Using comparators in reverse current applications

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ABSTRACT

This application note 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.

Contents

1 Introduction ................................................................................................................... 2
2 Definition of Reverse Current ...................................................................................... 2
3 Traditional Methods for Preventing Reverse Voltage ................................................ 2
4 Reverse Current Protection Using MOSFET and a Comparator ...................................... 4
5 P-Channel Reverse Current Protection Circuit ........................................................... 7
6 P-Channel Reverse Current Protection With Overvoltage Protection ............................. 8
7 ORing MOSFET Controller ....................................................................................... 9
8 References .................................................................................................................. 9

List of Figures

1 Simple Diode Reverse Voltage and Reverse Current Protection .................................... 2
2 Simplified P-Channel Reverse Voltage Protection ....................................................... 3
3 Simplified N-Channel MOSFET Reverse Voltage Protection Circuit ............................. 4
4 Simplified Operational Theory ................................................................................... 4
5 N-Channel Reverse Current Schematic with Oscillator ............................................... 6
6 P-Channel Reverse Current Schematic ....................................................................... 7
7 Adding Overvoltage Protection Using SHDN Pin ......................................................... 8
8 N-Channel OR'ing MOSFET Controller Example ....................................................... 9

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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 & 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 1V 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](image)

3.2 MOSFETS

MOSFETS are commonly used to provide reverse voltage protection. The low Drain Source resistance ($R_{DS_{ON}}$) when the MOSFET is conducting, can be as low as a few milli-Ohms, which reduces the voltage drop to negligible levels and resulting 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 resistance.

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

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 \( V_{\text{BATT}} \) using a pull-down resistor. Figure 2 shows the basic P-Channel circuit. As the supply voltage increases, so does the \( V_{\text{GS}} \) 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 pull-down resistor play two functions. The MOSFET has a specified maximum gate-to-source (\( V_{\text{GS}} \)) voltage, usually in the range of 5 to 20V. The Zener prevents damage to the gate by clamping the \( V_{\text{GS}} \) 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 \( V_{\text{GS}} \) 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 will allow 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 \( V_{\text{BATT}} \) voltage to cause the MOSFET to conduct. The circuit complexity is increased due to the need for a second supply higher than \( V_{\text{BATT}} \).

If a higher voltage is not available, a charge-pump can be added to generate the greater-than-\( V_{\text{BATT}} \) gate voltage required to turn on the MOSFET.
Reverse Current Protection Using MOSFET and a Comparator

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 MOSFET’s 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 will allow 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 MOSFET’s Source and Drain terminals (monitoring \( V_{DS} \)) to determine the direction of the current. These circuits can also protect against reverse voltage.
When the current is flowing from the battery ($V_{BATT}$) to the load ($V_{LOAD}$), the battery voltage will be 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 will detect this voltage and turn "on" the MOSFET so that the load current is now flowing through the low loss $R_{DS(ON)}$ path.

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

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

For a N-Channel MOSFET, the gate must be driven 4V 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, $V_{GS}$ will be in the -600mV to -1V range due to the forward voltage drop ($V_F$) of the MOSFET body diode. Response to this large voltage will be immediate.

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

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

$$V_{TRIP} = V_{OS(max)} + \left( \frac{V_{HYST}}{2} \right) = 5 \text{ mV} + 7 \text{ mV} = 12 \text{ mV}$$  \hspace{1cm} (1)

The actual current trip point will depend 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:

$$I_{TRIP} = \frac{V_{TRIP}}{R_{DS(ON)}} = \frac{12 \text{ mV}}{22 \text{ mΩ}} = 545\text{mA}$$  \hspace{1cm} (2)

### 4.2 Calculating Actual Reverse Current Trip Point

The actual trip point will be 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.

$$I_{TRIP} = \frac{(V_{GS} + (V_{HYST}/2))}{R_{DS(ON)}}$$  \hspace{1cm} (3)

Blah, Blah, Blah....

### 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 $V_{BATT}$.  

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4.3.1 N-Channel Oscillator Circuit

The oscillation frequency is determined by R5 and C5. The default configuration oscillates around 40kHz (depending on RC component tolerances). For further information on selecting these RC values, please see the Engineers Cookbook Circuit entitled Oscillator Circuit (SNOA998). Do note that R5 does present 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 $V_{\text{LOAD}}$ voltage minus the TLV1805 output saturation (approximately 300mV). With a maximum supply voltage of 40V for the TLV1805, the oscillator circuit is capable of generating up to 39Vpp!

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

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 4.5V or lower than $V_{\text{BATT}}$. To accomplish this, the comparators Inverting input is tied to the battery side of the MOSFET to set the output low during forward current.

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 will not exceed the $V_{\text{GS(MAX)}}$ 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 will see 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 $V_{\text{DS(MAX)}}$ of the MOSFET.

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

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

$$P_{\text{R4(MAX)}} = \frac{V_{\text{R4(MAX)}}^2}{R_4} = \frac{9V^2}{560\Omega} = 145mW$$

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 pull-down 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 $V_{\text{BATT}}$ 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.

Figure 6. P-Channel Reverse Current Schematic
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 will be in body diode mode when the comparator is disabled.

6 P-Channel Reverse Current Protection With Overvoltage Protection

The SHDN pin can be utilized 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](image)

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 will pull 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 pull-down resistor RPD must be chosen to create 1.8 V at the desired Zener diode current (usually 100µA to 1mA) 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 will be 12.5 V. We will choose a 100µA Zener current. The required Zener diode breakdown voltage is determined from:

\[
V_B = V_{OV} - 1.8\ V = 14.3\ V - 1.8\ V = 12.5\ V
\]

\[
RPD = 1.8\ V / 100\ \mu A = 18\ k\Omega
\]

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 5.5V, 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 $V_{\text{BATT}}$ does not exceed the $V_{\text{GS(MAX)}}$ 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 MOSFET's $V_{\text{GS(MAX)}}$, 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

- TLV1805 Datasheet, Texas Instruments, Literature Number SNOSD50
- TLV1805-Q1 Datasheet, Texas Instruments, Literature Number SNOSD52
- "TLV1805-Q1 Comparator Based Discreet Reverse Current Protection Circuit Evaluation Module", http://www.ti.com/tool/TLV1805EVMQ1
- "TLV1805-Q1EVM Evaluation Board Users Manual", Texas Instruments, Literature Number SNOU158
- "Relaxation Oscillator Circuit", Texas Instruments Cookbook Circuit, Literature Number SNOA998
- "Reverse Current Protection Using MOSFET and Comparator to Minimize Power Dissipation", Texas Instruments Application Note, Literature Number SNOA971
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