AN1198

Load Dump Protection Using Ideal Diode Controllers

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Introduction

The automotive sector is undergoing a major transformation driven by advancements in semiconductor technology. These components enable critical innovations such as autonomous driving, enhanced passenger protection, and seamless vehicle-to-vehicle connectivity. As safety remains the cornerstone of advanced driver-assistance systems (ADAS), manufacturers are increasingly incorporating specialized ICs to improve reliability and safeguard passengers.

One of the most important factors in achieving system-level safety is designing robust power management and protection circuits that can withstand high-energy transients. Without proper safeguards, these pulses can cause severe damage to downstream electronics. This application note explores strategies for mitigating load dump events in automotive systems, following ISO 16750-2 guidelines for Test A (without centralized suppression) and Test B (with centralized suppression). These scenarios correspond to the former ISO 7637-2 classifications 5a and 5b.

Before diving into strategies for shielding electronic modules from load dump transients, it's essential to grasp the foundational layout of modern automotive power systems.

Vehicles are generally categorized by their electrical demands. Passenger cars fall under the light-duty segment and typically operate on a 12-volt electrical system, while commercial and industrial vehicles such as trucks, agricultural machinery, and construction equipment rely on 24-volt configurations to support heavier loads.

At the heart of any vehicle's electrical infrastructure lies a network composed of key elements: the battery, an alternator for power generation, protective circuitry, voltage conversion stages (DC-DC converters), and a series of downstream electronics. These downstream blocks include low-dropout regulators (LDOs) and various electronic control units (ECUs), each responsible for specific vehicle functions.

Among these, the downstream electronics are particularly vulnerable to voltage fluctuations. Designers face the critical task of maintaining stable voltage levels from the battery to ensure reliable operation of sensitive components such as sensors and microprocessors embedded within the ECUs.

With this system architecture in mind, we can now explore the phenomenon of load dumps—what triggers them, and why they pose a serious threat to the integrity of automotive subsystems.

What is Load Dump?

Load dump transients in automotive electrical systems occur when the alternator continues supplying current after the battery connection is unexpectedly interrupted. This situation typically arises if a depleted battery becomes disconnected while the alternator is actively charging and other electrical loads remain tied to the alternator circuit. Figure 1 illustrates this scenario.

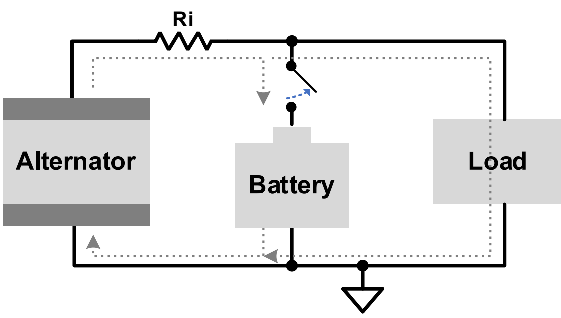

Figure 1. Load dump generation

To evaluate the impact of a load dump event on downstream electronics, it's essential to break down its key characteristics. A load dump consists of two primary parameters: the peak voltage (VPEAK) and the pulse duration (tD). The peak voltage is influenced by alternator speed and the level of field excitation at the moment the battery disconnects. The duration, on the other hand, is determined by the excitation circuit's time constant and the magnitude of VPEAK, as illustrated in Figure 2. In severe cases, VPEAK can reach up to 202V and persist for as long as 350ms before decaying. The total energy delivered to the load is further affected by the source's internal resistance (Ri), shown in Figure 1.

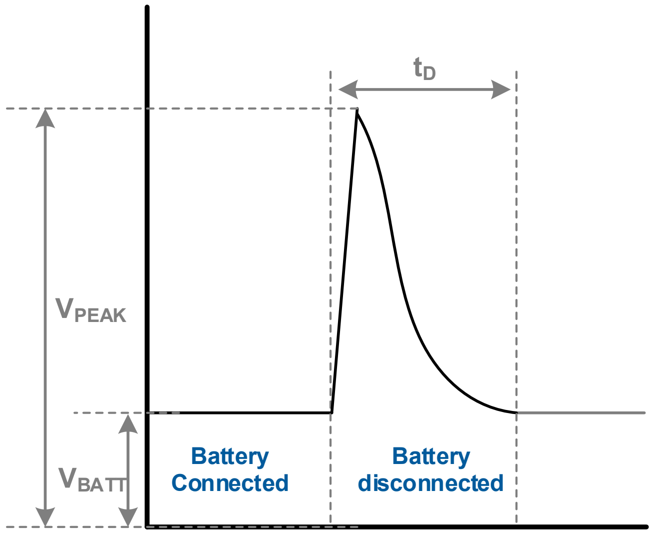

Figure 2. Output voltage of an alternator during a load dump event showing nominal battery voltage.

Load Dump Protection

Automotive electronics require robust strategies to withstand load dump transients. This application note highlights three proven approaches for mitigating these events and examines the advantages and limitations of each.

The first approach focuses on isolating sensitive circuits from the source of the transient. The second method employs voltage clamping to ensure the surge remains within the absolute maximum rating of the front-end DC-DC converter. Finally, a hybrid technique combines isolation and clamping to deliver enhanced protection and system reliability.

Approach #1. Isolate the load from the transient source using AP74502Q

One effective way to mitigate load dump transients is by isolating the source from sensitive downstream circuits. This can be achieved by using power MOSFETs as high-side switches, controlled by the AP74502Q protection IC, as illustrated in Figure 4. The AP74502Q continuously monitors the input voltage, and when it detects an overvoltage condition, it immediately turns off the MOSFET to disconnect the transient source from the load.

The AP74502Q offers a flexible design with programmable overvoltage and undervoltage thresholds, allowing system designers to configure limits across a wide operating range using external resistors. Its robust protection capability, covering voltages from -75V to +80V, ensures reliable defense against load dump surges and battery-reversal scenarios. These features make the AP74502Q an excellent choice for automotive applications requiring high reliability and safety.

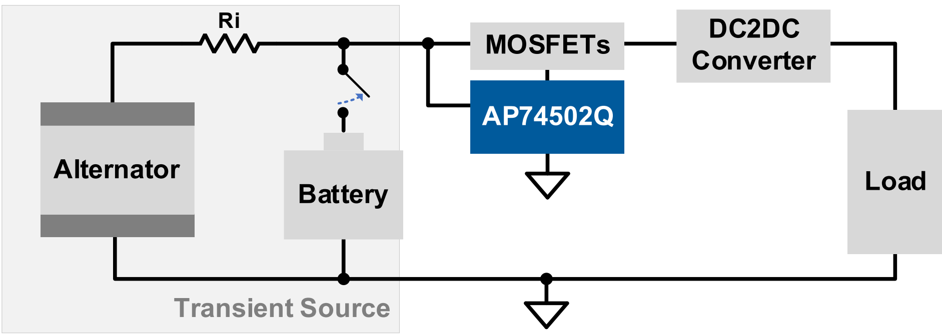

Figure 3. Isolation of the load dump source from the downstream load

To extend the protection capability of the AP74502Q, designers can add a Zener diode to the positive input pin (IN) along with a series current-limiting resistor (RP), as shown in Figure 5. During a severe load dump event, if the input voltage rises above +90V, the Zener diode clamps the voltage at this level while RP restricts the current flowing through the diode.

Selecting the right MOSFET for this configuration is critical because the full load dump voltage will appear across its drain and source terminals. The MOSFET should have a V_{DSS} rating at least 1.2 times higher than the peak surge voltage. However, keep in mind that higher V_{DSS} devices typically exhibit greater $R_{DS(ON)}$, which can reduce system efficiency under normal operating conditions.

This approach offers comprehensive protection against multiple electrical hazards, including load dump surges, cold-crank conditions, and reverse polarity events. Configuring overvoltage and undervoltage thresholds is straightforward—simply adjust the resistor network to achieve the desired limits.

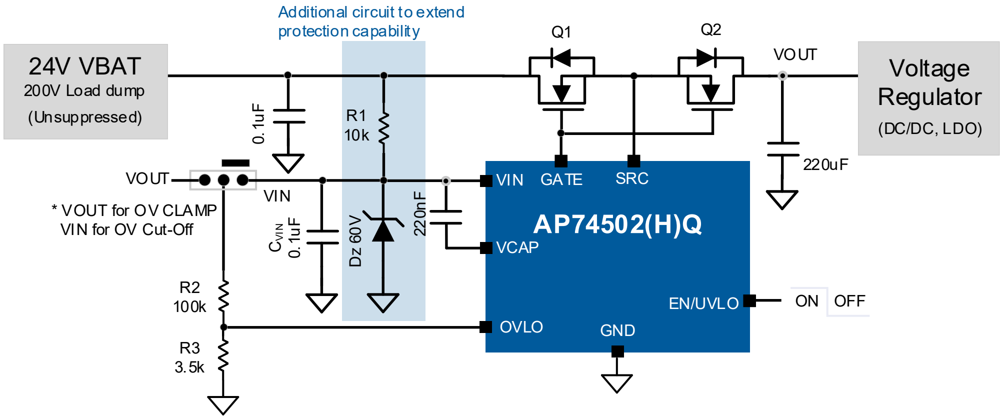

Figure 4. Increase the protection range of AP74502(H)Q

Approach #2. Clamp the Load Dump Pulse Using a TVS Diode

Another effective strategy for mitigating load dump surges is to clamp the transient voltage to a level that the DC-DC converter can safely tolerate. This is typically achieved using a transient voltage suppressor (TVS) diode, as shown in Figure 5. The TVS diode absorbs the surge energy and limits the voltage spike to a predefined safe level.

According to ISO 16750-2 Test A specifications, the alternator's internal resistance (Ri) generally falls between 1Ω and 8Ω, which helps restrict the total energy delivered to the TVS device. However, selecting the correct TVS diode is critical because the energy absorbed depends on several factors: the clamping voltage, the pulse duration, and the source resistance. Proper sizing ensures reliable protection without overstressing the diode during high-energy events.

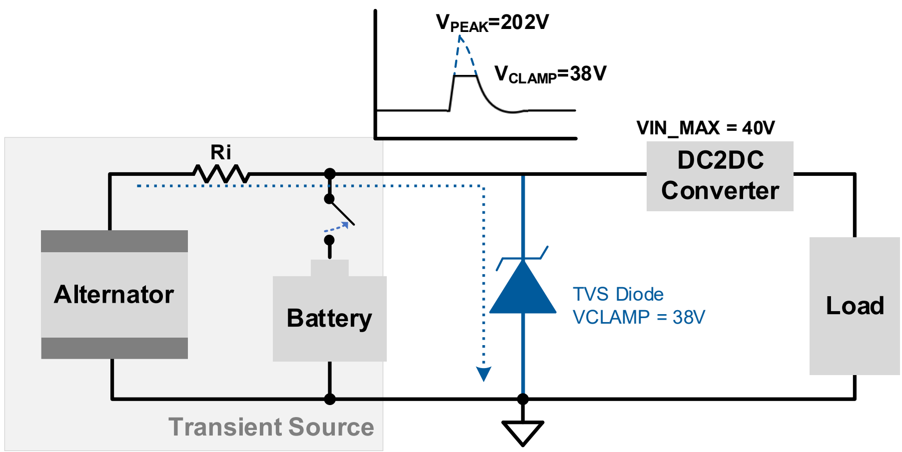

Figure 5. Clamp the load dump pulse to a safe operation voltage

To illustrate the limitations of TVS-based protection, let's analyze a load dump scenario using ISO 16750-2 Test A parameters: V_{Sa} = 151V, Ri = 1Ω, t_D = 100ms, and a clamping voltage (V_{CLAMP}) of 38V. In this case, the TVS diode must absorb a significant amount of energy while maintaining the voltage within safe limits for the DC-DC converter.

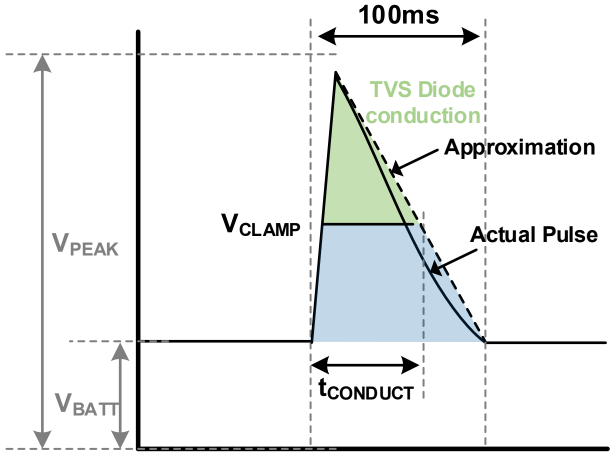

Figure 6. Approximate area of a pulse absorbed by a TVS diode during a load dump

$$I_{PEAK} = \frac{V_S - V_{CLAMP}}{R_I} = \frac{151 - 38}{1} = 113A$$
$$P_{PK} = I_{PEAK} \times V_{CLAMP} = 113 \times 38 = 4.294kW$$

Assuming a triangular pulse shape, the conduction time for the TVS diode ($t_{CONDUCT}$) and the absorbed energy can be estimated based on the peak current (I_{PEAK} = 113A) and a duration of approximately 74.83ms.

$$Slope\ of\ Pulse = \frac{V_S}{T_{Disconnect}} = \frac{151V}{100ms}$$
$$t_{CONDUCT} = \frac{V_S - V_{CLAMP}}{Slope\ of\ Pulse} = \frac{(151 - 38) \times 100ms}{151} = 74.83ms$$

Energy(E) absorbed by the TVS diode can be calculated using the following

$$E = \int_0^{t_{CONDUCT}} V \times I\, dt = V_{CLAMP} \int_0^{t_{CONDUCT}} I\, dt = \frac{V_{CLAMP} \times I_{PEAK} \times t_{CONDUCT}}{2} = 160J$$

While this approach works in theory, the practical challenge lies in selecting a TVS diode that can handle both the peak power and the required pulse duration. As shown in Figure 7, TVS devices exhibit an inverse relationship between peak power capability and pulse duration—higher power ratings typically allow shorter pulses. For example, common devices range from 15kW down to 400W, each with different duration limits.

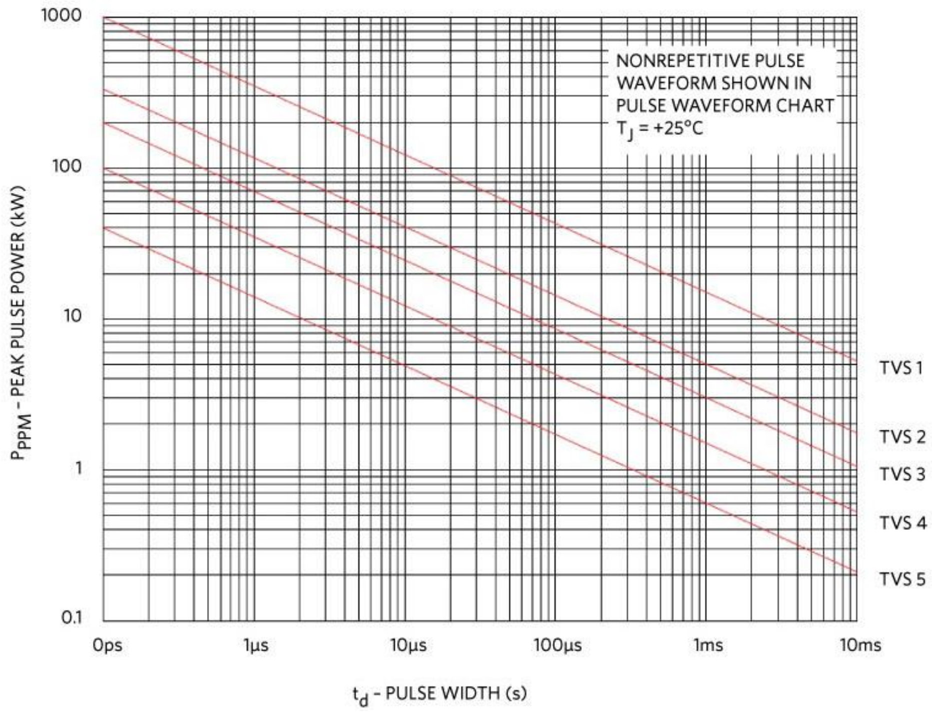

Figure 7. Peak pulse vs maximum pulse duration of a typical TVS diode

Compounding the issue, ISO 16750-2 requires systems to survive 10 consecutive pulses with one-minute intervals. Each event degrades the TVS diode, making it increasingly difficult to design a solution that relies solely on TVS protection for high-energy load dump conditions. For robust automotive designs, engineers often combine clamping with active protection circuits, such as those implemented using the AP74502Q, to achieve reliable and repeatable performance.

Approach #3. Isolate the load from the transient source using the AP74502Q and a TVS diode

A combined protection approach leverages both isolation and clamping techniques to overcome the limitations of using either method alone. Isolation with a series MOSFET and a protection IC, such as the AP74502Q, is constrained by the IC's voltage range and the MOSFET's breakdown rating. Similarly, clamping with a TVS diode is limited by its peak power dissipation capability.

By integrating both solutions, the TVS diode can be configured with a higher clamping voltage, reducing its energy absorption requirement, while the AP74502Q disconnects the downstream load from the surge source. This dual-layer design significantly improves system robustness against severe load dump conditions, as illustrated in
Figure 8.

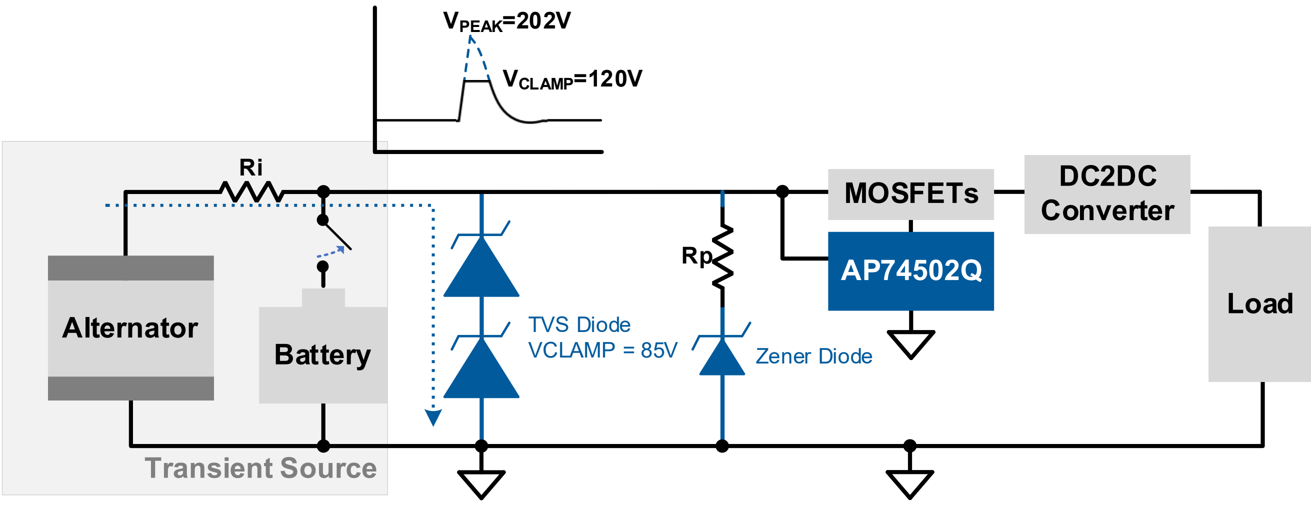

Figure 8. Load dump protection using a TVS diode and AP74502Q

We calculate the peak power of an ISO 16750-2 Test A pulse where V_{Sa} = 151V, Ri = 1Ω, t_D = 100ms, and V_{CLAMP} = 120V.

$$I_{PEAK} = \frac{V_S - V_{CLAMP}}{R_i} = \frac{150 - 120}{1} = 30A$$
$$P_{PK} = I_{PEAK} \times V_{CLAMP} = 120 \times 30 = 3.6kW$$
$$P_{PK}\ per\ TVS = \frac{3.6}{2} = 1.8kW$$

Calculating $t_{CONDUCT}$,

$$t_{CONDUCT} = \frac{V_S - V_{CLAMP}}{Slope\ of\ Pulse} = \frac{(151 - 120) \times 100ms}{151} = 19.86ms$$

Energy(E) absorbed by the TVS diode can be calculated using the following,

$$E = \int_0^{t_{CONDUCT}} V \times I\, dt = V_{CLAMP} \int_0^{t_{CONDUCT}} I\, dt = \frac{V_{CLAMP} \times I_{PEAK} \times t_{CONDUCT}}{2} = 35.74J$$

In this combined approach, the TVS diode handles the initial surge by clamping the voltage, while the AP74502Q provides isolation to protect downstream circuits. By raising the TVS clamping voltage, the diode dissipates less energy—around 1.8kW for a pulse duration of 19.86ms—making it easier to select an appropriate device. To further extend the protection range of the AP74502Q, a Zener diode with a series current-limiting resistor (RP) can be added, similar to the technique used in the isolation method.

This hybrid design offers an additional advantage: it allows the use of a lower-voltage MOSFET, reducing conduction losses during normal operation. For calculating the peak current through the Zener diode (I_{ZENER_PK}), the same formulas apply as before, assuming post-TVS conditions of V_{S_TVS} = 120V, V_{ZENER_CLAMP} = 85V, and RP = 1kΩ.

$$I_{ZENER\_PK} = \frac{V_{S\_TVS} - V_{ZENER\_CLAMP}}{R_P} = \frac{120 - 85}{1000} = 35mA$$

$$P_{PK} = I_{ZENER\_PEAK} \times V_{ZENER\_CLAMP} = 85 \times 35 = 2.975kW$$

$$PowerDissipation\ Across\ Rp = \left(V_S - V_{S\_TVS}\right) \times I_{ZENER\_PK} = (120 - 85) \times 0.035 = 1.225W$$

After determining the maximum power rating required, we selected an appropriate Zener diode and series resistor (RP) for the design. One critical consideration is the value of RP: increasing RP improves surge current limiting but also slows the system's response to detect overvoltage and undervoltage conditions. This delay occurs because RP, together with capacitor C_{VIN}, introduces a time constant in the sensing circuit, as illustrated in Figure 9.

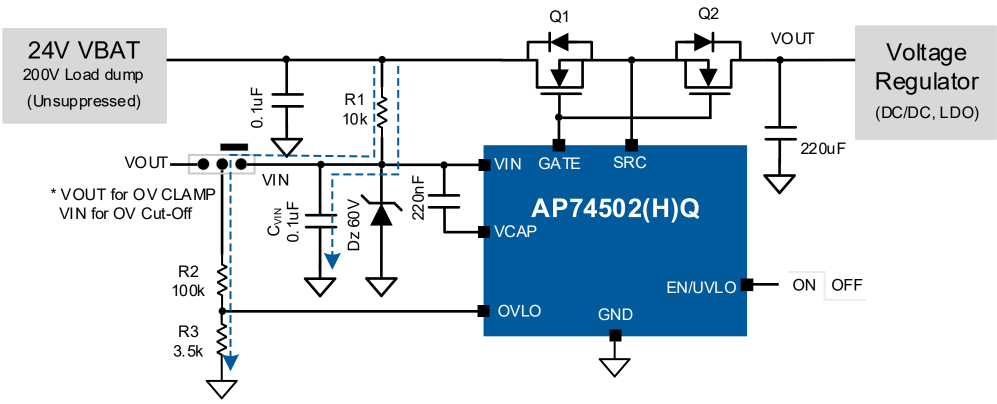

Figure 9. Time constant introduced by Rp/CVIN