Using a Smart Ideal Diode for Car Battery Front-End Protection

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Introduction

If the battery terminals in a car are reverse-connected during a jump start, vehicle maintenance, or repair, the components in the electronics control unit (ECU) may be damaged if they cannot handle this fault condition. On top of this, during normal operation the car battery voltage is not constant — the input voltage (V_{IN}) can even be negative under several transient tests regulated by the EMC standards, such as ISO 7637 and ISO 16750. These fluctuations mean that front-end protection is necessary.

Schottky diodes and P-channel MOSFETs (P-FETs) are widely used in automotive power system designs for reverse-battery protection and automotive electrical transient protection. However, these conventional solutions have significant power dissipation, which reduces thermal efficiency and makes it more difficult for designers to meet the system's cost and space requirements.

This article will review reverse polarity solutions. It will also use MPS's MPQ5850-AEC1 — a smart diode controller that can be used for automotive front-end protection — as an example while exploring the advantages of using a controller compared to traditional front-end protection solutions.

Using a Schottky Diode for Front-End Protection

The Schottky diode is the simplest reverse polarity protection schematic (see Figure 1). During normal operation, the diode (D1) conducts in the forward direction; when a reverse voltage is applied, D1 stops conducting.

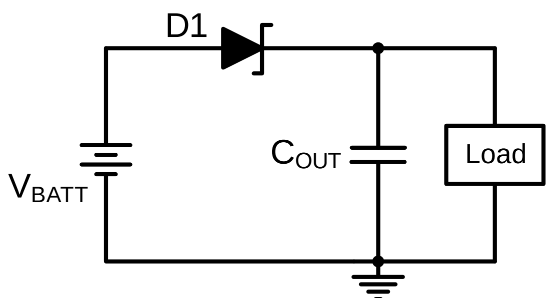

Figure 1: Using a Schottky Diode for Reverse Polarity Protection

Due to the diode's constant and significant forward voltage drop, as the normal operating current increases, the power consumed on the diode also increases proportionally, which results in bad thermal performance. Because of this, Schottky diode solutions are typically only used for low-current conditions. As time passes and better strategies are developed, it will become more difficult to meet system requirements with the Schottky diode due to its large reverse leakage and outdated architecture.

Using a P-Channel MOSFET for Front-End Protection

It is common to use a P-FET for reverse polarity protection in industrial and automotive applications because it results in a small voltage drop for low power loss. Figure 2 shows the schematic when using a P-FET.

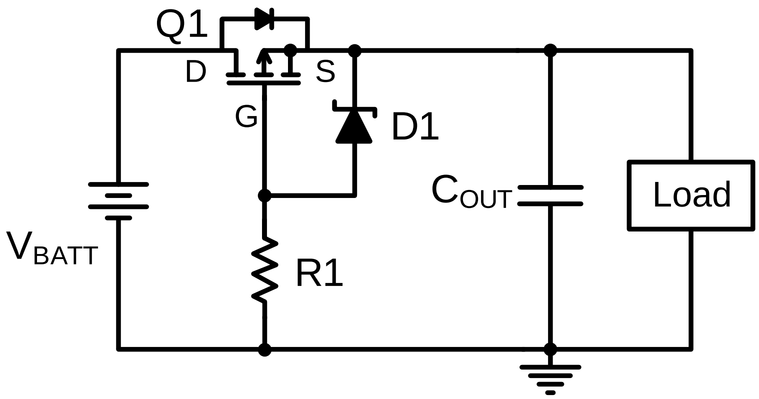

Figure 2: Using a P-FET for Reverse Polarity Protection

During normal operation, the current first flows through the P-FET's body diode, and the P-FET's source (S) voltage is close to the battery voltage (V_{BATT}). At this time, the gate (G) voltage is 0V; this is negative relative to the P-FET's source end, which is also the circuit's output. In this scenario, the P-FET (Q1) can conduct, and then the current flows from the drain (D) to the source (S). The solution's Zener diode (D1) can protect the gate-to-source voltage (V_{GS}) from exceeding the rated voltage.

When the system is under reverse-polarity conditions, D1 conducts forward, and V_{GS} is only about 0.7V. Then Q1 turns off to protect the system from damage caused by the reverse polarity voltage.

A P-FET is self-biased by simply pulling its gate pin low, which means that the P-FET has poor cold-crank performance (low V_{BATT} operation). During severe cold cranks (where V_{BATT} falls below 4V), the P-FET's series resistance increases drastically (see Figure 3). This leads to a higher voltage drop across the P-FET. During a cold crank, a higher gate-to-source threshold (V_{TH}) can sometimes lead to a system reset if the P-FET turns off.

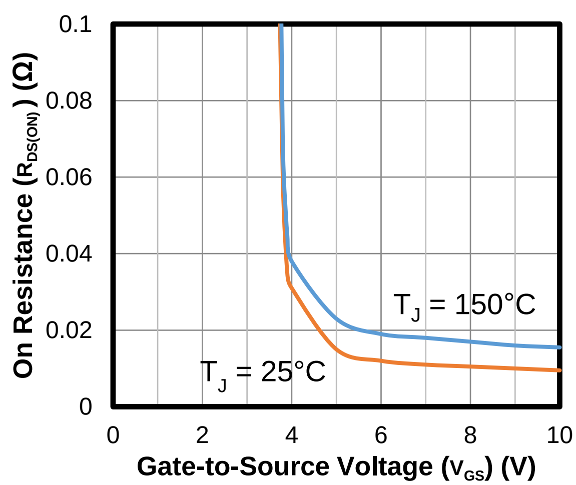

Figure 3: P-FET On Resistance vs. Gate-to-Source Voltage

However, using a P-FET can pose certain challenges. P-FET solutions need a protection circuit, which is composed of the Zener diode (D1) and current-limit resistor (R1) to avoid V_{GS} exceed its breakdown voltage (BV). Both D1 and R1 have a leakage current, which increases the system's quiescent current (I_Q). In addition, when adding an AC input voltage, the P-FET is fully on, which causes current backflow. This forces the electrolytic capacitor to repeatedly charge and discharge, ultimately leading to overheating.

Using a Smart Ideal Diode Controller for Front-End Protection

The traditional reverse polarity protection solutions described above struggle to meet many requirements for new systems, such as low cost, small space, high efficiency, and versatility. To meet these requirements, smart ideal diode controllers that drive external N-channel MOSFETs (N-FETs) has been developed.

The N-FET must be placed on the high side, and the smart diode controller IC also takes power from the high side. The internal supply voltage must exceed the battery voltage (V_{BATT}) to drive the N-FET. There are two methods to generate this supply voltage: via charge pump or boost, which are both described below (see Figure 4).

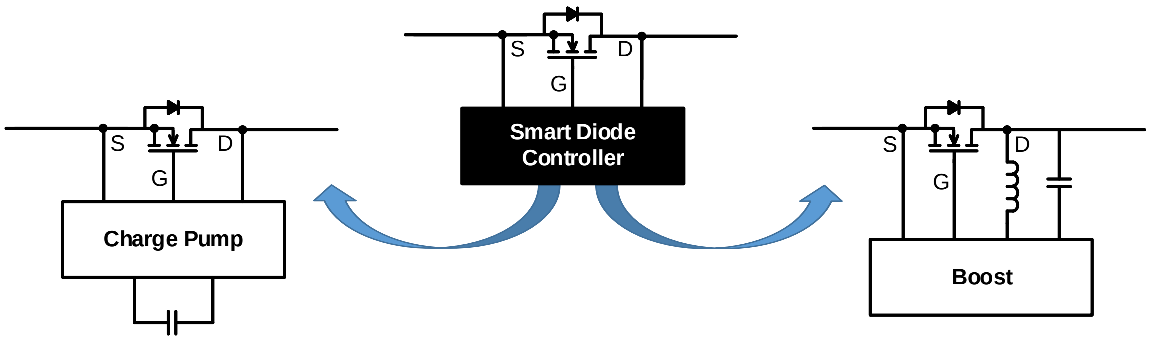

Figure 4: Smart Diode Controller Gate Drive Method

Charge Pump

Figure 5 shows the working principles for the charge pump method using four switches (S1, S2, S3, and S4). C_T is a low-value capacitor with fast charging and discharging speed, while C_{CP} is a high-value capacitor with a large load capacity. When the pulse-width modulation (PWM) signal of the clock is high, S3 and S4 conduct, and the internal source charges the C_T. When the PWM signal is low, S3 and S4 open, S1 and S2 conduct, and the charge pump capacitor (C_{CP}) is charged by C_T.

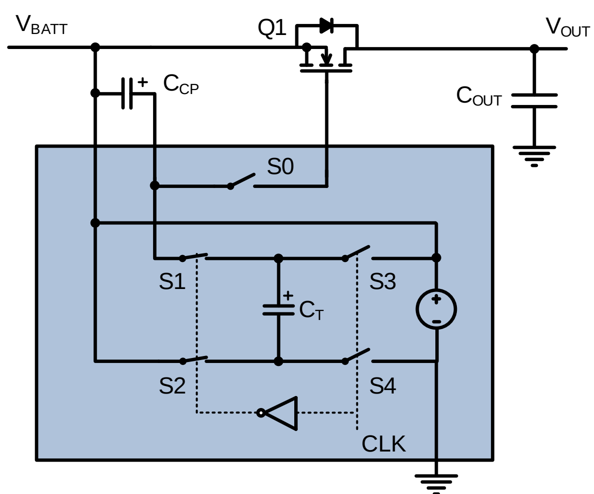

Figure 5: Internal Charge Pump Circuit

Therefore, through frequent switching between S1 and S2 (as well as S3 and S4), the charge on C_T can be continuously transmitted to C_{CP}. In addition, the C_{CP}'s negative terminal is connected to the battery voltage (V_{BATT}), so the N-FET can be driven by a voltage exceeding V_{BATT}.

The charge pump has a low efficiency and weak driving current capability, which usually only 10mA to 30mA pull-up. When V_{BATT} fluctuates rapidly (such as during an input superimposed high-frequency AC signal from ISO 16750-2 in Figure 6), it is easy to generate abnormal phenomena, such as gate drive pulse loss and gate drive pulse constantly on.

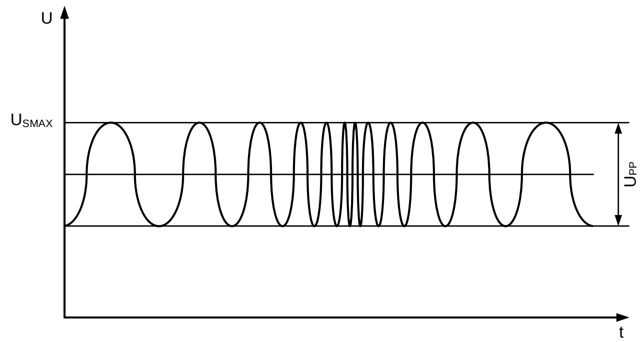

Figure 6: ISO 16750-2 Superimposed Alternating Voltage

If the gate drive pulse is lost, the N-FET remains off and the current is conducted by its body diode, resulting in a large amount of thermal loss. When the gate drive pulse is constantly on, the N-FET remains on and the output electrolytic capacitor (C_{OUT}) repeatedly charges and discharges, which can lead to overheating.

In addition, although the charge pump does not have an inductor, the charge pump circuit is a capacitive switching power supply that requires a very high operating frequency (f_{SW}) due to its low efficiency. Usually, the integrated capacitance for C_T is small (within the pF range) and the external capacitance for C_{CP} is large (within the µF range). Therefore, the charge pump's f_{SW} often exceeds 10MHz, which can lead to EMI issues and a higher I_Q.

In summary, the charge pump solution has a lower overall BOM requirement, which can reduce costs, but it is only recommended for low-current applications and lacks sufficient capacity for high-power applications.

Boost Converter

Figure 7 shows the working principles for a boost converter solution. When S1 is conducting, the inductor is charged by V_{BATT}, and the inductor current increases. Once the inductor current (I_L) reaches the fixed peak current threshold, S1 is open. I_L continues to flow through the diode (D1) and charges a capacitor (C1). When the voltage on C1 exceeds V_{BATT}, the N-FET's gate is driven high.

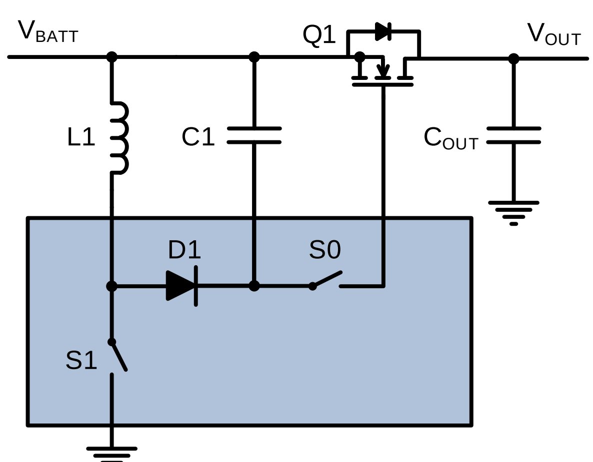

Figure 7: Internal Boost Circuit

When using a boost converter to drive an external N-FET, the boost converter's efficiency is relatively high. This converter can provide a greater driving current capacity (exceeding 100mA) and faster input interference response. Therefore, a smart diode controller solution with an integrated boost converter is recommended for high-power applications, and it can also achieve an excellent V_{IN} rectification effect.

In addition, the boost converter uses fixed peak current mode control, meaning the lighter the load, the lower the f_{SW}. Since the N-FET consumes only a small current, it results in a solution with extremely low f_{SW} and almost no EMI issues.

A New Smart Ideal Diode Solution

In response to the front-end's demand for a high current, fast response, and small footprint, MPS has developed the MPQ5850-AEC1, which can be used for automotive front-end protection (see Figure 8).

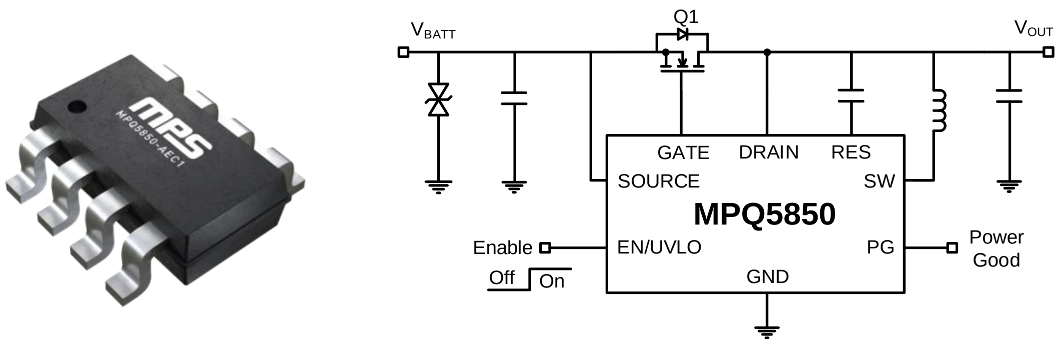

Figure 8: MPQ5850-AEC1 and Typical Application Circuit

The MPQ5850-AEC1 is a smart ideal diode controller that can drive an external N-FET to replace a Schottky diode or a P-FET for reverse input protection. The device integrates an internal boost to provide a boost voltage that turns on the external N-FET, even at a low input V_{BATT}. Figure 9 shows the device's functional block diagram.

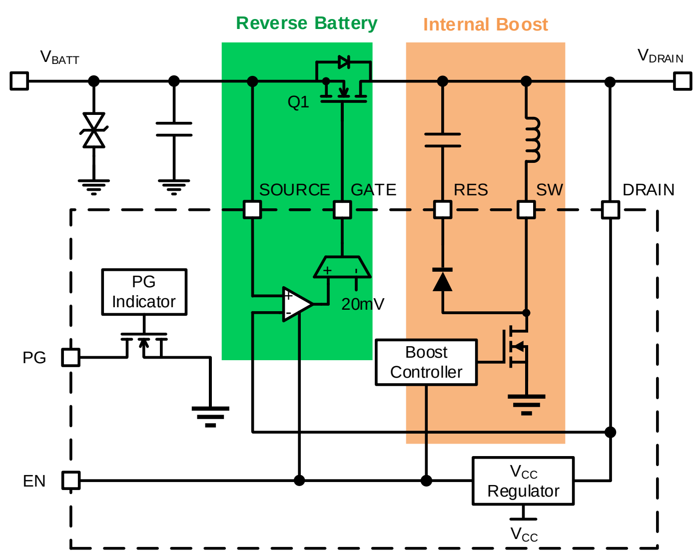

Figure 9: MPQ5850-AEC1 Functional Block Diagram

The MPQ5850-AEC1 can regulate the source-to-drain voltage (V_{SD}) to 20mV by modulating the gate of the external N-FET. The device's 20mV ultra-low dropout minimizes power loss and allows small negative currents to be easily detected.

The 4μA shutdown current and 30μA I_Q also make the device ideal for battery-powered applications. The MPQ5850-AEC1 features a strong gate drive ability (170mA pull-up and 430mA pull-down) for ultra-fast transient response, and it meets stringent ISO 16750 and ISO 7637 requirements such as Class 4 negative pulse and 100kHz input superimposed high-frequency AC signals. Figure 10 shows a few test waveforms.

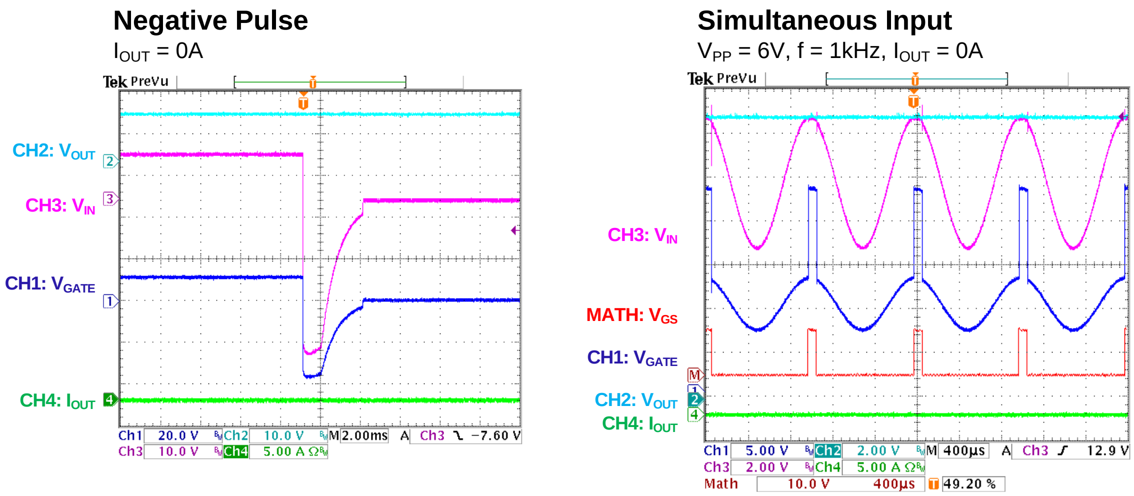

Figure 10: MPQ5850-AEC1 Negative Pulse and Simultaneous Input Test Waveforms

The MPQ5850-AEC1's internal circuitry is powered by the drain voltage (V_{DRAIN}) instead of V_{BATT}. If V_{DRAIN} exceeds its under-voltage lockout (UVLO) threshold, then the MPQ5850-AEC1 operates normally, even if V_{BATT} drops to 0V during a severe cold-crank condition.

If V_{DRAIN} drops below the UVLO threshold, the device pulls down the GATE pin to the SOURCE pin (which is also the N-FET's source) until the voltage on the reservoir capacitor discharges below its UVLO threshold. This allows the device to minimize forward-voltage drops during temporary low-voltage transients, such as cold-crank conditions. Figure 11 shows the cold-crank test waveforms.

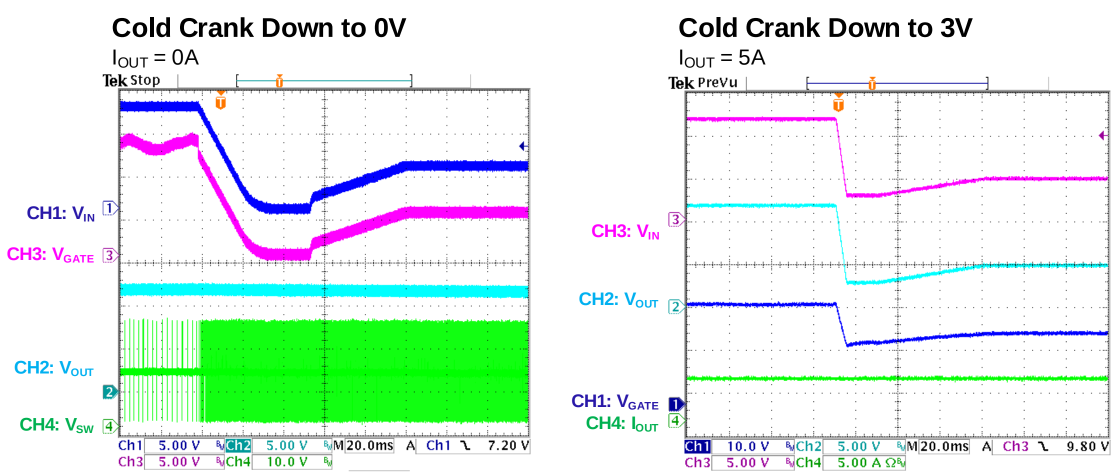

Figure 11: MPQ5850-AEC1 Cold-Crank Test Waveforms

The MPQ5850-AEC1 also integrates an open-drain power good (PG) signal pin to indicate certain statuses, such as when the boost capacitor is out of regulation, an over-current (OC) condition is active for longer than 17µs, or the device is disabled. In the meantime, the internal boost uses the low-frequency, fixed peak current mode controller, so the MPQ5850-AEC1 has excellent EMI performance (see Figure 12).

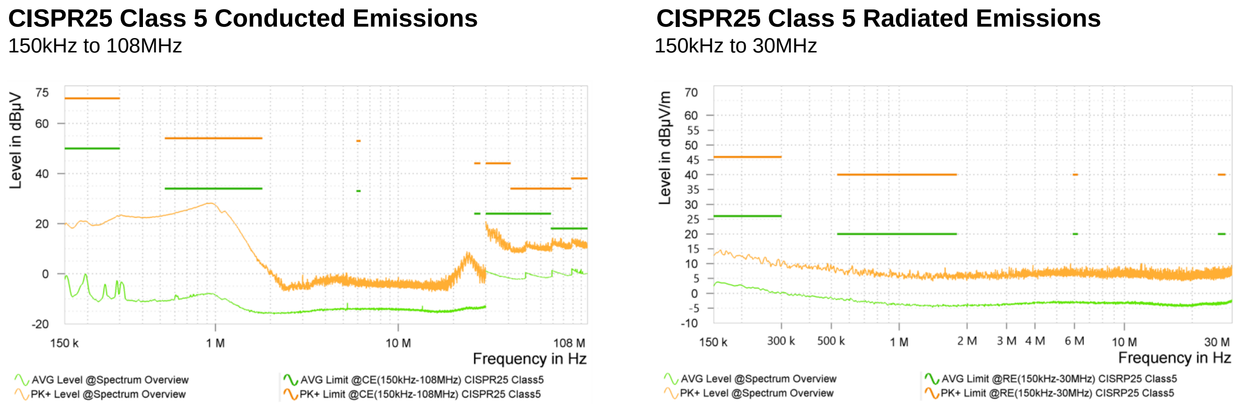

Figure 12: MPQ5850-AEC1 CISPR 25 Class 5 CE and RE EMI Performance

Summary

For front-end protection, Schottky diodes can be used in low-current applications with a low cost and simple circuit. However, as the current increases, the power and thermal loss of the solution also become increasingly severe. For higher currents, MOSFET circuits can be used instead, but a P-FET or an N-FET should be selected based on the specific application conditions. A P-FET cannot be used at low voltages, nor can it provide input rectification.

For the two methods using an N-FET, the charge pump drive solution has a lower overall BOM requirement, which can reduce costs. However, its EMC performance is poor and is more suitable for low-current applications, such as high-power charging modules for automotive USB power supply devices. A boost converter solution, such as MPQ5850-AEC1, can provide powerful driving capabilities and excellent EMC performance. This solution is recommended for high-current and high-performance environments, such as automotive domain controllers and audio systems.

Table 1 summarizes the different solutions described above.

Table 1: Comparing Front-End Protection Solutions

	Schottky Diode	P-FET	Charge Pump	MPQ5850 (Boost)
Speed	Very fast	Very slow	Slow	Fast
Voltage Drop	Very high	Medium	Low	Low
Solution Size	Small	Large	Small	Small
Minimum Cold Crank Voltage	0V	Not supported	3V	0V
EMI	No	No	Potential risk	Very low

Conclusion

This article compared four possible solutions that can be used to provide front-end protection for car batteries, particularly for revery polarity. Depending on an application's needs, it may be advantageous to select any of these options, such as a Schottky diode, P-channel MOSFET, or a smart controller with N-channel MOSFET. Using a smart controller such as the MPQ5850-AEC1 enables a complete solution while improving efficiency, minimizing EMI, and operating under harsh conditions (e.g. a cold-crank condition and input superimposed high-frequency AC conditions). Explore MPS's extensive portfolio of automotive-grade smart controllers that can help you meet your design requirements.