Application Report

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Using Comparators in Reverse Current Applications

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ABSTRACT

This application report describes how to implement Reverse Current Protection (RCP) using a comparator and a P-Channel or N-Channel MOSFET. Reverse Current Protection is a crucial protection scheme in load sharing applications where a disturbance in the source or the load can cause undesired current to flow back into the source supply from the load. This document presents a discrete alternative solution to protect against reverse current for cost-constrained systems.

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1 Introduction

As modern industrial applications continue to incorporate more and more electronics into their systems, they must also include more protection from various supply faults. Simple reverse voltage protection can be added using several schemes involving diodes and MOSFETS, but they do not protect against reverse *current* flow. Reverse current protection is important in distributed, redundant, or hot-swap power supply applications where the loads could potentially force current back into the main bus voltage.

2 Definition of Reverse Current

Reverse current is where the load attempts to force current back into the power source.

Such instances can occur when the power supply source is suddenly reduced or completely lost, and the load supply bypass capacitors or batteries attempt to force current back into the power source when first connected. Reverse current can also occur when the load tries to force voltage back into the main supply bus, such as back-EMF from an inductive circuit or motor, or a failed battery charging circuit.

3 Traditional Methods for Preventing Reverse Voltage

There are several methods commonly implemented to protect against reverse voltage. The following sections briefly describes the various schemes.

3.1 Diodes

The simplest form of reverse voltage and reverse current protection is a diode in series with the supply rail to block the current from flowing back towards the source, as shown in Figure 1.

The drawback of this technique is the power loss due to the forward voltage drop of the diode (up to 1 V or more under load). The losses increase as the load currents increase. A Schottky diode can be used to minimize losses due to the lower forward voltage, but is generally more expensive than a standard diode. Diode protection is used where load currents are under 1 Amp and a slight voltage loss is tolerable.

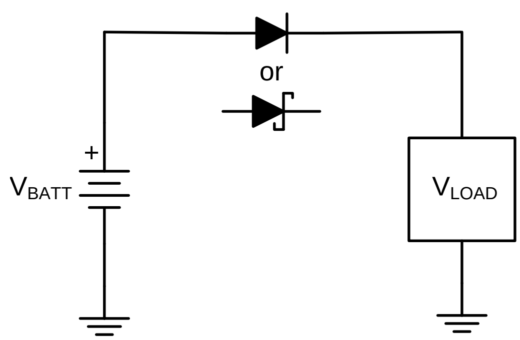

Figure 1. Simple Diode Reverse Voltage and Reverse Current Protection

3.2 MOSFETS

MOSFETS are commonly used to provide reverse voltage protection. The low Drain Source resistence (RDS_{ON}) when the MOSFET is conducting, can be as low as a few milli-Ohms, which reduces the voltage drop to negligible levels and results in negligible power losses.

The intrinsic parallel body diode provides the simple diode protection previously described, until the proper V_{GS} has been reached and the MOSFET channel starts to conduct with it's low on resistence.

To cause MOSFET channel to conduct, the gate voltage must be brought several volts beyond the source voltage. The direction of the gate voltage depends on the polarity of the MOSFET used.

3.2.1 P-Channel MOSFETS

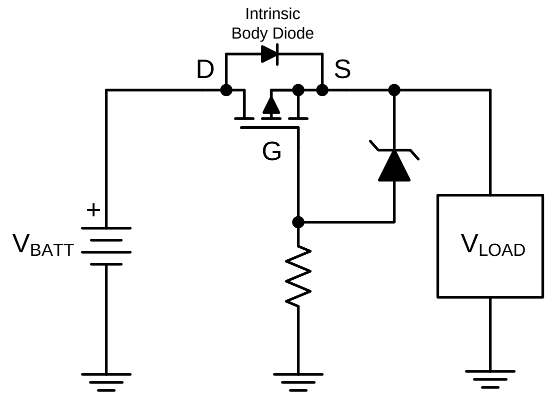

Figure 2. Simplified P-Channel Reverse Voltage Protection

The P-Channel MOSFET requires the gate voltage to be lower (more negative) than the source voltage. This makes for the easiest implementation as the gate can simply be pulled below V_{BATT} using a pulldown resistor. Figure 2 shows the basic P-Channel circuit. As the supply voltage increases, so does the V_{GS} voltage, turning on the MOSFET.

If the supply voltage goes negative (below ground), the Gate becomes more positive than the Source, and the MOSFET turns off. The intrinsic body diode also becomes reverse biased and blocks the reverse current.

The Zener and gate pulldown resistor play two functions. The MOSFET has a specified maximum gate-to-source (V_{GS}) voltage, usually in the range of 5 V to 20 V. The Zener prevents damage to the gate by clamping the V_{GS} voltage to a safe level and the resistor limits the current.

When the input voltage is reversed, the Zener is forward-biased and clamps the V_{GS} to a diode drop to ensure the MOSFET does not start conducting.

The single P-MOSFET circuit, as shown in Figure 2, does not protect against over or under voltage conditions. Even if the gate voltage is controlled, the body diode allows current to pass around the MOSFET. A second MOSFET, with the body diode the opposite the first MOSFET (connected Source to Source), is commonly used to provide true power-off functionality. Still, it does not protect against reverse current flow while the MOSFETS are conducting (current is bi-directional when conducting).

However, despite the Simple circuit, the P-Channel MOSFET tends to have higher I^2R losses, higher cost, and physically larger and slower than comparable N-Channel devices. P-Channels tend to be used with load currents up to 5 Amp.

3.2.2 N-Channel MOSFETS

The N-Channel MOSFET requires the gate voltage to be higher (more positive) than the Source voltage. This requires the Gate voltage to be higher than the incoming V_{BATT} voltage to cause the MOSFET to conduct. The circuit complexity is increased due to the need for a second supply higher than V_{BATT}.

If a higher voltage is not available, a charge-pump can be added to generate the greater-than-V_{BATT} gate voltage required to turn on the MOSFET.

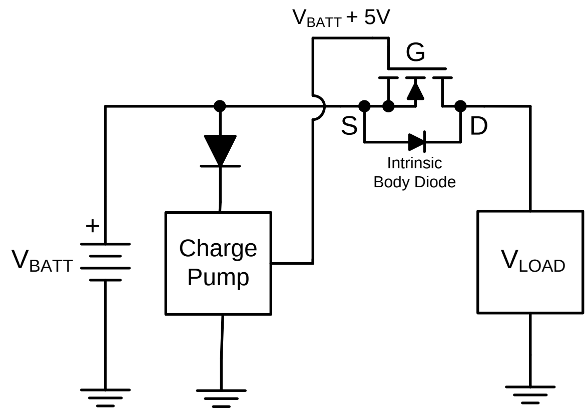

Figure 3. Simplified N-Channel MOSFET Reverse Voltage Protection Circuit

When V_{BATT} is positive, the charge pumps protection diode is forward biased, and the charge pump generates the gate voltage, turning on the MOSFET. If V_{BATT} is reversed, the charge pump blocking diode is reverse and does not conduct. The charge pump does not operate and the gate voltage is not applied. With no gate voltage, the MOSFET does not conduct. The MOSFETS Intrinsic body diode is also reverse biased and no current flows to the load.

The single N-MOSFET circuit, as shown, also does not protect against over or under voltage conditions. Even if the gate voltage is controlled, the body diode allows current to pass around the MOSFET. A second MOSFET, with the body diode the opposite the first MOSFET (connected Drain to Drain), is commonly used to provide true power-off functionality.

4 Reverse Current Protection Using MOSFET and a Comparator

The problem with the simple MOSFET based reverse voltage circuits previously described is they do not protect against reverse *current*. Once the MOSFET is conducing, current flow is bi-directional through the MOSFET.

A MOSFET may be used to protect against reverse current in conjunction with a comparator. Both the P-Channel and N-Channel circuits work on the same basic principle, where a comparator monitors the voltage across the Source and Drain terminals of the MOSFET (monitoring V_{DS}) to determine the direction of the current. These circuits can also protect against reverse voltage.

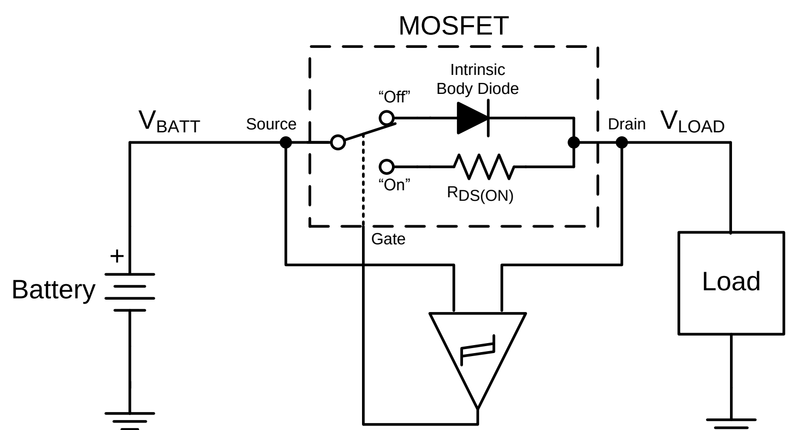

Figure 4. Simplified Operational Theory

When the current is flowing from the battery (V_{BATT}) to the load (V_{LOAD}), the battery voltage is higher than the load voltage due to voltage drop across the MOSFET caused by either the $R_{DS(ON)}$ or the intrinsic body diode forward voltage drop. The comparator detects this voltage and turns "on" the MOSFET so that the load current is now flowing through the low loss $R_{DS(ON)}$ path.

In a reverse current condition, V_{LOAD} is higher than V_{BATT}. The comparator detects this and drives the gate to set V_{GS} = 0 to turn "off" the MOSFET (non-conducting). The body diode is reverse biased and blocks current flow.

For a P-Channel MOSFET, the gate must be driven at least 4 V or more *below* the battery voltage to turn "on" the MOSFET.

For a N-Channel MOSFET, the gate must be driven 4 V or more *above* the battery voltage to turn "on" the MOSFET. If a higher voltage is not available in the system, a charge pump is usually required to generate a voltage higher than the battery voltage to provide the necessary positive gate drive voltage.

4.1 Minimum Reverse Current

There is a minimum amount of reverse current that is needed to trip the comparator. To detect this reverse current, a voltage must be dropped across the MOSFET (V_{MEAS}).

When the MOSFET is off, V_{GS} is in the -600 mV to -1 V range due to the forward voltage drop (V_F) of the MOSFET body diode. Response to this large voltage is immediate.

However, with the MOSFET "on" (conducting), the current required to create the trip voltage is much greater. The trip voltage drop required across the MOSFET $R_{DS(ON)}$ is the comparator offset voltage plus half of the hysteresis.

The maximum offset voltage of the TLV1805 is 5 mV with a typical hysteresis of 14 mV. The trip voltage can be calculated from:

$$V_{TRIP} = V_{OS(max)} + (V_{HYST} / 2) = 5 \text{ mV} + 7 \text{ mV} = 12 \text{ mV} \quad (1)$$

The actual current trip point depends on the MOSFET $R_{DS(ON)}$ and V_{GS} drive level. Assuming the MOSFET has a 22 mΩ on resistance, the trip current is found from:

$$I_{TRIP} = V_{TRIP} / R_{DS(ON)} = 12 \text{ mV} / 22 \text{ m}\Omega = 545 \text{ mA} \quad (2)$$

4.2 Calculating Actual Reverse Current Trip Point

The actual trip point is influenced by several factors, including the $R_{DS(ON)}$ of the MOSFET, and the offset voltage (V_{OS}) and hysteresis (V_{HYST}) of the comparator.

$$I_{RTRIP} = (V_{OS} + (V_{HYST} / 2)) / R_{DS(ON)} \quad (3)$$

4.3 N-Channel Reverse Current Protection Circuit

To turn "on" the N-Channel MOSFET, the MOSFET gate must be brought to a voltage higher than V_{BATT}. If a higher voltage is not available, a charge pump circuit is required to provide the comparator with a supply voltage above V_{BATT}.

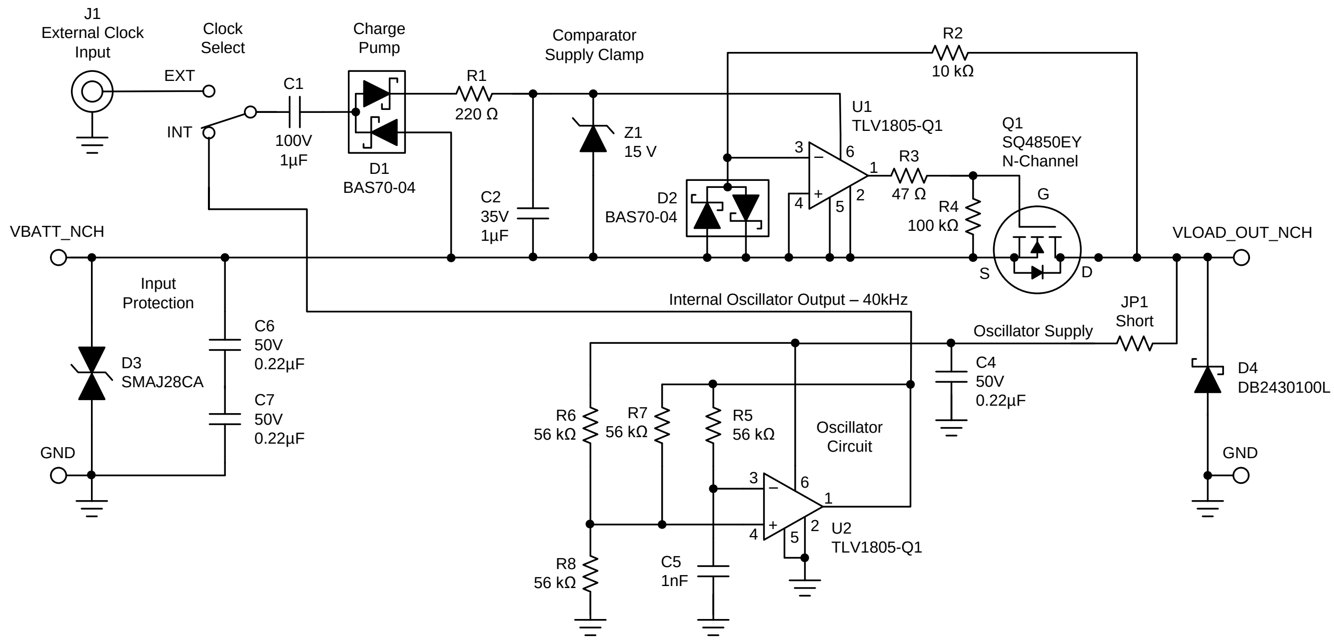

Figure 5. N-Channel Reverse Current Schematic with Oscillator

C1, D1, R1, and C2 form the charge pump. The AC drive signal is applied through C1. The result is a voltage across C2 that is approximately equal to the peak-to-peak amplitude of the AC waveform, minus 700 mV from the two Schottky diode drops. If a 12 Vpp square wave is applied to the C1 input, 11.3 V is generated across C2. This voltage is on top of the V_{BATT} voltage, so the total voltage seen from the R1-C2 junction to ground is 23.3 V. This provides the needed voltage above V_{BATT} to power the comparator and drive the MOSFET gate.

An external oscillator source may be used, such as the gate drive output of a switcher, system clock or any available clock source in the 1 kHz to 10 MHz range. The charge pump should ideally be fed by a 50 percent duty cycle square wave source of 5 Vpp or more. Because the input capacitor C1 of the charge-pump effectively AC-couples the input, the oscillator may be ground referenced.

R1 limits the peak oscillator current. R1 and Z1 form the comparator supply clamp to limit the gate drive to prevent exceeding the $V_{GS(MAX)}$ of the MOSFET during an overvoltage event. R1 must be sized to dissipate any expected overvoltage when Z1 starts clamping and limit the maximum AC current.

D2 and R2 clamp the input when V_{BATT} drops below V_{LOAD} (as in a supply reversal).

D3, C6, and C7 form the input protection network. D3 is a 28 V bi-bi-directional TVS that starts clamping at ±33 V. C6 and C7 are series connected filter capacitors that are mounted at right-angles to each other. This is a safety precaution common in Automotive and high reliability designs using ceramic SMT capacitors to prevent shorting the supply bus if one of the capacitors fail shorted. Mounting the capacitors at right angles increases the odds that one of the capacitors survives if the board is stressed.

The output diode D4 is used to "anchor" the output during light or floating loads. At light or no loads (less than reverse current threshold), there is a possibility the MOSFET could turn on due to the comparator offset voltage. The diode provides enough of a negative leakage to turn the MOSFET off.

4.3.1 N-Channel Oscillator Circuit

The oscillation frequency is determined by R5 and C5. The default configuration oscillates around 40 kHz (depending on RC component tolerances). For further information on selecting these RC values, see the Engineers Cookbook Circuit entitled *Relaxation Oscillator Circuit* (SNOA998). Note that R5 presents an AC load to the oscillator output, and must be sized appropriately to minimize the peak charging currents of C5 (use large resistors and small capacitors).

The output amplitude is roughly equivalent to the V_{LOAD} voltage minus the TLV1805 output saturation (approximately 300 mV). With a maximum supply voltage of 40 V for the TLV1805, the oscillator circuit is capable of generating up to 39 Vpp.

The TLV1805 oscillator typically starts oscillating when V_{LOAD} reaches 2.8 V, though full specified operation does not occur until 3.3 V.

5 P-Channel Reverse Current Protection Circuit

Figure 6 shows the P-Channel circuit. In order to turn "on" the P-Channel MOSFET, the Gate must be brought to a voltage 4.5 V or lower than V_{BATT} . To accomplish this, the comparators Inverting input is tied to the battery side of the MOSFET to set the output low during forward current.

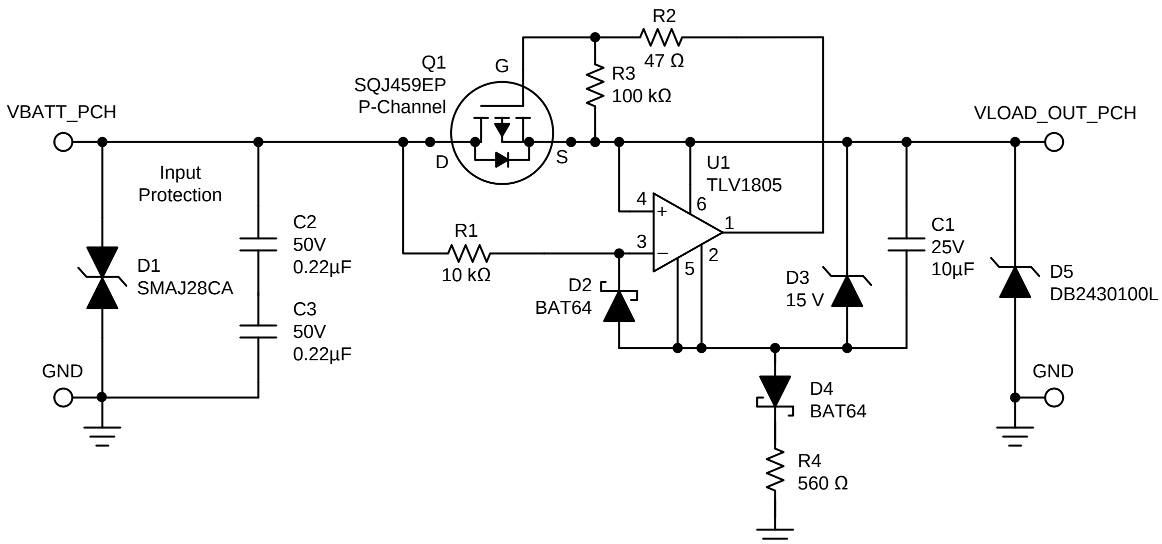

Figure 6. P-Channel Reverse Current Schematic

This design implements a "floating ground" topology, consisting of D3, D4, and R4, to allow for clamping the comparator supply voltage so that the output swing does not exceed the $V_{GS(MAX)}$ of the MOSFET. During a reverse voltage or supply drop, D4 also prevents C1 from discharging and allow some standby time to keep the comparator powered during the event.

During "normal" forward current operation, the quiescent current of the comparator circuit flows through D4 and R4. D3 provides the clamping during an overvoltage event.

R4 is sized to allow for minimum voltage drop during "normal" operation, but also to allow for dissipation during input overvoltage events. R4 sees the applied battery voltage minus the D3 Zener voltage during an overvoltage event. Because the comparator supply voltage is clamped by D3, the maximum battery voltage is determined by the power dissipated by R4 and the $V_{DS(MAX)}$ of the MOSFET.

Assuming a maximum overvoltage input of 24 V, the maximum power dissipation of R4 can be calculated from:

$$V_{R4(MAX)} = V_{BATT(MAX)} - V_{ZD3} = 24\text{ V} - 15\text{ V} = 9\text{ V} \tag{4}$$

$$P_{R4(MAX)} = V_{R4(MAX)}^{2} / R4 = 9\text{ V}^2 / 560\ \Omega = 145\text{ mW} \tag{5}$$

Assuming the minimum 2x safety factor is used, R4 must be a minimum of a ½ Watt resistor.

R2 limits the gate current if there are any transients and must be a low value to allow the peak currents needed to drive the MOSFET gate capacitance. R3 provides the pulldown needed when the comparator output goes high-Z during power-off to ensure the gate is pulled to zero volts to turn off the MOSFET.

R1 and D2 clamp the input voltage when the V_{BATT} input go below the floating ground Voltage (such as in a battery reversal). A bonus feature is that during a reverse battery voltage condition, D2 and R1 pull the floating ground down towards the negative potential, providing power to the comparator during reverse voltage.

The output clamp diode D5 is used to anchor the output during light or floating loads. At light or no loads, there is a possibility the MOSFET could turn on due to the comparator offset voltage. The diode provides enough of a negative leakage to turn the MOSFET off.

If shutdown of the comparator circuit is desired, a transistor or MOSFET switch can be placed between the ground end of R4 and ground. The MOSFET is in body diode mode when the comparator is disabled.

6 P-Channel Reverse Current Protection With Overvotlage Protection

The SHDN pin can be used to add overvoltage Protection (OVP) by adding a second MOSFET, zener diode, and resistor, as shown in Figure 7.

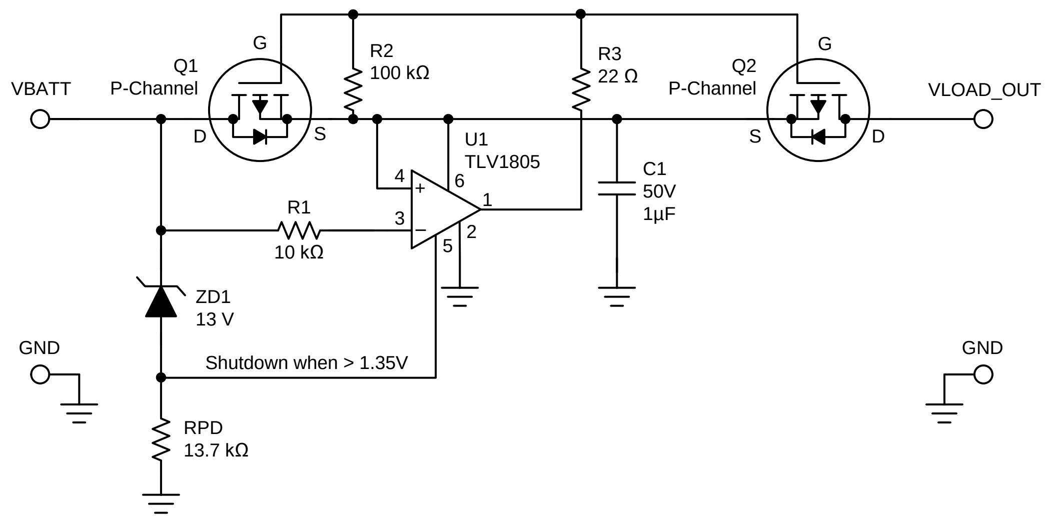

Figure 7. Adding Overvoltage Protection Using SHDN Pin

When the SHDN pin is pulled 1.8 V above V-, the comparator is placed in shutdown. During shutdown, the comparator output goes Hi-Z and R2 pulls the gate and source together to turn off the MOSFET (V_{GS} = 0 V).

RPD pulls the SHDN pin low while the Zener diode is not conducting (< V_Z). When ZD1 reaches its breakdown voltage and starts conducting, it pulls RPD up to a voltage calculated to place >1.8 V on the shutdown pin.

The Zener diode ZD1 must be chosen so that the breakdown voltage (V_B) is 1.8 V below the desired overvoltage point. The Zener must have low sub-threshold leakage and a sharp knee, such as the low power 1N47xx or BZD series.

The pulldown resistor RPD must be chosen to create 1.8 V at the desired Zener diode current (usually 100 µA to 1 mA) at the Zener breakdown voltage. Actual resistor value should be verified on the bench due to differences in actual Zener diode threshold voltages.

If a 14.3 V overvoltage trip point (OVP) is desired, the Zener Diode voltage is 12.5 V. A 100 µA Zener current was chosen. The required Zener diode breakdown voltage is determined from:

$$V_B = V_{OV} - 1.8\ V = 14.3\ V - 1.8\ V = 12.5\ V \tag{6}$$

$$RPD = 1.8\ V / 100\ \mu A = 18\ k\Omega \tag{7}$$

Resistor RPD may be split into two resistors to create a voltage divider if more precise trip points are needed, or a more convenient Zener voltage is desired. Series voltage references can also be used if more accuracy is desired. A second resistor in series with the Zener or reference can extend the breakdown voltage.

The maximum voltage allowed on the Shutdown pin is 5.5 V, so make sure the highest V_{BATT} voltage does not exceed 5.5 V.

Note that the above circuit, as shown for simplicity, does not protect against reverse voltage. Reverse clamping diodes would be needed on the -IN, SHDN and Load Output. Also make sure V_{BATT} does not exceed the $V_{GS(MAX)}$ of the MOSFET.

7 ORing MOSFET Controller

The previous reverse current circuits may be combined to create an OR'ing supply controller, utilizing either the P-Channel or N-Channel topologies.

For the previous P-Channel circuit, if no negative input voltages are possible, and the input voltage is below the $V_{GS(MAX)}$ of the MOSFET, then the "floating ground" may be eliminated. To eliminate the floating ground, D3, D4, and R4 may be eliminated (and the D2 anode, U1 pins 2 and 5, and C1 can be directly grounded).

For the N-Channel circuit, the oscillator drive can be shared between the channels, or eliminated if a higher system voltage is available to provide the higher voltage.

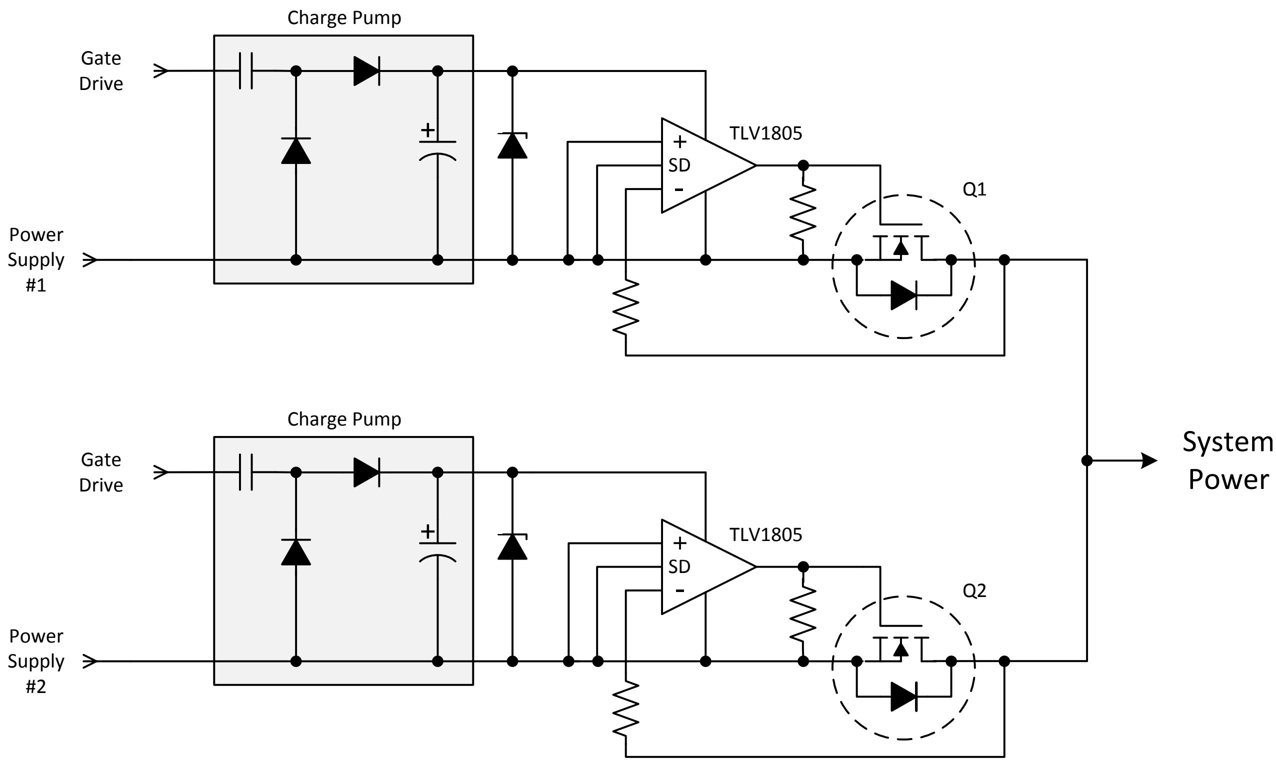

Figure 8. N-Channel OR'ing MOSFET Controller Example

8 References

- Texas Instruments, *TLV1805 40V, Rail-to-Rail Input, Push-Pull Output, High Voltage Comparator Datasheet* (SNOSD50)
- Texas Instruments, *40V, microPower, Push-Pull Automotive High Voltage Comparator with Shutdown Datasheet* (SNOSD52)
- TLV1805-Q1 Comparator Based Discreet Reverse Current Protection Circuit Evaluation Module, http://www.ti.com/tool/TLV1805EVMQ1
- Texas Instruments, *TLV1805-Q1EVM Users Manual*
- Texas Instruments, *Relaxation Oscillator Circuit Cookbook Circuit* (SNOA998)
- Texas Instruments, *Reverse Current Protection Using MOSFET and Comparator to Minimize Power Dissipation Application Report* (SNOA971)

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (January 2019) to A Revision	Page
• Edited application report for clarity.	1
• Removed text in Calculating Actual Reverse Current Trip Point section.	5