Backwards Batteries: Protecting Automotive Motor-Drive Systems from Reverse Polarity Conditions

Michael Bifalco
Advanced Protection Motor Drivers

ABSTRACT
Electronics are integrated into virtually every system of the modern automobile, from safety to infotainment. Now more than ever it is important for manufacturers to build robust protection into the electrical systems of their vehicles.

One danger that all electrical systems face is a reversed polarity from the power source. This event can be caused by a short circuit, but is usually caused by simply switching the power and ground terminals when connecting a power supply. In the case of an automobile, the power for most electronics is supplied from the battery. A car battery that is installed with the terminal connections reversed could damage the electrical systems if they are not protected. The electronics could also be damaged from reverse polarity if a jump-start is attempted with the jumper cables reversed.

Several techniques exist that can be used to provide reverse battery protection when designing electrical systems, but all have the common purpose of preventing current flow when the battery terminals are connected in reverse.

Contents
1 Technique 1: Series Diode Method .............................................................. 2
2 Technique 2: Single FET ........................................................................ 2
3 Technique 3: IC Solution ....................................................................... 2
4 Technique 4: NMOS and BJT ................................................................. 3
  4.1 Using Technique 4 With DRV3205-Q1 .............................................. 3
5 Comparison of Power Dissipation .......................................................... 5

List of Figures
1 Reverse Battery Protection With Diode at Supply Terminal ..................... 2
2 Reverse Battery Protection With Diode at Ground Terminal ....................... 2
3 Reverse Battery Protection With PMOS FET ............................................ 2
4 Reverse Battery Protection With NMOS FET .......................................... 2
5 Reverse Battery Protection With BJT and NMOS .................................... 3
6 Reverse Battery Protection With DRV3205-Q1 ....................................... 4
7 Regulator Voltage versus VS .................................................................. 5
1 Technique 1: Series Diode Method

The first technique for implementing reverse battery protection is to include a diode in series with the power supply path, as shown in Figure 1 and Figure 2. If the battery terminals are connected in reverse, the diode will be reverse biased and will not allow current to flow through the system. This technique prevents the reversed polarity condition from harming the electronics or the battery.

Figure 1. Reverse Battery Protection With Diode at Supply Terminal

Figure 2. Reverse Battery Protection With Diode at Ground Terminal

This technique is cost effective as it requires only a single diode to implement in the simplest form, but it comes with the drawbacks of lower efficiency and a smaller usable battery range because of the voltage drop introduced by the diode. Furthermore, the diode could overheat in high-current applications. A heatsink can be added to the diode or multiple diodes can be connected in parallel to spread out the power dissipation, but both of these solutions increase the component cost and use valuable board space.

2 Technique 2: Single FET

Another technique for reverse battery protection is to include a power FET in series with the power supply path. Either a p-channel power FET (PMOS) or an n-channel power FET (NMOS) can be used as shown in Figure 3 and Figure 4. When properly connected, the battery will briefly conduct current into the system through the body diode of the FET while the FET is switching on. Afterwards, the FET conducts the current with an extremely low on resistance. When the battery is connected in reverse, the FET will be off in either implementation and no current can flow. This technique helps protect the system and the battery from the reversed polarity condition.

Figure 3. Reverse Battery Protection With PMOS FET

Figure 4. Reverse Battery Protection With NMOS FET

This technique is more efficient than using only a diode because of the low Rdson of power MOSFETs. With an Rdson value in the tens of milliohms or lower, the voltage drop introduced by the FET is often far lower than the forward voltage of a diode, resulting in better efficiency, lower loss of usable battery voltage, and less heat. However, using this circuit has some drawbacks. The Rdson of a PMOS is higher than that of an NMOS of the same size, so an NMOS is usually the better choice from a cost perspective. The NMOS implementation can lift up the ground reference which could affect sensitive circuits.

3 Technique 3: IC Solution

Integrated circuits designed specifically to accomplish reverse battery protection are also an option in an automotive system. Texas Instruments’ LM74610-Q1 smart diode controller is one such device. For a reference design using this device, go to www.ti.com/tool/PMP9498.
4 Technique 4: NMOS and BJT

The circuit in Figure 5 makes use of a power NMOS and an NPN bipolar junction transistor (BJT) to achieve reverse battery protection. If the battery is connected in reverse, the body diode of the NMOS will not conduct current nor will the NMOS turn on, thereby protecting the system from the reverse polarity condition. When the battery is connected correctly, the circuit permits current to flow with very little power lost because of the low \( R_{\text{dson}} \) of the NMOS.

![Figure 5. Reverse Battery Protection With BJT and NMOS](image)

For the power NMOS to turn on, the gate voltage must be higher than the source voltage which cannot be accomplished with \( V_{\text{BAT}} \) alone. Therefore the gate is tied to a signal called OVERDRIVE, representing a gate driving voltage. This technique usually requires additional circuitry to produce a suitable gate-to-source voltage to turn on the NMOS, often in the form of a charge pump or boost regulator.

The BJT is used to ground the NMOS gate during the reverse polarity condition to ensure the NMOS turns off. When the battery is connected correctly, the base voltage is lower than the collector and emitter voltages so the BJT will be off. When the battery terminals are connected in reverse, the ground node becomes the positive battery terminal and the \( V_{\text{BAT}} \) node becomes the negative battery terminal. A positive voltage is present from the base to the emitter of the BJT, so the BJT will turn on which connects the NMOS gate to ground through the BJT and turns off the NMOS.

The resistor, \( R_{\text{BASE}} \), is used to limit the current into the base of the BJT, and the diode prevents current from entering the BJT when the battery is connected correctly.

The low \( R_{\text{dson}} \) of the NMOS results in excellent efficiency and less loss in battery voltage range from the protection circuit. This technique also removes the disadvantage of lifting the ground up that is caused by the single NMOS solution.

4.1 Using Technique 4 With DRV3205-Q1

This technique is particularly well-suited for motor drive applications. The DRV3205-Q1 motor drive device includes an integrated boost regulator that can support the required overdrive voltage for the NMOS gate without the need for additional external circuitry. The following example demonstrates the implementation using the DRV3205-Q1 device. However, the example applies to any motor drive device that uses a charge pump or boost regulator architecture that follows the supply voltage.

![Figure 6 shows the circuit for reverse battery protection using the DRV3205-Q1 device.](image)
The body diode of the FET allows current to flow into the device initially, allowing the boost regulator to power on. When the device is powered on, the boost regulator (BOOST) on the DRV3205-Q1 device provides a typical voltage of 15 V above the supply voltage. The BOOST provides a strong overdrive to the gate of the NMOS, ensuring low Rdson to maximize efficiency of the reverse battery protection circuit. To minimize cost and simplify the bill of materials (BOM), the same power NMOS model used for the half bridges of the driver stage can be used as the reverse battery protection NMOS.

A system designer must select a BJT that supports the different voltages it can be exposed to in the system. When the battery is connected correctly, the collector-to-emitter voltage of the BJT is effectively the same as the boost voltage is with respect to supply (15 V for DRV3205-Q1). Most BJTs designed for power applications can accept that level of collector-to-emitter voltage. The BJT must also have a sufficiently large collector-to-base voltage specification to avoid damage from the boost voltage. This voltage specification is required because the base will remain grounded when the battery is connected correctly, but the boost output will increase with respect to ground as the supply increases. For example, the boost will regulate at 29 V when the battery is 14 V (typical) so the BJT must support at least 29 V from collector to base. When selecting the BJT, also consider automotive conditions such as load dump that can effect the voltages that the system is exposed to.

When the battery is connected in reverse, the specified base-to-emitter voltage must be greater than the battery voltage because the battery voltage will appear from base to emitter. The base resistor must be selected to limit the current into the base. Most BJT data sheets recommend a resistor of a few kilo-Ohms.

The resistor between the boost output and the gate of the FET should be sized so that the external current limit of the boost regulator is not exceeded, including any additional load from other external circuitry. As an example, assume that the current is limited to half the maximum external load to give margin for powering other external loads in the system. For DRV3205-Q1, this limit is 20 mA and the typical voltage is 15 V above supply. The BJT will be in cutoff mode when the battery is connected correctly, so current will be sourced only into the gate of the FET. Use Equation 1 to calculate a value for the current limiting resistor ($R_{limit}$).

$$R_{limit} = \frac{V_{BOOST} - V_{BAT}}{I_{load}}$$

$$R_{limit} = \frac{15 \text{ V}}{20 \text{ mA}}$$

$$R_{limit} = 750 \Omega$$ (1)

The slew rate of the charge pump or boost regulator at startup will also limit the current. The FET will take longer to turn on for larger values of $R_{limit}$, which decreases efficiency at startup. Allowing for a larger current limit when possible will improve the efficiency.
As shown in Figure 7, the boost regulator of DRV3205-Q1 is referenced to the supply and increase as it increases. The VCPH curve represents a charge pump that is also referenced to supply and provides a typical voltage of 10 V above supply. Either of these regulators could supply the VGS required to turn on the NMOS even as the supply voltage changes.

Compare this scenario to a motor drive device that uses a bootstrap architecture. The bootstrap architecture can integrate a regulator that has a fixed voltage rather than one that is referenced to the supply voltage. For example, such a device could include a regulator that provides a fixed 13-V output with respect to ground to power its gate drivers (VREG in Figure 7). A typical automotive battery is around 12.5 V, so this device would be unable to supply the gate-to-source voltage required for the NMOS to turn on in the reverse battery protection circuit. Either additional components or a different technique for reverse battery protection would be required for a system using a bootstrap architecture.

![Figure 7. Regulator Voltage versus VS](image)

### 5 Comparison of Power Dissipation

A comparison of the power dissipation of the different circuits can be made by choosing a current and solving for the power. For an example, assume that 30 mA flows into the device (typical quiescent current of DRV3205-Q1).

For Technique 1, if the forward voltage of the diode is 300 mV, use Equation 2 to calculate the power dissipation ($P_D$).

$$ P_D = IV $$

$$ P_{D\text{(diode)}} = 30 \text{ mA} \times 0.3 \text{ V} $$

$$ P_{D\text{(diode)}} = 9 \text{ mW} \quad (2) $$

For Technique 2, either a PMOS or NMOS can be used. With a 30-mA current, and assuming a PMOS with $R_{\text{ds(on)}}$ of 10 mΩ, use Equation 3 to calculate the $P_D$.

$$ P_D = IV = I^2R $$

$$ P_{D\text{(PMOS)}} = (30 \text{ mA})^2 \times 10 \text{ mΩ} $$

$$ P_{D\text{(PMOS)}} = 9 \mu\text{W} \quad (3) $$

In general, a PMOS will have a higher $R_{\text{ds(on)}}$ for the same area (and therefore a higher cost) as an NMOS. With a 30-mA current and an NMOS with a 2-mΩ $R_{\text{ds(on)}}$, use Equation 4 to calculate the $P_D$. 

$$ P_{D\text{(NMOS)}} = \frac{(30 \text{ mA})^2}{2 \text{ mΩ}} $$

$$ P_{D\text{(NMOS)}} = 90 \mu\text{W} \quad (4) $$
\[ P_D = IV = I^2R \]

\[ P_{D_{\text{NMOS}}} = (30 \text{ mA})^2 \times 2 \text{ m}\Omega \]

\[ P_{D_{\text{NMOS}}} = 1.8 \mu W \] (4)

**Technique 4** will have nearly identical performance as the single NMOS case. The power dissipated across the current limiting resistor at startup is negligible. Using an NMOS over a PMOS or diode for reverse battery protection has a clear power advantage.

The improvement in power dissipation offered by **Technique 4** is clear when considering that the current of the entire system flows through the reverse polarity protection circuit. For example, if the average system current is 20 A the NMOS will dissipate only 0.8 W, while the single diode solution in **Technique 1** would dissipate 6 W. The diode solution contributes significantly more heat and drives the efficiency of the system down.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

<table>
<thead>
<tr>
<th>Products</th>
<th>Applications</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td><a href="http://www.ti.com/audio">www.ti.com/audio</a></td>
<td>Automotive and Transportation</td>
</tr>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
<td>Communications and Telecom</td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
<td>Energy and Lighting</td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
<td>Medical</td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
<td>Security</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
<td>Space, Avionics and Defense</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
<td>Video and Imaging</td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
<td></td>
</tr>
<tr>
<td>OMAP Applications Processors</td>
<td><a href="http://www.ti.com/omap">www.ti.com/omap</a></td>
<td>TI E2E Community</td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
<td></td>
</tr>
</tbody>
</table>

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2016, Texas Instruments Incorporated