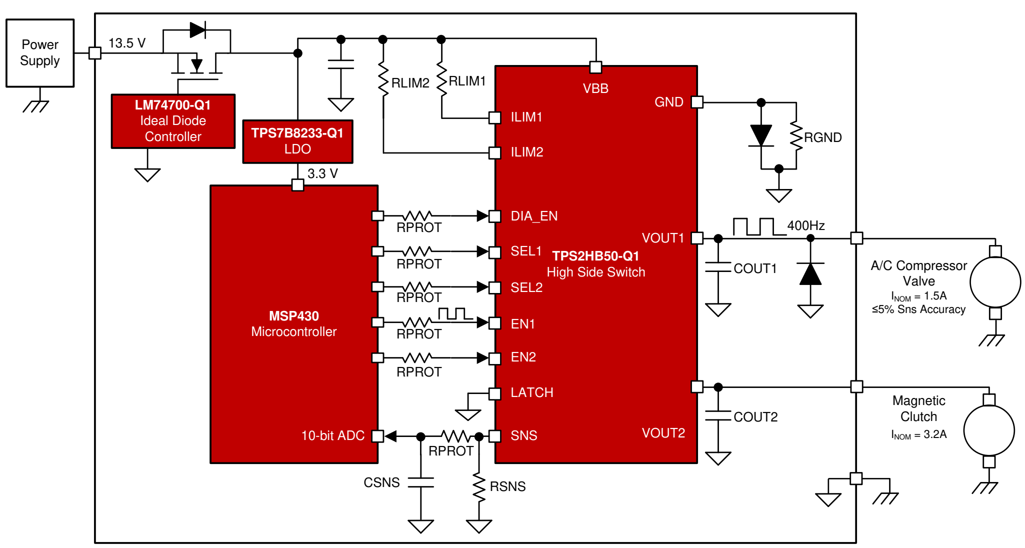
A detailed analysis of the reverse battery condition is found in the *Reverse Battery Protection For High Side Switches Application Report*. This application report details each of the cases of reverse battery and how TI's portfolio of high-side switches mitigate a reverse battery event. However, this reference design has a unique scenario that is true of loads where there is a shunting diode, often referred to a flyback diode, on the output. This is due to the fact of the two loads being on the same ground connection and if current flows back into one of the loads, it will hurt operation. For more information about these specific loads, see Section 3.1. If this is the case during a reverse battery there is more current going through the load than in maximum operation.

Figure 3. Reverse Battery Condition With a Shunting Diode Across Load



For small load currents a designer can simply put a blocking diode on the input to stop all reverse current. However, with loads such as this design covers, approximately 5 A combined, a blocking diode would dissipate a lot of power and is not practical. This is why body control modules typically have a reverse current blocking IC on the main input of the battery that is then distributed to all of the loads. Since this IC is generic to all of the loads on a BCM, it is not covered in this design. However, if this functionality is necessary, TI's ideal diode controller portfolio can handle this event. Figure 4 is a block diagram this reference design with the LM74700-Q1 ideal diode controller.

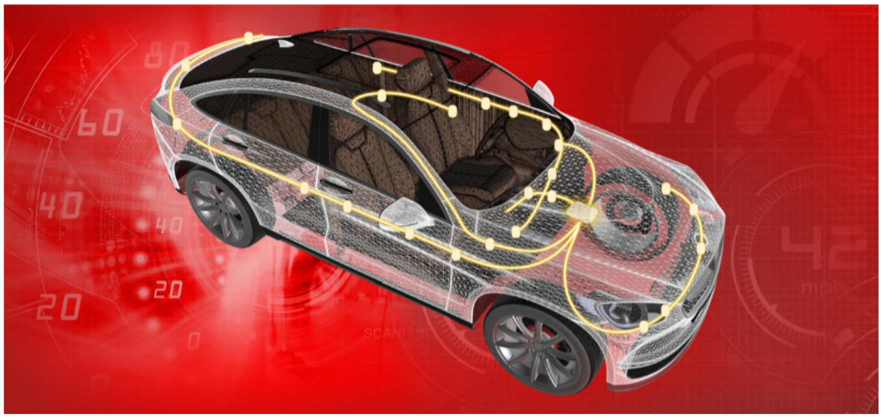
Figure 4. TIDA-00971 With LM74700-Q1 for Reverse Current Blocking



2.2.2 Short-Circuit Reliability

One of the most typical fault cases in automotive applications is short circuit. A short-circuit event can happen anywhere the load is not on the same board, which for vehicles is practically every load. When a short occurs it is the responsibility of the device providing power to make sure that it protects the system as a whole from this event. Short-circuit events are tricky in the context of a vehicle: however, because they can happen in several different locations that can cause issues for the system and must be mitigated when laying out the board.

Figure 5. Typical Vehicle Wiring Diagram



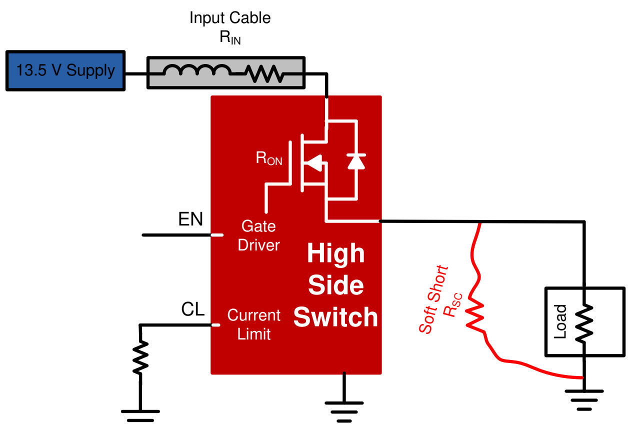
As Figure 5 illustrates, these wires can be up to 3 meters long and have to be routed around large mechanical components of the vehicle. This means that while the resistance is very low the inductance of the wire can be up to 5 µH. This is also true of the output cables that go to the load. However, since they are obviously carrying less current than the input cable, their resistance per unit length will be high because they are smaller gage.

All of these factors come into play during the short-circuit event because it will effect different nodes in different ways depending on the short. The next few sections document the different ways there can be a short circuit and what the effects are and also how TI's adjustable current limiting mitigates them.

2.2.2.1 Soft Short at the Output

Soft shorts refer to the case when the load is not fully shorted to ground, that is, approximately 0 Ω, but rather just a lower impedance than the load was intended to be. This can happen often with corrosion, or miswiring, or even human error.

Figure 6. Soft Short



As previously discussed, existing high-side switches have a very high current-limit threshold and will not shut the current off to the load unless it passes that threshold or hits thermal shutdown. Therefore, if the short-circuit resistance is 1.5 Ω, then the current through the output is calculated by Equation 1.

$$I_{SC} = V_{BATT} / (R_{IN} + R_{ON} + R_{SC}) = 13.5\ V / (50\ m\Omega + 50\ m\Omega + 1.5\ \Omega) = 8\ A \quad (1)$$

Where R_{IN} is the input cable resistance and R_{SC} is the short-circuit resistance. For a typical 50-mΩ, high-side switch, the current limit is 25 A. Also with a board area of 76.4 mm × 114.3 mm × 1.5 mm the junction to ambient temperature coefficient, $R_{\theta JA}$ is 32°C/W. Therefore, Equation 3 shows that a device that is only rated for nominally 3 A from both channels or 4.5 A from one channel if in an environment where the ambient temperature is 25°C is now giving out 8 A and is not reaching thermal shutdown.

$$P_{DIS} = I_{SC}^2 \times R_{ON} = (8\ A)^2 \times 50\ m\Omega = 3.2\ W \quad (2)$$

$$T_J = T_A + P_{DIS} \times R_{\theta JA} = 127.4°C \tag{3}$$

This phenomenon gets worse when using a switch with a lower R_{ON}. Take for instance an 8-mΩ, high-side switch with a $R_{\theta JA}$ of 31°C/W, a short circuit minimum current limit of 77 A, a short-circuit resistance of 0.6 Ω, and an ambient temperature of 25°C.

$$I_{SC} = V_{BATT} / (R_{IN} + R_{ON} + R_{SC}) = 13.5\ V / (50\ m\Omega + 8\ m\Omega + 0.5\ \Omega) = 20.5\ A \tag{4}$$

$$P_{DIS} = I_{SC}^2 \times R_{ON} = 20.5\ A^2 \times 8\ m\Omega = 3.36\ W \tag{5}$$

$$T_J = T_A + P_{DIS} \times R_{\theta JA} = 25°C + 3.36\ W \times 31°C/W = 129.2°C \tag{6}$$

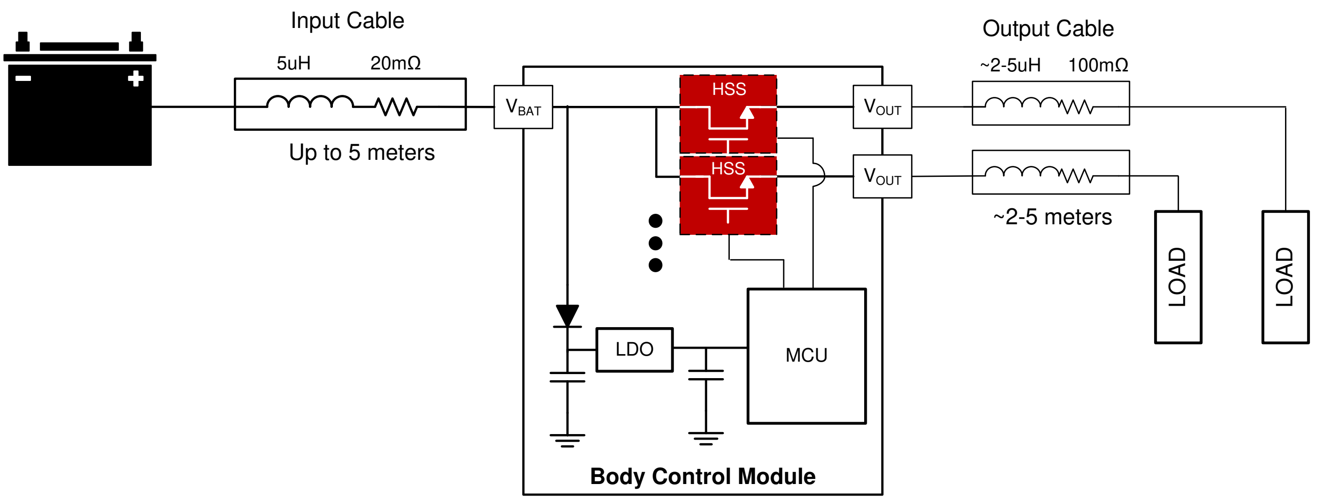
This is especially dangerous on the output cables, connectors, and PCB traces as they are only rated for the nominal currents that are seen. With TI's smart high-side switch, the current limit can be set just above the peak nominal value such that if any event happens that raises the current, it will be shut off immediately. While it is true that the first time the typical switch has this issue the cables, wire harness, and PCB traces will not immediately burn up, care should be taken to know that violating the absolute maximum current rating will most definitely affect long term reliability and potentially damage equipment. This case is seen in the *Improved Automotive Short Circuit Reliability Through Adjustable Current Limiting Tech Note*.

The natural concern comes up that the case described seems very specific. Most of the time soft shorts might not exactly be the value to keep the switch on, and the switch will naturally eventually hit thermal shutdown. Therefore, is there a benefit of using TI's adjustable current limiting to lower the current level at which the device turns off? Is there any downside if both TI's smart high side switches and standard high side switches shut off, but the standard switch lets a higher peak current through for a short amount of time? The "short" answer is yes; there is a big concern when switching off large currents with a smart high-side switch which is discussed in Section 2.2.2.2.

2.2.2.2 Short-Circuit Shut Off

As previously mentioned, there are input and sometimes long output cables that are connected to the BCM and by proxy to the load. With these long cables comes relatively large inductances.

Figure 7. Input and Output Cables Coming From the Battery and to the Load



The input cable does the job of isolating the V_{BATT} node from the actual car battery. As described in Section 2.2.1, the series impedance of the power source itself is extremely low and typically a single load short circuiting would not pull enough current for it to drop much voltage across. However, with this input cable with a series impedance much greater than the series impedance of the car battery, during a short-circuit event there can be a large voltage drop across this cable. Moreover, due to the large inductance on the cable, there is a lot of large ringing on V_{BATT}. This can be a critical issue for the high-side switch itself and for any other IC on the board that is receiving the battery voltage. If this ringing on the V_{BAT} lines goes below an undervoltage threshold for the high-side switches connected to this node, then they shut off causing any loads driven to not be powered until V_{BAT} ringing settles.

For the high-side switch, when the device hits the current limit it will shut it off for an set amount of time and then retry several more times until it finally goes into foldback mode where it does not allow large currents to go through. However, most high-side switches have an undervoltage protection where if they are not receiving > 3–5 V they will shut down and the device gets reset. This means that during the ringing caused by shutting down the switch with input inductance, if the V_{BATT} or V_{BB} can go below that threshold and it will reset itself. Then the high side switch tries to enable back into the short circuit indefinitely, or at least until the ringing stops. So instead of shutting off and waiting a cool down period and then trying again, it will continually retry immediately which could be damaging to the switch itself if the device is too hot.

Also in a vehicle there are many safety-critical features that cannot be disturbed during a fault somewhere else. If a load on the BCM shorts and the V_{BATT} voltage gets too low for the rest of the board, the other ICs will lose functionality. Therefore, to mitigate this issue there must be a large capacitance on the V_{BATT} line to hold the voltage up during a fault. The equation for the current through a capacitor is

$$I = C \times \Delta V / \Delta t \tag{7}$$

In this scenario, the I is the short-circuit current, because we want the capacitor to take that current to inhibit the change in the voltage, ΔV / Δt. In this reference design, the smart high-side switch is driving approximately a 3-A load and a maximum 1.5 A load so the current limits are set to be 4 A and 2 A per channel, respectively. Comparatively, the standard high-side switch short-circuit current for any channel is 25 A. This means that the relative input capacitance must be 12.5 × to keep the same small change in voltage as the TI smart high-side switch.

$$I_{TI} = C_{TI} \times \Delta V_{TI} / \Delta t \tag{8}$$

$$I_{SHSS} = C_{SHSS} \times \Delta V_{SHSS} / \Delta t \tag{9}$$

$$\Delta V_{TI} = \Delta V_{SHSS} \tag{10}$$

$$I_{TI} / C_{TI} = I_{SHSS} / C_{SHSS} \tag{11}$$

$$I_{TI} \times C_{SHSS} = I_{SHSS} \times C_{TI} \rightarrow C_{SHSS} = 12.5 \times C_{TI} \quad (12)$$

The input capacitance is a key issue when driving loads with high-side switches because designers typically want to use ceramic capacitors since they are relatively cheap and have a low ESR. The voltage rating of ceramic capacitors is very important because the capacitance derates with increasing voltage. Since load dump pulse can be up to 40 V (as discussed in Section 2.2.1), the capacitor should be rated for 50 V. The issue is that there is no single ceramic capacitor that is 50-V rated and higher than approximately 10 µF. This means either there needs to be many capacitors in parallel which takes up large amounts of space, or the designer must use an electrolytic capacitor. The electrolytic capacitor becomes extremely problematic because it now opens the system up to being susceptible to reverse battery conditions, since a negative voltage on an electrolytic capacitor will cause it to be damaged. This means more protection is necessary on the board and the designer must use an ideal diode as described in Section 2.2.1.1.

All of these issues are mitigated by using TI's smart high-side switch devices. This shows that not only does TI's smart high-side switches improve the reliability of the system but it also lowers the size, and therefore cost, of the components.

2.2.3 Current Sensing

This section shows that even with driving a smaller load than the nominal load it is rated for, the current sense accuracy is still strong enough for the system.

In the automotive environment there are many different control loops. In this reference design the HVAC system is being discussed which itself has a large control loop. The A/C unit of a vehicle consists mainly of a compressor, a condenser, an evaporator, and a pressure sensor. The coolant is moved through the system by the compressor and changes pressure. When it is flowing through the evaporator it is low pressure to make the air cold. When the coolant is flowing through the condenser the pressure is high which makes the coolant hotter. In the system there is also a pressure sensor as Figure 8 shows. The compressor also has a valve inside of it that can minutely control the pressure inside of the compressor. This means that the current controlling the valve in the compressor is directly related to the overall pressure measured by the pressure sensor. This reference design covers TI's smart high-side switches control of the current going into the valve and how accurate it can be.

Figure 8. Air Conditioning Control Loop

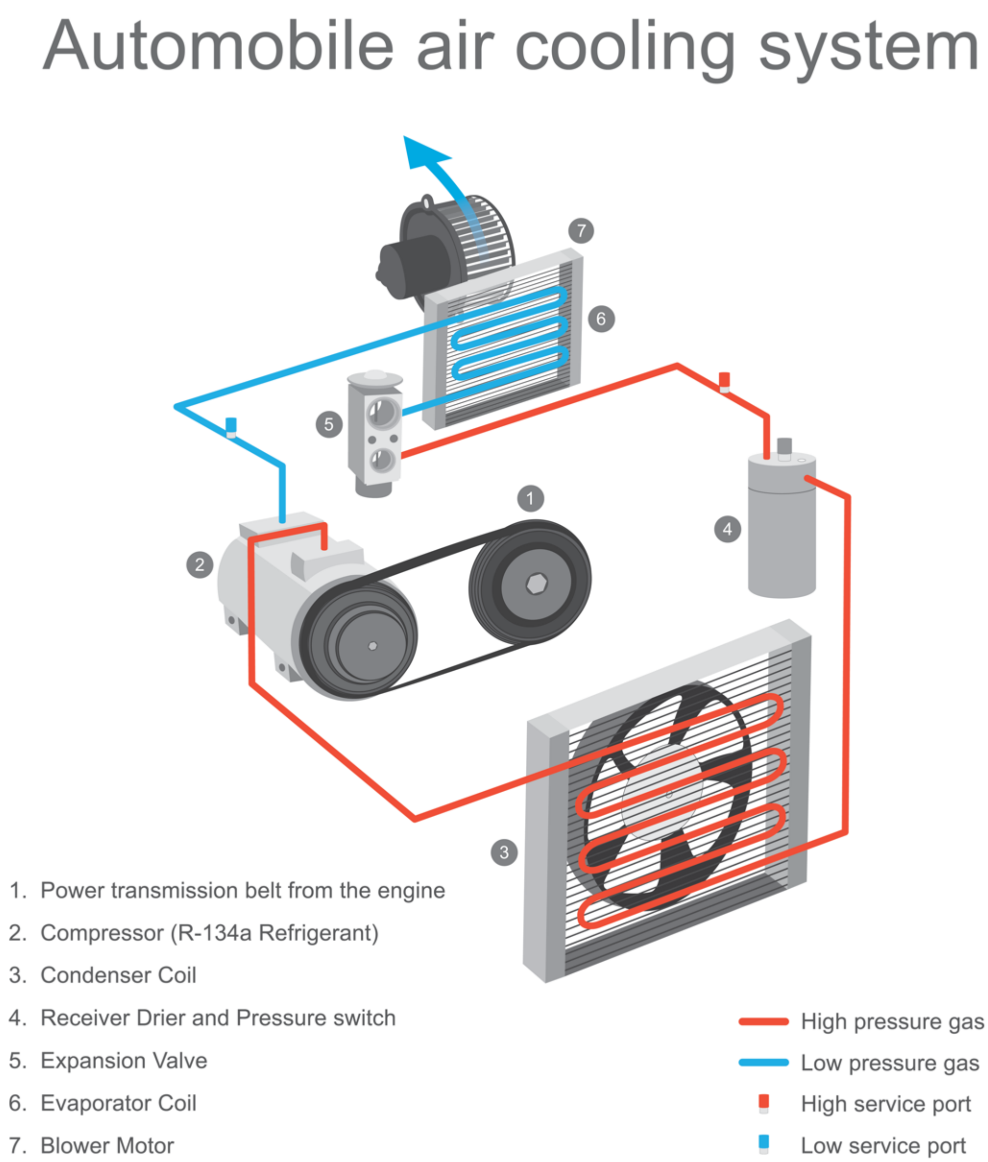


Figure 8 shows the total A/C system, the current that is flowing through the compressor valve is directly proportional to the pressure in the system. The main microcontroller takes the current sense reading, relates it to the pressure reading from the pressure sensor and then adjusts the current through the switch to the valve to adjust the pressure. If the system is not accurate in the current to the load and if that current is not accurately adjusted for the pressure of the system, the overall HVAC system may be operating inefficiently. Therefore, current sensing applications must be very accurate to not damage the system as a whole.

The TPS2HB50-Q1 device has very accurate current sensing capability that allows the user to know the current going through the switch. This is highlighted in the *TPS2HB50-Q1 40-V, 50-mΩ Dual-Channel Smart High-Side Switch Data Sheet* and implemented by an output pin SNS that has a load current ratio of 1500. Taking this reference across a sense resistor and connecting it to an ADC input converts this into an analog voltage that can relate the current going into the load. The ADC has a certain resolution to it based on the number of bits which corresponds to the current resolution in the design. This process is seen in the following equations:

$$I_{SNS} = I_{LOAD} / 1500 \quad (13)$$

$$V_{SNS} = I_{SNS} \times R_{SNS} \quad (14)$$

$$\text{ADC Step Size} = V_{ADCmax} / 2^{\#\ \text{of bits}} \quad (15)$$

$$\text{ADC Resolution} = ADC_{STEP} / V_{ADCmax} \quad (16)$$

For this design, there is a specific channel that is being measured. The maximum load is 1.5 A, and the ADC voltage maximum is 3.3 V. Therefore, when 1.5 A is going through the V_{OUTx} pin the SNS current output is 1 mA. Having 1.5 A as the largest ADC value wanted to be read for the design, the SNS resistor chosen corresponds to 3.01 kΩ. This also means that the lowest acceptable load to read is 200 mA, which gives 13%-100% control. Table 2 shows these values.

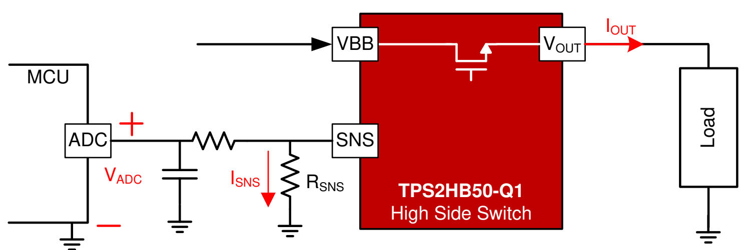
Table 2. ADC Voltage Calculation

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

2.2.3.1 *Accuracy*

Additionally there is some error associated with the TPS2HB50-Q1 SNS pin. This error is quantified on the data sheet in the electrical characteristics which states that for loads over 1 A, there is a maximum ±4% error. The error increases in the device as the load current goes down. With the lowest load current being 200 mA, the associated error in the device is approximately ±7%. Figure 9 shows the current-sense circuit.

Figure 9. Current-Sensing Circuit



To calculate the total error in the system, several system tolerances must be accounted for.

Table 3. Parameters

CIRCUIT	PARAMETER, (PERCENT ERROR)
$I_{SNS@1.5A}$	1 mA, (±4%)
$I_{SNS@0.2A}$	0.13 mA, (±7%)
R_{SNS}, Current Sensing Resistor	3.01 kΩ, (±1%)
ADC number of Steps	1023
ADC Tolerance	±4 bits
V_{REF}, ADC reference voltage generated by the LDO	3.3 V, (±2%)
I_{LEAK}, ADC input Leakage	±3.5 µA

Note that the high-side switch leakage is not in the table because it is already factored into the I_{SNS} error in Table 3. Taking into consideration all of these factors, Table 4 shows the calculation of the worst-case accuracy.

Table 4. Calculated Worst-Case Error

CONFIGURATION	I_{OUT} (A)	I_{SNS} MAX (mA)	I_{SNS} TYP (mA)	I_{SNS} MIN (mA)	ADC MIN (BITS)	ADC TYP (BITS)	ADC MAX (BITS)	% -ERROR	% +ERROR
Full Load	1.5	1.04517	1	0.95804	864	933	1009	7.44%	8.14%

Table 4. Calculated Worst-Case Error (continued)

CONFIGURATION	I_{OUT} (A)	I_{SNS} MAX (mA)	I_{SNS} TYP (mA)	I_{SNS} MIN (mA)	ADC MIN (BITS)	ADC TYP (BITS)	ADC MAX (BITS)	% -ERROR	% +ERROR
Lowest Load	0.2	0.21403	0.2	0.18698	165	187	210	17.53%	20.43%

Table 5 shows the corresponding typical high-side switch error calculations.

Table 5. Calculated Typical High-Side Switch Error

CONFIGURATION	I_{OUT} (A)	I_{SNS} MAX (mA)	I_{SNS} TYP (mA)	I_{SNS} MIN (mA)	ADC MIN (BITS)	ADC TYP (BITS)	ADC MAX (BITS)	% -ERROR	% +ERROR
Full Load	1.5	0.94	0.833	0.747	673	778	872	13.48%	12.19%
Lowest Load	0.2	0.16	0.111	0.082	70	104	154	32.25%	48.43%

NOTE: The calculation method used in Table 4 to generate the total percent error is highly pessimistic since it simply adds the worst case maximum error for each variable.

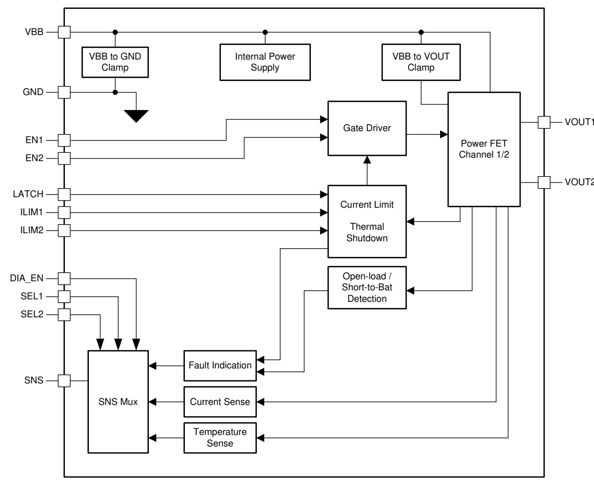
In a real system, however, each variable has a distribution associated with its percent error. For this reason, the actual percent error observed should be less than the one calculated by adding the worse case values.

2.3 Highlighted Products

2.3.1 TPS2HB50-Q1

The TPS2HB50-Q1 device is a dual-channel smart high-side switch intended for use with 12-V automotive batteries. The device integrates many protection and diagnostic features. The device provides a high-accuracy analog current sense that enables improved diagnostics of complex loads (such as multiple parallel loads driven by the same switch). The TPS2HB50-Q1 device includes a programmable current limit, which allows for optimized protection in a wide variety of load applications. The device operates with an input voltage down to 3 V (as measured with respect to the device GND pin). This input voltage allows for continued operation when the battery voltage drops during cold crank.

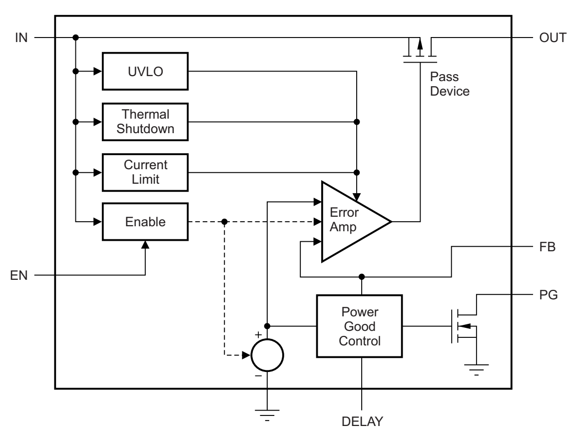
Figure 10. TPS2HB50-Q1 Functional Block Diagram



2.3.2 TPS7B8233-Q1

The TPS7B8233-Q1 ultra-low power, low-dropout (LDO) voltage regulators offer the benefits of ultra-low quiescent current, high input voltage, and miniaturized, high-thermal-performance packaging. The TPS7B8233-Q1 devices are designed for continuous or sporadic (power backup) battery-powered applications where ultra-low quiescent current is critical to extending system battery life. The TPS7B8233-Q1 devices offer an enable pin (EN) compatible with standard CMOS logic and an integrated open-drain active-high power-good output (PG) with a user-programmable delay. These pins are intended for use in microcontroller-based, battery-powered applications where power-rail sequencing is required.

Figure 11. TPS7B8233-Q1 Functional Block Diagram



3 Board Design, Hardware, Software, Testing Requirements, and Test Results

3.1 Board Design

Section 2.2 covers the requirements generically for many different automotive loads. This section covers specific details of the board design and the nature of the A/C compressor valve and magnetic clutch loads.

3.1.1 A/C Compressor Valve

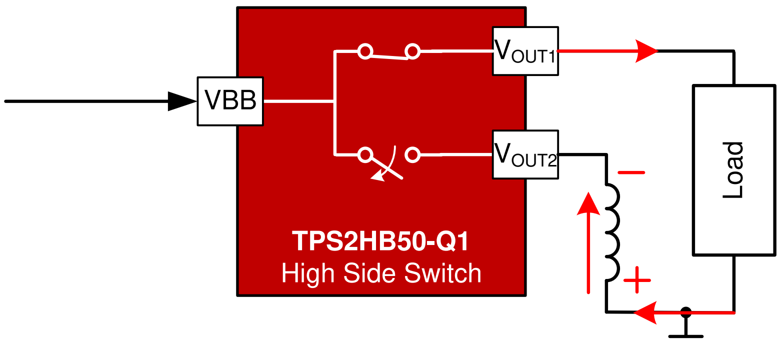
Figure 12. A/C Compressor Valve

The A/C compressor valve affects the pressure inside the compressor. The signal to the compressor valve is pulse-width modulated so that the current flowing through it can be adjusted. The compressor valve acts as a solenoid load, which means it has the characteristics of an inductor. Therefore, when it turns off there is a large negative transient because the inductor is resisting the change in the current. Equation 17 shows that when there is a negative change in current, the voltage goes negative as well.

$$V = L \times dI/dt \quad (17)$$

This means some sort of clamping diode is necessary. It is important to note that, as described in the *How To Drive Inductive, Capacitive, and Lighting Loads With Smart High Side Switches Application Report*, the high-side switch device can drive this load easily because it has an internal clamping diode that keeps the part safe. However, since this load is physically attached to the magnetic clutch load and they share the same ground, the negative transient voltage means that current will start flowing from one load that is on into the other load. This is pictured in Figure 13. With this valve being greatly influential in the control loop for knowing the amount of pressure through the system, this is not acceptable to have a back flow of current.

Figure 13. Inductor Turn off With Second Load



Since this load is pulse-width modulated it is constantly turning on and off quickly which makes the addition of a flyback diode even more necessary.

3.1.2 A/C Magnetic Clutch

Figure 14. A/C Compressor Magnetic Clutch

The magnetic clutch is used to engage the compressor. Technically it acts as a big solenoid or electro magnet that when a current is applied connects the two discs together. The larger disc with groves around it is what is connected to the main belt of the vehicle, and when the vehicle is on, it is spinning. The smaller disc in front of it is the other half of the solenoid, and when it has current going through it, it connects to the bigger disc. This basic functionality controls if the compressor (and therefore the A/C) is on or off while the car is on (main belt spinning). The magnetic clutch in an A/C compressor varies slightly in the amount of current from one vehicle to another, but the one tested in this design maintained a constant 3.2 A when powered.

This load is just like most other automotive loads in that it is susceptible to a short-circuit event. During this short-circuit event, typical high-side switches will allow large amounts of current as discussed in Section 2.2.2.1. When doing the layout, wire harness, and wiring for this load it is questionable to have all of them rated for the typical current seen through the load. Since a typical high-side switch will not know the difference between normal operation and high current operation unless it hits thermal shutdown: also discussed in Section 2.2.2.1. This is a key factor in TI's adjustable current limiting as it allows the device to be shut off immediately if the load goes into a higher current state and keep the reliability of PCB trace and wire harness attached to it.

As with the compressor valve, this is a solenoid that, when the device does turn off, there is a large negative voltage on the power line to this load. This also means the addition of a flyback diode is necessary since other loads are connected to the same ground as discussed in Section 3.1.1. The compressor used in this reference design has an integrated flyback diode but there was space provided on the board for one if necessary.

3.2 Required Hardware and Software

The following sections describe the required hardware and software for correct functionality of the TIDA-00971 reference design.

3.2.1 Hardware

The following hardware is required for testing:

- One TIDA-00971 board
- A microcontroller capable of reading in an ADC value and adjusting a PWM output, the MCU used is a MSP430 LaunchPad™
- A/C compressor with valve and magnetic clutch
- Car battery or large capacitor bank to mimic a car battery
- Long, low resistance cable to mimic cable inductance (approximately 5 µH) and resistance (approximately 20 mΩ) in vehicle
- Oscilloscope with voltage and current probes

3.2.2 Software

The TIDA-00971 reference design comes capable of connecting to a MSP430 LaunchPad that can do the current sensing and adjusting of the output PWM duty cycle. Any microcontroller with this functionality will work for this design and the code behind it will vary greatly depending on the MCU.

3.3 System Setup

If a car battery is used, connect it directly to the J4 and J5 terminals which power the whole board. If not, then a 13.5-V supply must be connected to the capacitor bank and then to the positive terminal (J4) and negative terminal (J5) to power up the board (see Figure 15). The power supply and cables used for connection must be rated for 5 A.

Figure 15. Default Board Setup

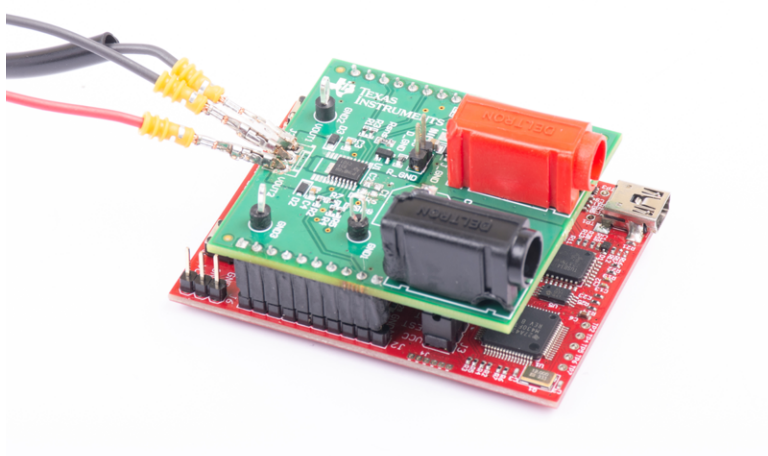


Table 6 shows the function of test points.

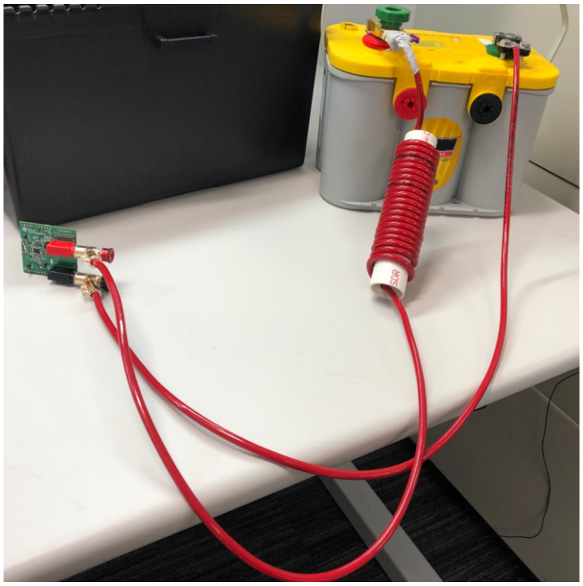
Table 6. Key Design Items

NAME	VALUE	DESCRIPTION
J4, J5	Power terminals	These are the two banana jack terminals that are for the input and ground of the car battery
C_IN	Not Populated	Example footprint needed if current limit is too high, as discussed in Section 2.2.2.2
C1	2.2 µF	Input capacitance on VBB
GND1, GND2, GND3, GND4	Ground test points	Ground test points to connect probes to
J_GND	Jumper	This jumper is to bypass the diode resistor ground network on the IC ground of the device. For more information see Section 2.2.1.1
Rsns	3.01 kΩ	Current sensing resistor discussed in Section 2.2.3
D2, D3	Flyback diode	Flyback diodes for the outputs needed because the design has solenoid loads

4 Testing and Results

The TIDA-00971 reference design is characterized by running the short-circuit testing to see what happens to the system with TI's adjustable current limiting and existing industry high fixed current limit. Also, the testing covers the current sensing output difference between what is measured through the ADC of the MCU and what is measured in the system. The following subsections detail the procedures, results, and conclusions of the adjustable current limiting and accurate current sensing for automotive load diagnostics.

Figure 16. TIDA-00971 With Car Battery Test Setup



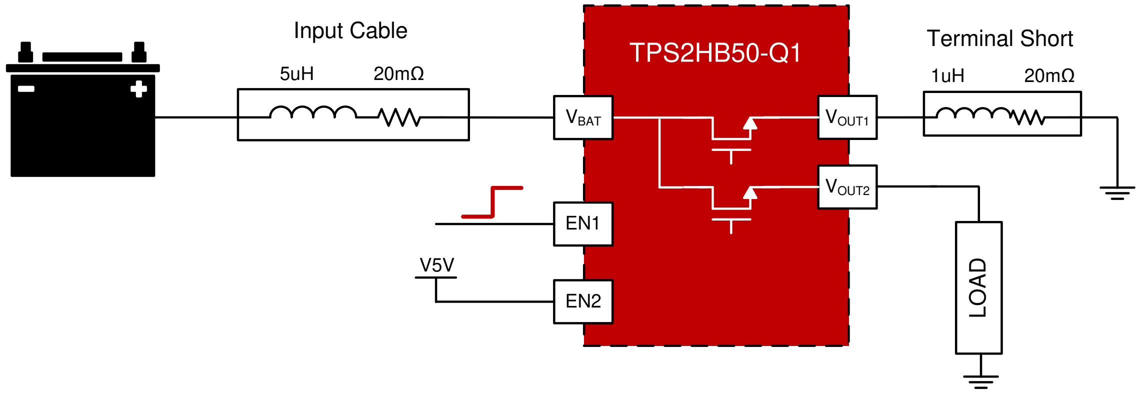
4.1 Short-Circuit Condition

This section offers the detailed testing procedure and results of short-circuit event.

4.1.1 Test Setup

For this test the "long cable" (5 meter 8 AWG) was used at the input to mimic the actual cabling in a vehicle. This introduces a large inductance (approximately 5 µH) with relatively small impedance (approximately 20 mΩ) on the input separating the car battery from the board. Next the output was terminally shorted, which in the real world can be modeled with a 1-µH, 20-mΩ inductor. The second channel of the device was connected to the magnetic clutch load. This simulates a short on the compressor valve output.

Figure 17. Short-Circuit Test Setup Diagram



The oscilloscope was connected to measure the V_{BB} pin, enable signal (EN1), V_{OUT2}, and the input current waveform. For this test the input capacitance was a 2.2-µF ceramic capacitor, which is very common in automotive applications and is small enough to not be too expensive. Also the Rlim value is set at 25 kΩ which according Equation 18 from the data sheet, corresponds to an approximately 8-A current limit. A 30-A current limit was then used to model a typical high-side switch device.

$$I_{CL} = K_{CL} / \text{Rlim (k}\Omega) = 200 / 25 \text{ k}\Omega = \sim 8 \text{ A} \quad (18)$$

The magnetic clutch load is enabled (EN2) at the start of the test and the first channel tries to start up into a terminal short.

4.1.2 Test Results

The waveforms show that with a traditional high, fixed current limit switch, the V_{BB} swings so low that it puts the device in UVLO state which turns off the output of the second channel. With the TI adjustable current limit switch the device still rings, but the amplitude of the ringing is much lower since the change in current is much less as described in Equation 17. The teal waveform is the enable signal which turns the first channel on. The blue waveform is the current going into the switch. The green waveform is measured at the V_{BB} pin. The purple waveform is the output voltage on the second channel at the V_{OUT2} pin. The second channel enable signal is high so the second channel is suppose to be always on. However, Figure 18 shows that for a typical high side switch the V_{OUT2} goes up wit the spike on V_{BB} but then the channel shuts off because V_{BB} swings backdown and hits the under voltage threshold. In Figure 19 using TI's smart high side switch the current and voltage does not swing as high or low which means the second channel stays on after short circuit event ends.

Figure 18. Typical High-Side Switch Current Limit Short-Circuit Waveform

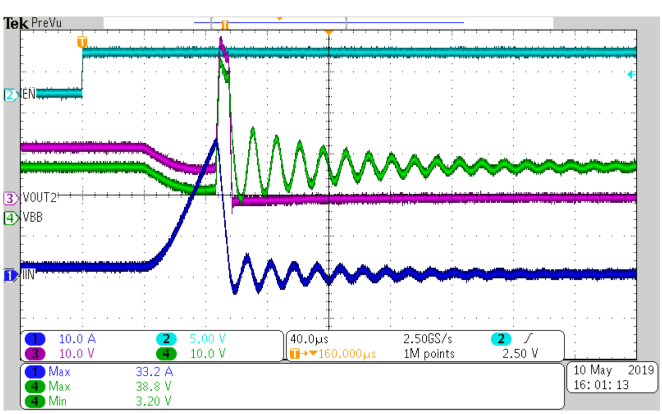
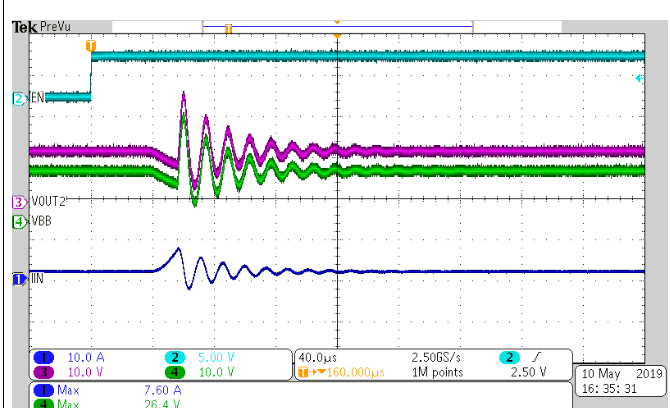


Figure 19. TI Adjustable Current Limit Short-Circuit Waveform



This is unacceptable for most applications that a short circuit on one output can cause other outputs to turn off. It is obvious that the cable inductance is causing the VBB of the device to ring which rings the output. However, with setting the current limit low for the specific load, the disturbance on VBB is limited and does not cause the entire part to go into an undervoltage event and shut down.

This can be extrapolated for other high-side switches connected to the same VBB net. All of the high-side switches on the ECU experience this undervoltage event and shut down. Having a low short-circuit current can reduce the fault case from happening to all the loads on the board down to just the original channel.

The disturbance on the line is very minimal because the TI smart high-side switch hits current limit so quickly and shuts off to protect the system.

4.2 Accurate Current Sensing

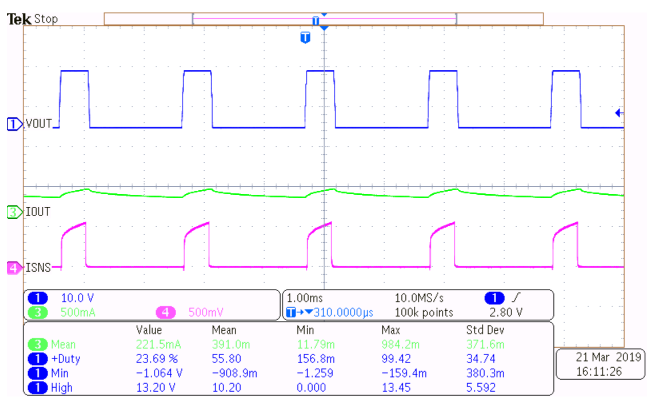
4.2.1 Test Setup

For the current sensing the output was connected to the A/C compressor valve and was measured using a current probe. The enable pin was pulse-width modulated at 200 Hz and the duty cycle was varied from down to 24% up to 95%. While the SNS pin goes to an ADC pin of the microcontroller, the microcontroller output varies widely depending on code. For a more reliable output value, the direct voltage going into the ADC was measured. This means that obviously the accuracy will be higher than worst-case analysis because the microcontroller error is not factored into the measurements. The output current sense shuts off when the device disables which means the microcontroller must be measuring the times at which it was currently enabling the device, which is easy, since it is the one doing the pulse-width modulating of the enable pin.

4.2.2 Test Results

Figure 20 shows the result for 24% duty cycle. The average current flowing through the load was 221 mA.

Figure 20. Current Sense Accuracy at 24% Duty Cycle



Since the current sense mechanism is measuring the current going through the switch, when pulse-width modulating the enable pin, the current sense output turns off. So taking into consideration that the measured current is only valid when the part is enabled gives an error graph of Figure 21 and an average error of 3.19%. However, looking at the error graph, the error does increase for the light load and, decreases as the current rises.

Figure 21. Error Graph at 24% Duty Cycle

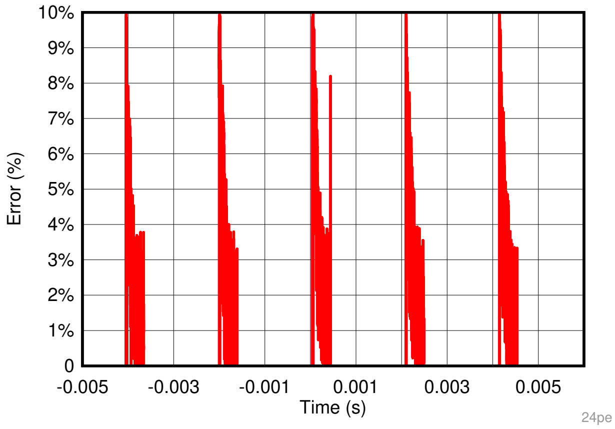
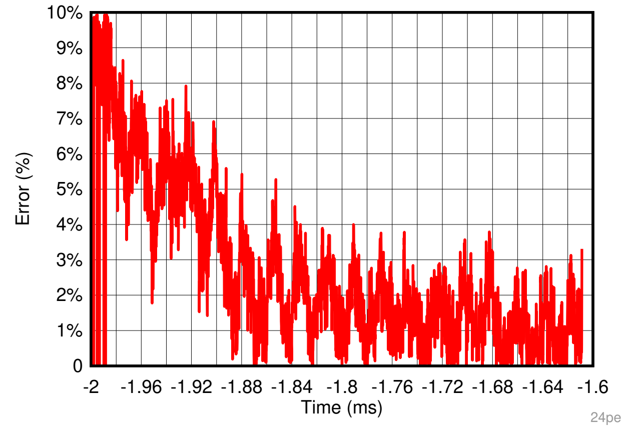


Figure 22. Zoomed in Error Graph at 24% Duty Cycle



The next duty cycle is at 95%. This is essentially almost the full load but still has a distinction of not being fully on. The average load current was 1.03 A.

As with the 24% duty cycle case, the average error was only taken into consideration when the device was turned on. This yielded a slightly high average error of 4.32% but it was more constant throughout the load profile.

Figure 23. Current Sense Accuracy at 95% Duty Cycle

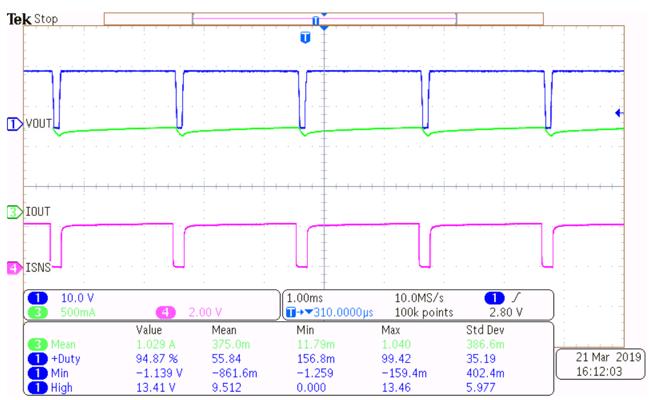
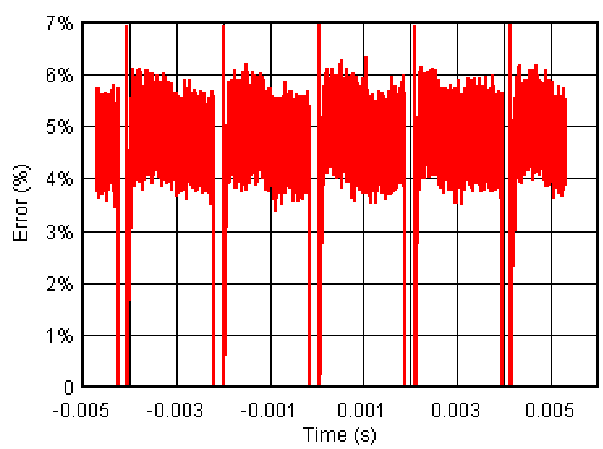


Figure 24. Error Graph at 95% Duty Cycle



5 Conclusion

Short-circuit events are very common in automotive applications. These events can be dangerous to the system as a whole. Typically, high-side switches have a very high current limit that means during a short-circuit event the current can easily go up to ten times the nominal value. This can cause an unstable supply to the power of the rest of the board and even cause them to all shut down. TI's adjustable current limiting allows the system to be protected from a short-circuit event and causes minimal disturbances to the other devices. Additionally, TI's accurate current sensing allows for precise measurement of the load current in the system which helps in the overall control loop of the system. The control loop can adjust the duty cycle to decrease and increase the output current according to the system needs. Together these two design challenges are solved using TI's smart high-side switches.

6 Design Files

6.1 Schematics

To download the schematics, see the design files at TIDA-00971.

6.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00971.

6.3 PCB Layout Recommendations

Each device follows the layout recommendations as specified in the respective data sheet. All power traces are made thick enough to handle the maximum current for each power rail. All bypass capacitors are placed as close to each device as possible.

6.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-00971.

6.4 Altium Project

To download the Altium project files, see the design files at TIDA-00971.

6.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00971.

6.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00971.

7 Related Documentation

1. Texas Instruments, *TPS2HB50-Q1 40-V, 50-mΩ Dual-Channel Smart High-Side Switch Data Sheet*
2. Texas Instruments, *Adjustable Current Limit of Smart Power Switches Application Report*
3. Texas Instruments, *How To Drive Resistive, Inductive, Capacitive, and Lighting Loads With Smart High-Side Switches Application Report*
4. Texas Instruments, *Reverse Battery Protection for High-Side Switches Application Report*

7.1 Trademarks

MSP430, LaunchPad are trademarks of Texas Instruments.