REVERSE BATTERY PROTECTION SCHEME FOR AUTOMOTIVE APPLICATIONS

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ABSTRACT

Many self-contained critical electronic systems and subsystems, especially in the field of automotive applications, use a 12 V or 48 V storage battery as the primary power source. Unless steps are taken to design-in protection systems from voltage polarity reversal at the correct level, these systems remain exposed to extensive damage during their operational life.

This application note discusses a method to protect automotive systems that contain Allegro MicroSystems motor driver integrated circuits from an accidental reversal of battery polarity.

The general concept of a power MOSFET transistor-based scheme that provides very low insertion losses at low cost is presented in this application note.

INTRODUCTION

The purpose of a protection network is to prevent a reverse voltage from being applied to the components in a system, usually an integrated circuit driver, MOSFET bridge, and motor combination, if the power supply connections from the storage battery are reversed.

If this were to occur, an uncontrolled rise in current would almost certainly destroy most of the semiconductors used in the main circuit.

An ideal protection network has the same characteristics as an ideal diode—zero resistance to current flow under normal polarity conditions and infinite resistance under reverse conditions.

A battery polarity reversal event is most likely to occur during routine servicing or replacement of the battery or an emergency start using an external power source. It is normally possible to reverse the voltage polarity across a system either by installing a battery incorrectly or by attempting to jump-start a vehicle that has a discharged battery using another power source or fully charged battery.

The power dissipation in a protection network is $I^2 \times R$, where I is the system supply current and R is the effective resistance of the protection network. Automotive systems that only require a peak operating current of less than 10 A are usually protected by inserting a suitably rated diode in series with the power supply. Losses can be minimized by using a Schottky diode that has a low forward voltage.

Where the automotive system has peak and operating currents that are much higher, typically greater than 10 A, power MOSFET bridges can be used to drive motors. The MOSFETs used in the bridge carry most of the current supplied to the system and feature very low on resistances to minimize self-heating and power loss to the motor load. Hence, a reverse battery protection scheme that features very low power loss is required. Another feature of this scheme is that, if the battery polarity is reversed, the body diodes included in each MOSFET become forward biased. If the reverse polarity voltage is greater than approximately 2 V, this condition leads to current rise limited only by the diode characteristics.

REVERSE BATTERY PROTECTION CIRCUIT

A simplified block diagram of the reverse battery protection systems using the charge pump voltage, V_{CP}, terminal to drive reverse protection circuitry is shown in Figure 1. The voltage source, V_{CP}, is referenced to V_{BB} or V_{BRG} and provides the gate voltage required to turn on transistor Q_1 (N-channel power MOSFET). During normal operation, the N-channel power MOSFET, Q_1, carries the full load current to the subsystem. This provides a very-low-resistance current path to minimize insertion losses when operating with normal polarity and an adequate voltage-blocking rating when battery polarity is reversed.

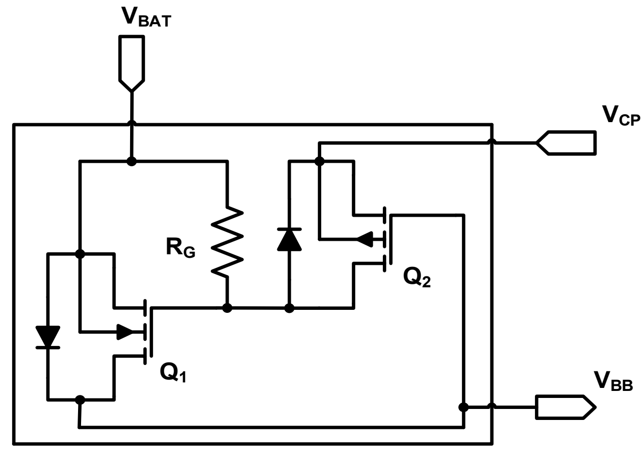

Figure 1: Reverse battery protection circuitry

It should also be noted that the source and drain connections to the N-channel MOSFET, Q_1, are intentionally reversed in this application to ensure that there is a current path through the body diode of the N-channel MOSFET, Q_1, making it possible for control circuitry within the motor driver integrated circuits to start to operate during a power-up sequence.

Transistor Q_2 is a normally connected P-channel small-signal MOSFET and is used to control the gate of transistor Q_1 in the normal and reverse battery conditions. Both Q_1 and Q_2 must be correctly rated for the full peak reverse battery voltage. Depending on the applications and requirements, a suitably rated Zener diode may be used and connected between the gate and source terminals of both transistors, Q_1 and Q_2, to protect the reverse battery circuitry against any overvoltage.

The voltage source, V_{CP}, is either produced by the driver integrated circuit itself or circuitry closely associated with it. This means that the V_{CP} voltage will not be present when V_{BB} = 0 V, or when a reverse polarity is applied. V_{CP} voltage also takes some time to rise to a final stable value after V_{BB} is applied. The resistor, R_G, is used to control the gate-to-source voltage of the N-channel, Q_1, and is powered from the V_{CP} supply. To reduce the current drains from the V_{CP} terminal, resistor R_G should have a minimum value of 100 kΩ ±1%.

CIRCUIT OPERATION WITH V_{CP}

Analysis of Operation with Correct Battery Polarity

The position of impedance Z_L is shown in Figure 2. Impedance Z_L provides a current path from V_{BB} to ground via the power bridge and the motor under all conditions.

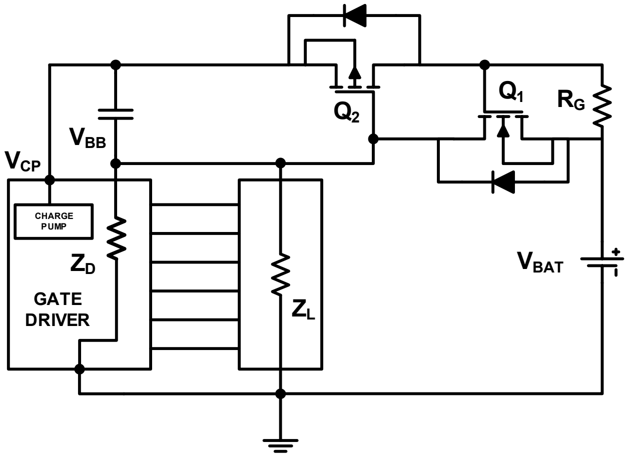

Figure 2: Correct battery polarity with V_{CP} terminal

The sequence of events during start-up is as follows:

- With V_{BAT} = 0 V, there is no current flowing in Z_D and Z_L and the V_{CP} voltage = 0 V.
- V_{BAT}, with the correct polarity, is applied to the gate driver.
- Current flows through the forward-biased body diode of transistor Q_1 and into the gate driver, causing it to execute a power-on reset cycle and initialize.
- During initialization, the gate driver sets the signals from the drive to the MOSFET power bridge into a safe state.
- As the gate driver progresses through its various control states, it causes the value of the V_{CP} voltage referenced to V_{BB} or V_{BRG} to increase from zero and to raise the voltage on the source of Q_2 to be more positive than V_{BB} or V_{BRG}. This action increases the gate-to-source voltage on Q_2.
- As V_{CP} rises above the conduction threshold of Q_2, it starts to turn on, and the current flowing through it produces a voltage across R_G. This voltage appears across the gate and source of Q_1, and it also starts to turn on.
- As Q_1 starts to conduct, the main supply current from V_{BAT} is shared between its body diode and source-to-drain path.
- At sufficiently high values of V_{CP}, the on-resistance, R_{ON}, of Q_1 becomes sufficiently low that the source-to-drain voltage falls below the forward voltage of the body diode in Q_1, and conduction ceases. All the current then flows between the source and drain of Q_1 to produce an insertion loss ($I^2 \times R_{ON}$).

Analysis of Operation with Reverse Battery Polarity

The reverse battery polarity condition is shown in Figure 3. In this condition, the V_{CP} voltage is always 0 V because the gate driver never achieves an operating condition.

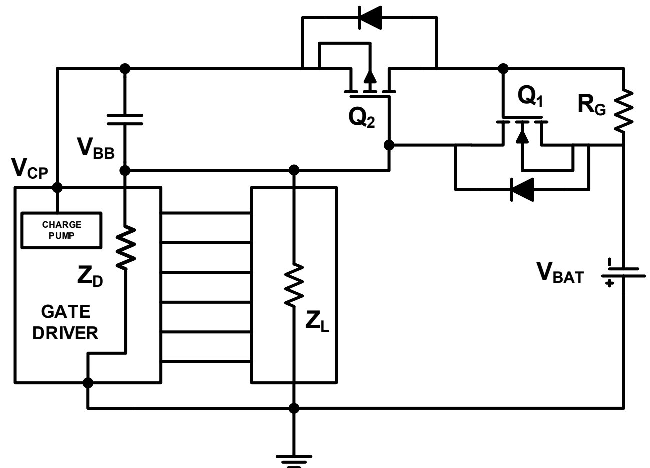

Figure 3: Reverse battery polarity with V_{CP} terminal

The sequence of events during start-up is as follows:

- At start-up, V_{BAT} = 0 V, and the gate-to-source voltage, V_{GS}, on Q_2 is held at 0 V through the load impedance, Z_L. The V_{GS} voltage on Q_1 is also held at 0 V through R_G. Therefore, in this condition, both Q_1 and Q_2 are turned off, and no voltage bias is applied across the gate driver and Z_L.
- As V_{BAT} increases in a negative direction, the 0 V V_{GS} condition persists on the gates of Q_1 and Q_2, and both transistors remain turned off.
- Because Q_1 and Q_2 remain turned off, all applied reverse voltage appears across the source and drain connections of Q_1 and Q_2. As a result, voltage across the gate driver and Z_L remain at 0 V.
- The net result is that, when V_{BAT} is in the reverse polarity condition, current does not flow through the gate driver or the equivalent-load impedance Z_L.
- This condition is stable until the source-to-drain voltage breakdown rating of either Q_1 or Q_2 is exceeded by the reverse voltage on V_{BAT}.

CIRCUIT OPERATION WITH INTERNAL CHARGE PUMP

Many products from Allegro feature an output from an internal regulator charge pump that runs and switches continuously. The signal of the internal regulator charge pump, C_{P1}, may be used to pump a circuit that creates a voltage supply equivalent to the V_{CP} voltage presented in Figure 1, Figure 2, and Figure 3. Operation of the circuit, as illustrated in Figure 4 under both correct and reverse voltage polarity conditions, closely follows the earlier description in the Circuit Operation with V_{CP} section.

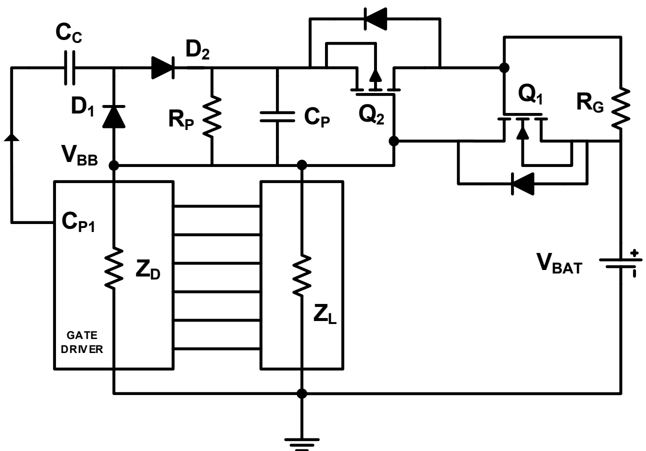

Figure 4: Battery protection with C_{PI} terminal

CIRCUIT OPERATION WITH BOOTSTRAP CAPACITOR

Some Allegro products have neither an internal charge pump to provide the V_{CP} voltage nor an internal regulator charge pump to provide continuous running and switching. Instead, they use bootstrap capacitors, C_{BOOTX}, to create the gate voltage required by the high-side power MOSFETs in the main output power bridge. Bootstrap capacitors are connected between bootstrap supply terminals C_A, C_B, and C_C and corresponding reference pins S_A, S_B, and S_C, as shown in Figure 5.

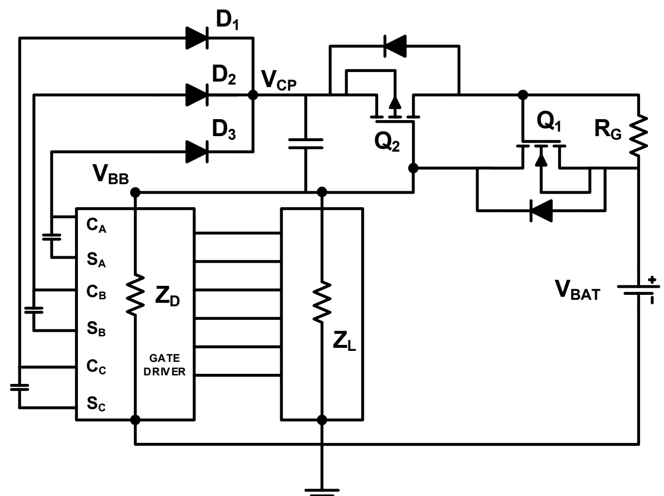

Figure 5: Battery protection with C_A, C_B, and C_C terminals

When the system operates with a positive polarity on V_{BAT}, the operation of the bootstrap capacitors, C_{BOOTA}, C_{BOOTB}, and C_{BOOTC}, normally results in the voltage on the C_A, C_B, and C_C terminals of the gate driver switching higher than the V_{BB} voltage when any high-side driver in the power bridge is commanded to turn on. Diodes D_1, D_2, and D_3 (see Figure 5) ensure that the peak voltage from any of the C_A, C_B, and C_C terminals is delivered to the source of the P-channel small-signal MOSFET, Q_2, as presented in Figure 5. The P-channel small-signal MOSFET, Q_2, operates as a normal on-switch, unless the voltage on the C_A, C_B, and C_C terminals is kept below the turn-on threshold of the P-channel small-signal MOSFET, Q_2. Therefore, the peak voltage from C_A, C_B, or C_C is applied to the gate of the N-channel MOSFET, Q_1. The gate-to-source capacitance of the N-channel MOSFET, Q_1, can store charge from the bootstrap capacitors and produce a DC voltage for the gate of the N-channel MOSFET, Q_1. From the description above, a voltage supply equivalent to V_{CP} voltage presented in Figure 1, Figure 2, and Figure 3 has been created. Operation of the circuit, as illustrated in Figure 5 under correct and reverse voltage polarity conditions, closely follows the earlier description in the Circuit Operation with V_{CP} section.

If a bootstrap capacitor does not operate any of the bridge high-side MOSFET for a long time, the charge on the gate of the N-channel MOSFET, Q_1, will decay through R_G. This will eventually result in the N-channel MOSFET, Q_1, turning off. Any low voltage to the bootstrap capacitor terminals on the gate driver may not allow turn-on of both transistors, Q_1 and Q_2. However, most Allegro gate drivers of this type have a bootstrap capacitor under voltage detection that activates on this condition, and all high-side MOSFETs in the bridge are turned off and system current is reduced. Some products include a top-off charge pump in the gate driver that activates if the voltage on the bootstrap capacitors drop below a safe level.

COMPONENTS SELECTION

Transistor Q1 requires a large positive overdrive voltage, represented by the V_{CP} terminal, between its source and gate, to ensure the source-to-drain resistance is kept very low. In most practical circuits, the voltage source, V_{CP}, is usually maintained at approximately 10 V, so it is important to review the maximum V_{GS} rating of potential candidates for the Q_1 and Q_2 MOSFETs to ensure the rating supports the application. With Q_1 fully turned on, its internal power dissipation is low and maximum power is delivered to the load impedance, Z_L. However, if the V_{CP} voltage does not achieve its operating voltage because a fault develops, power dissipation in Q_1 can be significant. If there is no safeguard to reduce the load current through the bridges if the V_{CP} voltage is too low, a suitable heat sink for the Q_1 MOSFET must be provided. Transistor Q_2, a low-power P-channel small-signal MOSFET, is used as a switch to transfer the voltage, V_{CP}, to the gate of Q_1. The current flowing through Q_2 is low, and a small-signal transistor with lower turn-on power dissipation is normally adequate. Both transistors must have a V_{DS} voltage rating greater than the maximum reverse-polarity value of V_{BAT}.

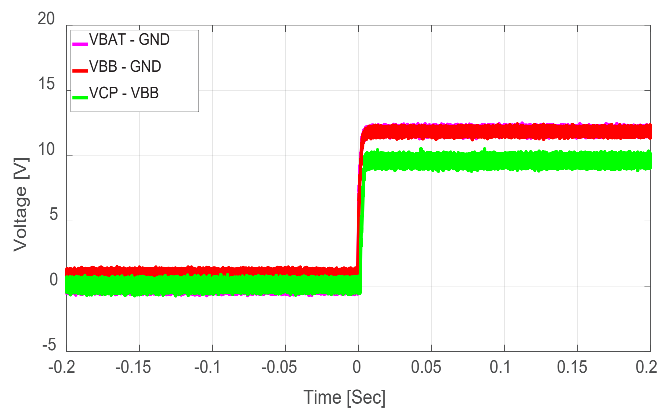

Figure 6: V_{BAT} voltage with correct polarity

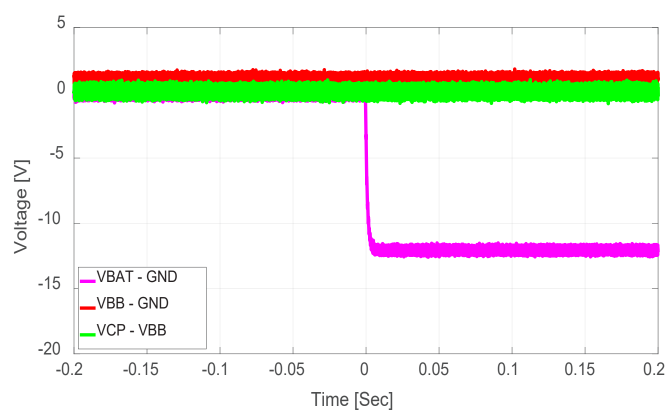

Figure 7: V_{BAT} voltage with reverse polarity

EXPERIMENTAL RESULTS

The performance of the reverse battery protection circuit presented in Figure 1 was experimentally verified on the bench. Several experiments were performed on the bench using the AMT49107 gate driver, which has an internally designed charge pump terminal, V_{CP}. The test bench contains a dual DC power supply, commercially available 1 GHz scope, and Allegro AMT49107 demonstration board, which has a built-in reverse battery protection circuit. For the experimental test, commercially available transistors were selected for the N-channel MOSFET and P-channel MOSFETs, and the parameters of both transistors are presented in Table 1. To reduce the current drains from the V_{CP} terminal of the AMT49107 gate driver, resistor R_G of 100 kΩ with ±1% tolerance was connected between the gate and source of transistor Q_1.

Table 1: Q_1 and Q_2 Transistor Parameters

Parameters	Q_1 Transistor	Q_2 Transistor
R_{DSON} [mΩ]	4.2	6000
V_{DS} [V]	60	60
V_{GS} [V]	20	20
I_{DS} [A]	90	0.185

The experimental tests were carried out by applying stepped voltage changes—from 0 V to 12 V and 0 V to –12 V—on the battery under test and observing the performance of the reverse battery protection circuit by monitoring the V_{BAT}, V_{BB}, and V_{CP} signals. The V_{BRG} and V_{BB} terminals of the AMT49107 gate driver were connected during bench test evaluation. The results are presented in Figure 6 and Figure 7. The performance of the reverse battery protection with the correct polarity is shown in Figure 6: During power-up, the initial system current is supplied to V_{BB} through the forward-biased source-to-drain diode of transistor Q_1 until V_{CP} voltage has exceeded the threshold voltage of transistor Q_1 and turned it on. The behavior of the reverse battery circuit with reverse polarity is shown in Figure 7: When the battery voltage is reversed, the voltage between V_{CP} and V_{BB} is zero, the gate-to-source voltage on transistor Q_1 is zero, and its source-to-drain diode becomes reverse biased. In this condition, transistor Q_1 blocks the current flowing to V_{BB}, and the voltage between V_{BB} and ground remains at approximately 0 V.

SUMMARY

A list of the most prevalent Allegro gate drivers in automotive applications is provided in Table 2 along with the corresponding reverse battery protection techniques described in this application note. The reverse battery protection circuitry is selected for a given gate driver based on the structure of the gate driver—the gate driver has either an internal charge pump, V_{CP}, an internal regulator charge pump, C_{P1}, or bootstrap capacitor, C_{BOOTX}, terminals, as presented in Table 2.

This application note has discussed the reverse battery protection that can be used with Allegro gate drivers for automotive applications that employ gate drivers that have an internal charge pump terminal or an internal regulator charge pump terminal, or that use bootstrap capacitor terminals. Experimental results demonstrate that the gate driver can be protected against the reverse battery polarity that can occur by changing the battery of a vehicle or during routine maintenance work on electronic systems.

Table 2: Gate Drivers and Reverse Battery Protections

Gate Driver	V_{CP} Terminal	C_{P1} Terminal	Bootstrap Terminals
A3921	No	Yes	Yes
A3922	No	No	Yes
A3924	No	No	Yes
A3941	No	Yes	Yes
A4911	No	No	Yes
A4913	No	No	Yes
A4916	No	No	Yes
A4918	No	No	Yes
A4919	No	No	Yes
A4933	No	No	Yes
A4935	No	No	Yes
A4939	No	No	Yes
AMT49106	Yes	No	Yes
AMT49107	Yes	No	Yes
A6861	Yes	No	No
A6862	Yes	No	No

Revision History

Number	Date	Description	Responsibility
–	November 18, 2022	Initial release	K. Tshiloz