Reverse battery protection for high side switches

Mahmoud Harmouch, Cameron Phillips

ABSTRACT

Reverse battery, often referred to as reverse polarity, is extremely common in automotive applications. This application report details the reverse battery mechanism, impact and protection of TI smart high side switches and the MCU as well. This document also goes through the different circuit topologies in order to protect the system from reverse polarity events.

Contents

List of Figures

List of Tables

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

Reverse polarity is a common mistake. The way that a reverse polarity event is defined is by connecting what should be the system ground to a positive potential (voltage) and grounding what should be the supply port. It can happen after maintenance or during reconnecting the battery when the wires get crossed. Reverse polarity can lead to catastrophic damage in the electronic circuit even in a short time. The main cause of damage is the non-controlled reverse current through ESD cells inside the high side switch and potentially the MCU. Reverse polarity protection consists of limiting the reverse current or blocking it completely. There are several areas that are susceptible to reverse battery conditions. This document goes through each of the areas and their mitigation.

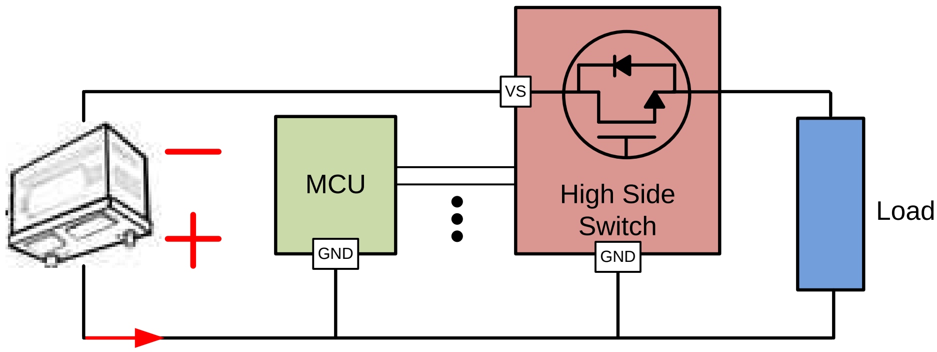

Figure 1. Reverse Battery Configuration

Table 1. Reverse Battery Causes and Mitigation

Failure Cause During Reverse Battery	Mitigation
Excess Reverse Current Through High Side Switch Ground Pin	Diode + Resistor Ground Network
Excess Current Through MCU Pins into High Side Switch	Current Limit Resistors on all MCU Connected pins
Excess Reverse Current Through Load into High Side Switch	Blocking Diode

2 Methods of Mitigating Reverse Polarity

There are several different methods of blocking the reverse current: adding a diode resistor ground network to limit the current flow into the device, adding a blocking diode on the supply to prevent the current loop, or adding current limiting resistors in between the MCU and the high side switch. Naturally using all of the methods will have the most protection but each have their own benefits if designers are constrained to a subset of them. These methods are detailed below and will ensure that the system is safely protected during reverse polarity events.

2.1 Ground Network

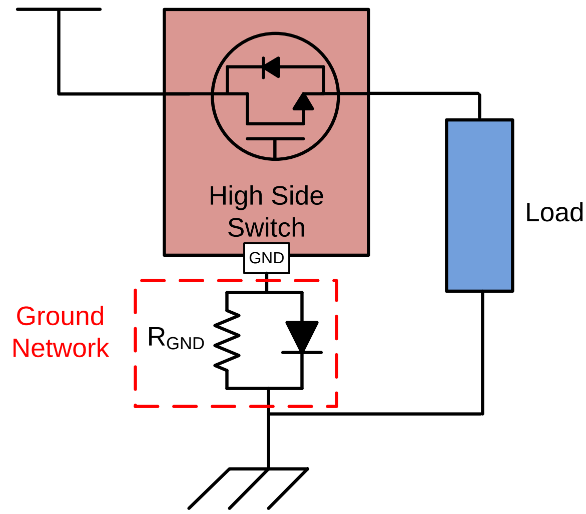

Figure 2. Diode-Resistor Ground Network

The first method consists of current limiting resistor and a diode between high side switch device ground and system ground (GND network) shown in Figure 2. The GND network is a cheap solution and does not consume any power during normal operation. This is due to the fact that during normal operation the diode is forward biased to ground bypassing the resistor. However when there is a reverse current, the resistor will limit the flow back into the device to a safe level. The GND network limits the current through the ground pin of the high side switch by Equation 1

$$I_{GND} = V_{BATT} / R_{GND} \quad (1)$$

The datasheet of the high side switch will have the acceptable reverse current allowed. The selection of the R_{GND} has to also take into consideration that there will be a power dissipation through the resistor during a reverse battery event. Calculate the power going through the resistor during a reverse battery event using Equation 2 to appropriately size the resistor for each application .

$$P_{RGND} = V_{BAT}^2 / R_{GND} \quad (2)$$

For most applications TI recommends a 1-kΩ resistor. This protects the high side switch from internal damage due to ESD cell between the supply pin and device ground. As can be seen in Figure 3 the current is regulated through the GND pin up the ESD cell and out the supply pin. Figure 3 also shows all of the ESD cells that are on the pins and the pins names. Note that the pin names in parenthesizes apply to the low R_{ON} family of TI high side switches, TPSxHBxx-Q1 such as TPS2HB08-Q1 but function similar to the higher R_{ON} devices, TPSxHxxx-Q1 devices. The device will also only have either R_{LIM} or R_{CL} based on if it is a low R_{ON} device or 100 mΩ and above. Reverse current paths and directions are shown in red.

Also note that the resistor diode ground network does not protect the reverse current in the main FET. This FET current is only limited by the load itself, if the load can not limit the FET current that is electrolytic capacitor load, a blocking diode is necessary as discussed in Section 2.3.

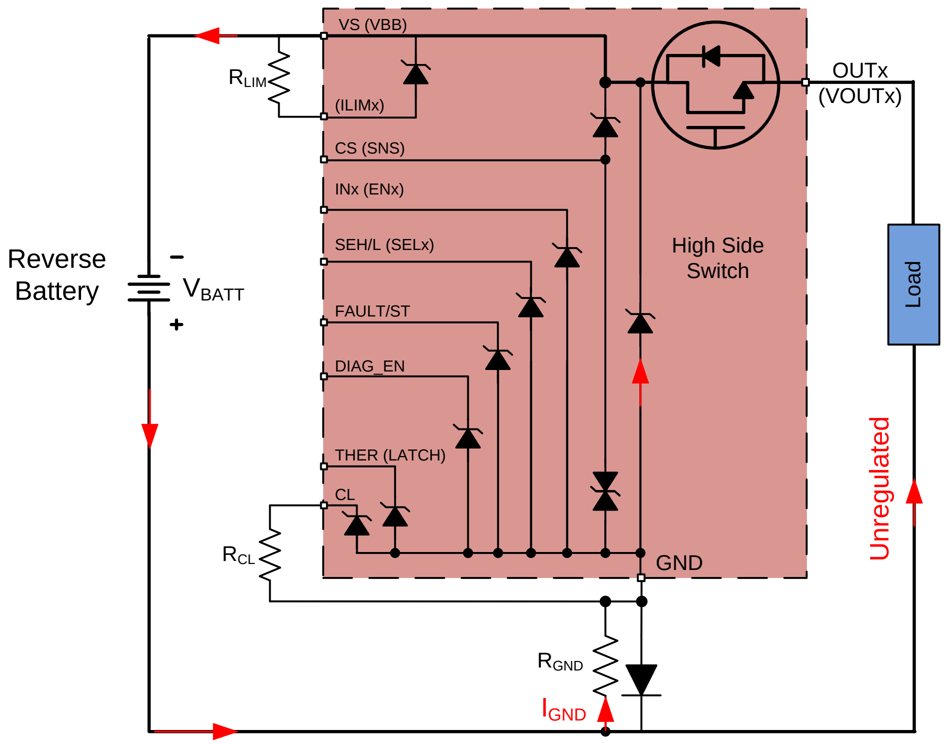

Figure 3. Ground Network Protection Application

2.2 MCU Current Limiting Resistors

In the typical application of high side switches, there is a microcontroller that monitors the diagnostics and decides to enable or disable the device. The pins being used of the microcontroller are the ADC pins (for current and fault sensing) and GPIO pins (for enabling device and other setting). The ADC pins of the microcontroller would go internally to some comparator that would be high impedance inputs, however there would be an internal ESD diode on the pin that would go to the ground of the MCU. Quite similarly to the high side switch, this ESD cell is an issue as it will conduct current in the negative direction during a reverse polarity condition.

Additionally, the GPIO pins of most MCU's have push-pull operation which mean they have pull up FETs and pull down FETs to enable high or low signal output. This is also an issue in context of a reverse polarity scenario because the body diode of the pull down FETs will conduct current. The mitigation for these issues is to have current limiting resistors on the lines connected to the MCU that regulate the current that flows out of the MCU pins into the high side switch pins. This can be seen in Figure 4.The current through the resistor can be calculated using Equation 3.

$$I_{PROT}=(V_{BATT}-V_{F\_MCU}-V_{ESD\_HSS}) / R_{PROT} \quad (3)$$

Typically the forward voltage of the body diode and ESD diode, V_{F_MCU}, will be approximately 0.7-1V. The DC reverse breakdown voltage of the V_{ESD_HSS} will normally be shown in the absolute maximum value of the datasheet, that is TPS4H160-Q1 has –7 V as the maximum value for the control pins. It is important that the I_{PROT} is acceptable for the MCU to output and for the high side switch to take in. For that reason TI recommends R_{PROT} to be 10 kΩ or another high impedance resistance. Figure 4 also shows the ground network as discussed in Section 2.1. As in the previous section though the current flow through the load is not regulated and has to be accounted for by a blocking diode.

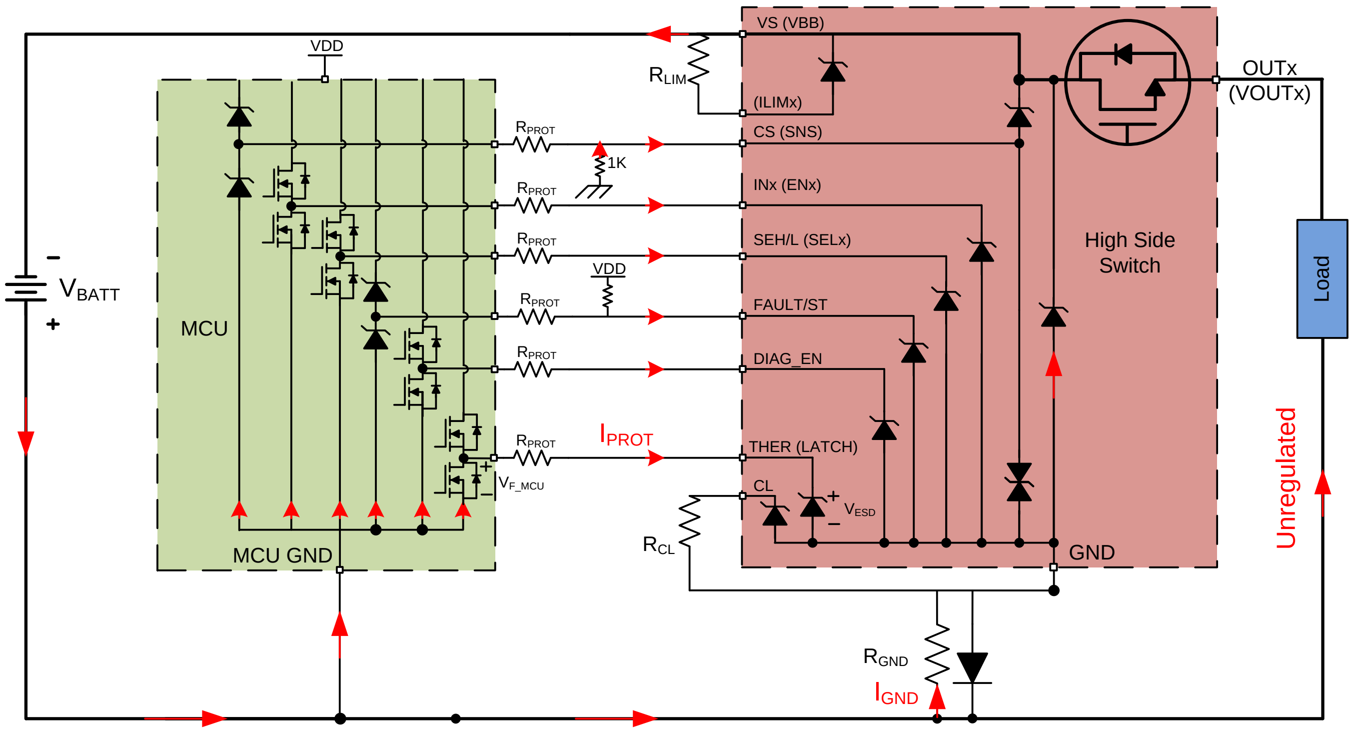

Figure 4. MCU Current Limiting Resistor Application

2.3 Blocking Diode

A blocking diode placed between the high side switch supply pin prevents any current flow in the system during a reverse battery condition. The blocking diode blocks the reverse current in any path. The MCU GND and the device GND are at the same voltage as well as the current through the ESD cells is now blocked. As can be seen in Figure 5, reverse current is zero and the blocking diode protects the high side switch, MCU and load from damage.

The issue with the blocking diode is that there is power dissipation associated with the diode. Typically shottky diodes can have from 300 mV to 1 V of forward voltage with the nominal DC currents of the high side switch. For instance if the voltage drop is 500 mV at 2 A current the DC power dissipation would be 1 W. This means the diode needs to be appropriately sized for the maximum power dissipation that could be seen in it.

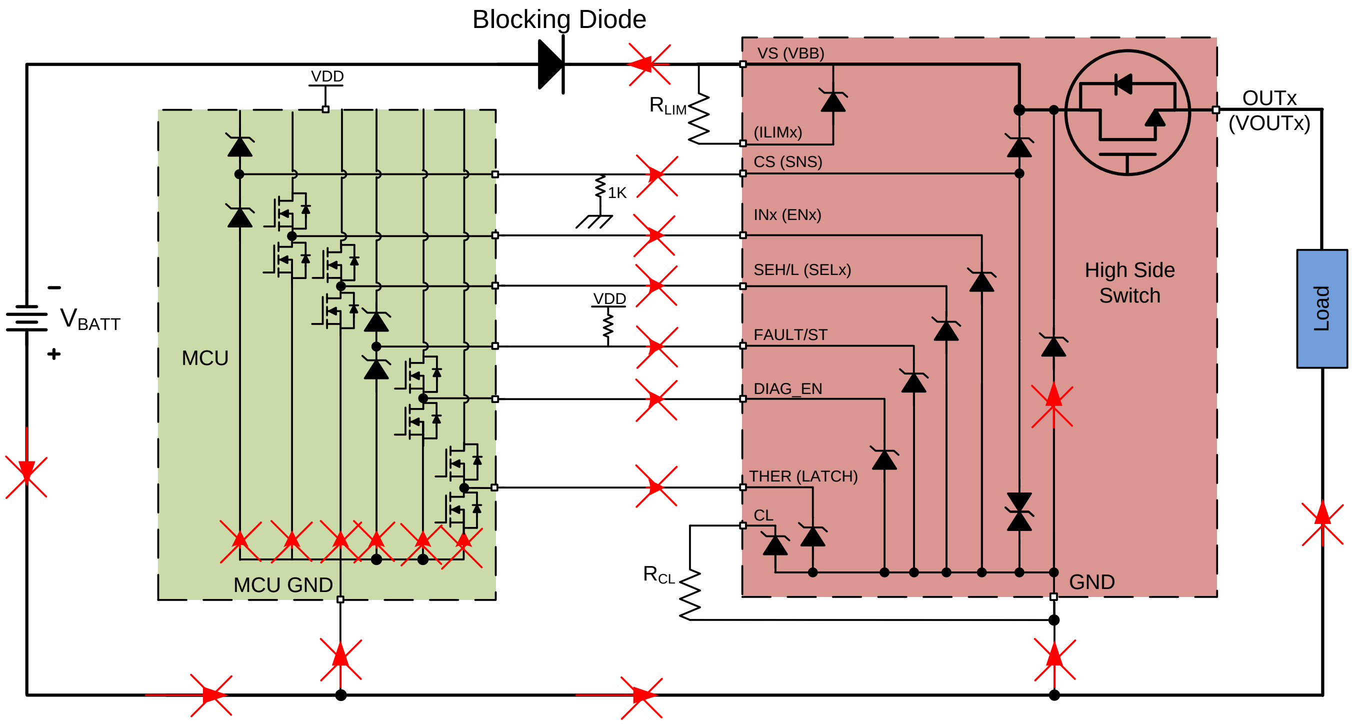

Figure 5. Blocking Diode

3 Bench Test Verification

In order to test the capability and protection of the high side switches during a reverse polarity event, the EVM for the high side switches was modified to test out the different protection topologies. This section goes through a couple devices to show that they can survive a high negative voltage on the supply. Note also that the blocking diode was not tested as by definition it will protect the device from damage since there is no negative flow of current.

Since the MCU just provides a body diode or ESD drop and allows the current to flow through as discussed in Section 2.2, to test this on the bench the CS, INx, SEH/L, DIAG_EN and THER pins were connected to ground through a 10kΩ resistor effective bypassing the MCU voltage drop and putting the full negative voltage on the protection resistors. This can be thought as absolute worst case.

3.1 TPS4H160-Q1 Reverse Polarity

Using the TPS4H160EVM and connecting the control pins to ground through a 10 kΩ, we are able to measure the values of the pins. Table 2 shows the voltages and currents value on each I/O pin at 36-V reverse voltage. Figure 6 shows the EVM setup and connection. The test was done with putting a –36-V supply to simulate worst case negative battery transient. Note that the VBAT waveform in the oscilloscope screen shots is the System GND from the setup and all waveforms are with respect to the VS pin.

One very important note: unlike the rest of the pins, the CS pin has a lower impedance to it's ESD diode than any of the rest. That is due to the fact that the CS pin in all devices has to be in an acceptable range to reflect the output current during normal operation. Because of this, one of the big keys when running this test is to make sure the current through that resistor is not too high to break the internal ESD diode. This also will come into use when going to the higher current devices such as the low R_{ON} high side switches that will require lower resistor values on the current sensing output which in turn means more current flowing through in reverse polarity.

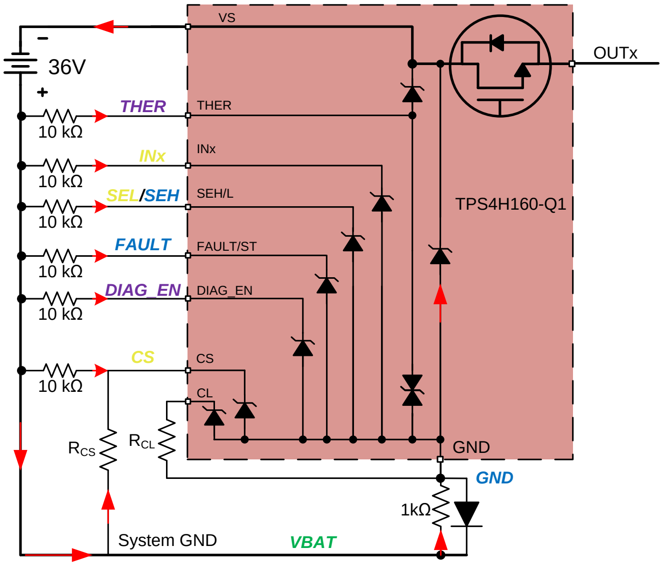

Figure 6. TPS4H160EVM Setup

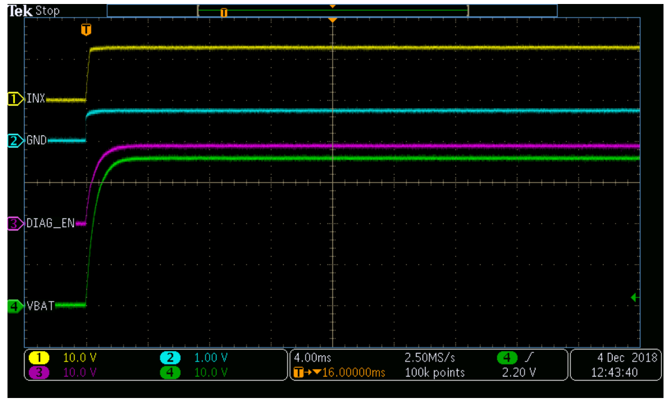

Figure 7. INx, GND, DIAG_EN

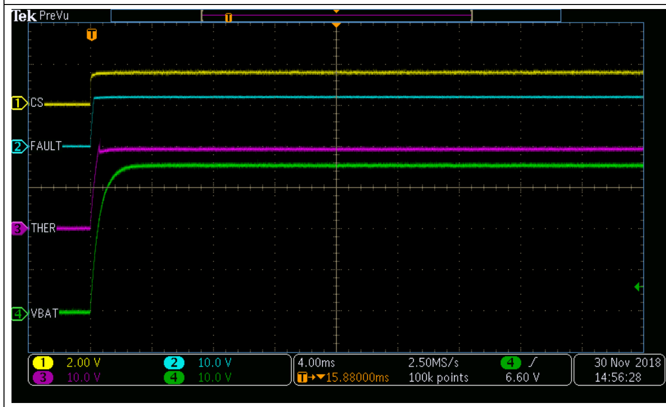

Figure 8. CS, FAULT, and THER Voltage

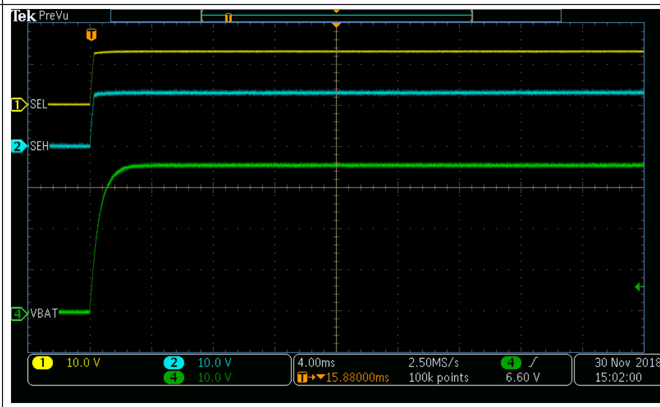

Figure 9. SEL and SEH Voltage

Table 2. TPS4H160-Q1 Reverse Polarity Measurements

VS to System GND	Device GND to System GND	Device GND to VS	INx to Device GND	DIAG_EN to Device GND	CS to Device GND	FAULT to Device GND	THER to Device GND	SEL to Device GND	SEH to Device GND
–36 V	35.3 V	0.7 V	12 V	18 V	0.9 V	11.3 V	18.3 V	12 V	12 V
Current	35.3 mA	N/A	2.4 mA	1.8 mA	13 mA	2.47 mA	1.8 mA	2.4 mA	2.4 mA

3.2 *TPS1H100-Q1 Reverse Polarity*

TPS1H100-Q1 is a single channel high side switch and has less I/O pins than TPS4H160-Q1. Figure 10 shows the test setup for TPS1H100-Q1 in reverse polarity. Notice it is similar to Figure 6 but with less I/O pins. Table 3 shows the voltages and currents during the reverse polarity testing.

TPS1H100-Q1 was tested at 18-V and 24-V reverse voltage. Since the TPS1H100-Q1 is a lower R_{ON} and single channel, it can have higher nominal currents than the TPS4H160-Q1. This means to have a current sense range large enough for the full range of nominal currents, the R_{CS} resistor must be smaller than it was on the TPS4H160-Q1. This means more current will be flowing through that resistor during a reverse polarity event. For this reason the TPS1H100-Q1 was tested at 18 V and 24 V so that the current would be at a safe level. This trade off of how high reverse polarity voltage can be taken by the device must be taken into consideration when designing the system as a whole.

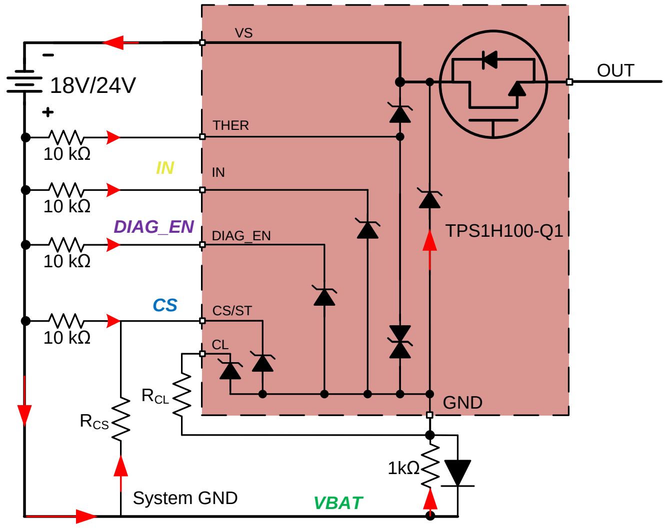

Figure 10. TPS1H100EVM Setup

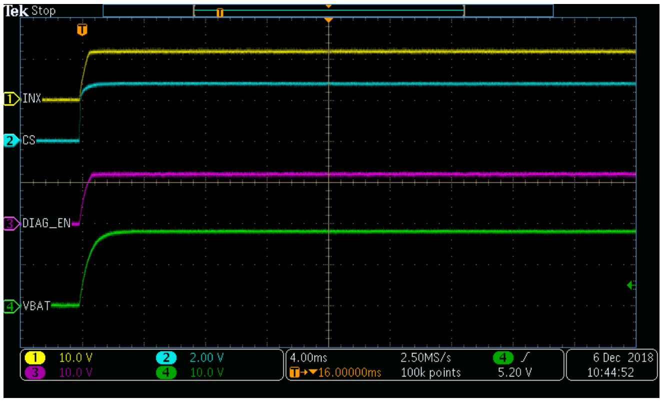

Figure 11. IN, CS, DIAG_EN and VBAT at 18 V

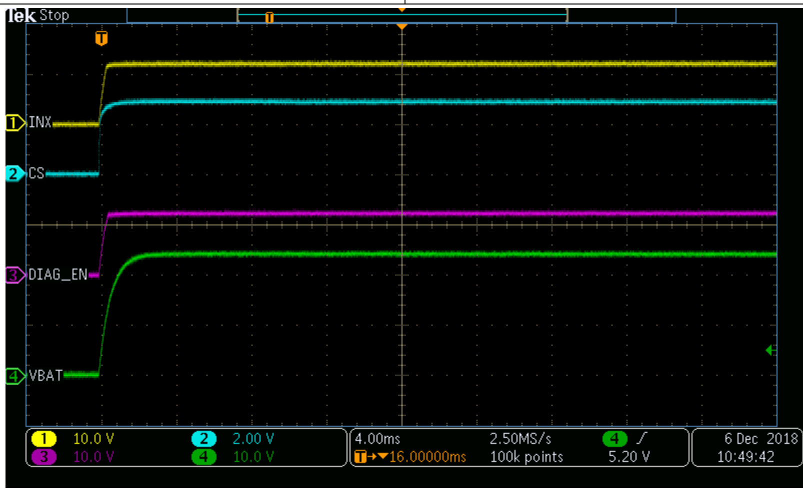

Figure 12. IN, CS, DIAG_EN and VBAT at 24 V

Table 3. TPS1H100-Q1 Reverse Polarity Test Voltages and Currents

VS to System GND	Device GND to System GND	Device GND to VS	INx to Device GND	DIAG_EN to Device GND SCR	CS to Device GND
–18 V	17.3 V	0.7 V	11.3 V	11.6 V	2 V
Current	17.3 mA	N/A	0.67 mA	0.64 mA	24 mA
–24 V	23.3 V	0.72 V	11.31 V	11.85 V	2.11 V
Current	23.7 mA	N/A	1.27 mA	1.26 mA	33 mA

4 Conclusion

TI Smart High Side Switches have robust protection and capability of protecting during reverse battery events with the use of several techniques. As laid out in Table 1 a ground network, protection resistors and blocking diodes all help to provide system level protection during reverse polarity. Using these tips during the design phase will save the MCU and high side switch from damage while still enabling normal functionality.

IMPORTANT NOTICE AND DISCLAIMER