

Going TVS-less in Automotive Reverse Battery Protection Designs

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Introduction

An automotive battery connects to multiple loads, including electronic control units (ECUs), relays and motors. Several system-level events, such as turning inductive loads on or off, can create voltage transients along battery supply lines. All reverse-polarity protection circuits must protect downstream electronic loads against these system level transient events.

Ideal diode reverse-battery protection typically comprises of an ideal diode controller, N-channel metal-oxide semiconductor field-effect transistor (MOSFET) and an input-side transient voltage suppression (TVS) diode to clamp transient events. This TVS diode consumes as much as 70% of the solution footprint, however, which is a challenge when designing dense ECU designs such as automotive driver assistance system (ADAS) cameras, USB hubs and display ECUs. Removing the input-side TVS saves system cost, reduces solution size and improves system reliability.

This article describes a TVS-less reverse-battery protection system design using an ideal diode controller, analyzing the system architecture for protection and electromagnetic compliance (EMC) in accordance with International Organization for Standardization (ISO) 7637-2 and 16750-2, and original equipment manufacturer (OEM) standards such as VW8000 (LV124) from German auto manufacturers.

Automotive reverse-battery protection with ideal diode controllers

An ideal diode controller driving an N-channel MOSFET is a low-loss reverse-polarity protection solution that replaces traditional solutions based on power diodes and P-channel MOSFETs. Apart from providing protection against input polarity reversal, an input protection solution should also safeguard downstream electronic circuits from various system-level transient events. Automotive standards such as ISO 7637-2, VW 80000 (LV124) and ISO 16750-2 define such system-level transient events.

A typical application circuit comprises an ideal diode controller driving an N-channel MOSFET and an input-side TVS diode used to suppress various automotive EMC transients. The main purpose of the input-side TVS diode is to protect against automotive high-energy negative transient generated from the disconnection of supply from inductive loads and described by ISO7637-2 Pulse 1 transient event. As shown in **Figure 1**, voltage transients occur when current through inductive load is interrupted. As per ISO7637-2 standard, this transient event typically lasts for 2 ms (t_d) with amplitude (U_S) ranging from -75 V to -150 V. The total duration between two consecutive pulses is 200 ms (t_2). There are other low energy, short-duration transient events defined by the ISO 7637-2 standard such as Pulse 2A, 3A, 3B caused by sudden switching and current interruption in the inductance of wiring harness. The input and output capacitors used in ideal diode protection circuit filters

these short duration transients and do not impact overall system performance.

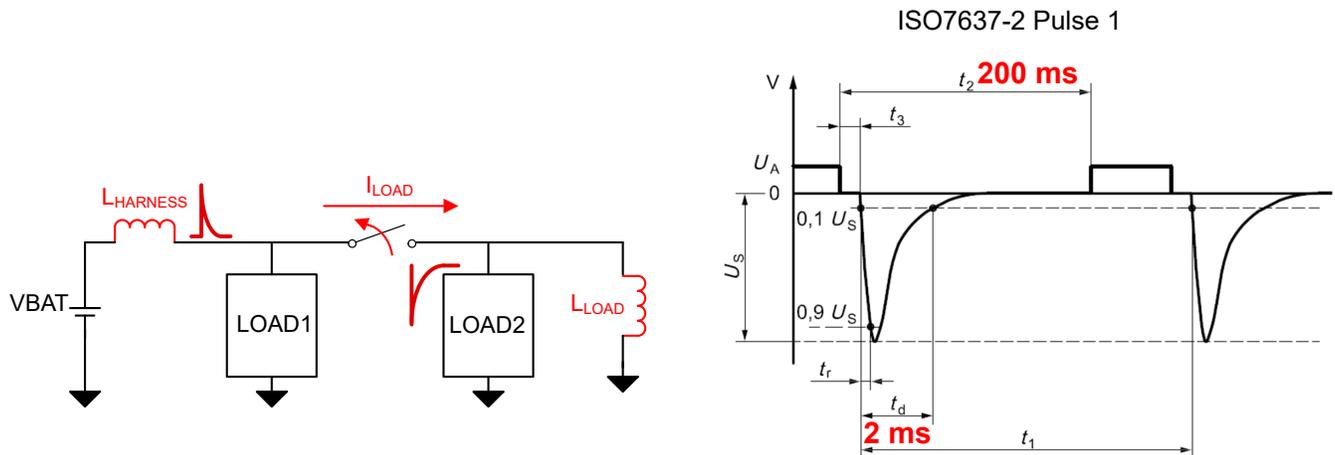
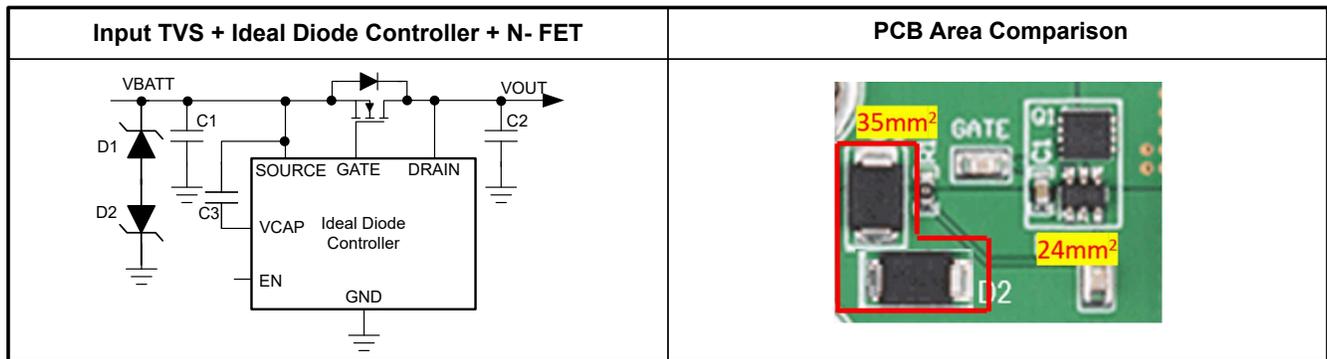


Figure 1. ISO 7637-2 Pulse 1 characteristics.

Most vehicles have a centralized load-dump clamp that, in the case of 12-V battery-powered vehicles, clamps the maximum transient voltage during a load-dump event to 35 V. But electronic circuits need protection from negative transients that occur when turning off of an inductive load. An input-side TVS diode clamps these transients within the safer limits so that electronic circuits can continue to operate without any damage.

Figure 2 shows a typical printed circuit board (PCB) for an ideal diode reverse-polarity protection solution and the contribution of the input TVS diode toward the total solution size. For space-constrained ECU designs such as ADAS cameras, Radar and LIDAR ECUs, and USB hubs, eliminating the input-side TVS diode and simultaneously ensuring robust system-level EMC performance has many advantages. Eliminating the input-side TVS diode also improves overall reliability, because there is no longer a need for a shunt component between the battery and ground line.



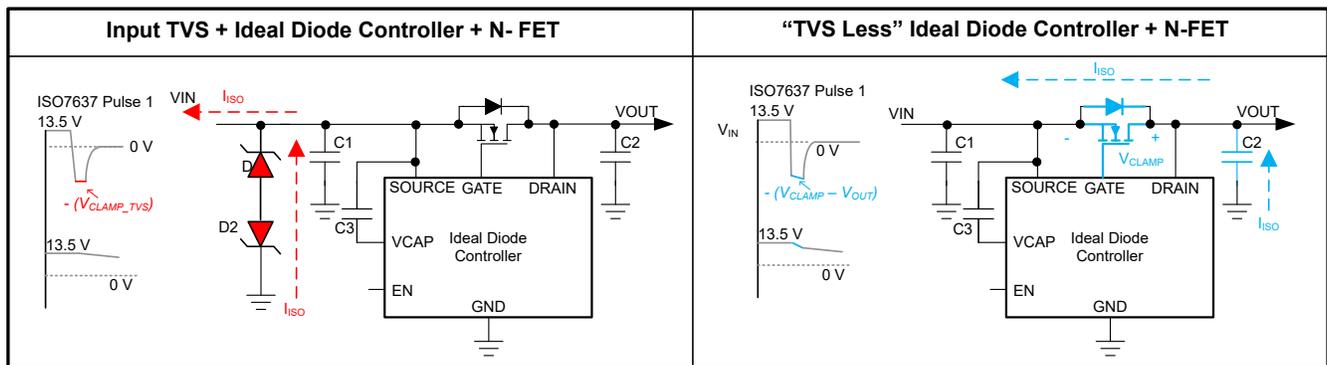
- Size, cost and efficiency over conventional power diode and P-Channel MOSFET solutions benefit at higher current levels
- Robust system level EMC performance
- 2 x Input TVS diodes required for transient voltage suppression
 - D1: Mainly to block forward current from D2 in normal operation
 - D2: Mainly to suppress negative transient ISO7637-2 Pulse 1
- Area of Ideal Diode Controller + N-Channel MOSFET: 24 mm²
- Area of 2 x input TVS diodes (D1, D2): 35 mm²
- The TVS occupies ~ 70% of total system solution of ideal Diode
- The TVS adds additional system cost and BoM count
- Removing the TVS improves the system reliability due to removal of a shunt component on the VBATT terminal

Figure 2. Typical ideal diode application circuit and PCB area comparison.

TVS-less automotive reverse-polarity protection using ideal diode controllers

TI's LM74701-Q1 and LM74721-Q1 ideal diode controller integrates a unique feature to achieve a TVS-less input reverse-polarity protection solution. The device operates an external MOSFET as an active clamp element to dissipate the energy of negative transient event described by ISO 7637-2 Pulse 1. During a ISO 7637-2 Pulse 1 transient event, where there is no output voltage holdup requirement, these devices regulate the voltage across the external FET to a pre-defined threshold by monitoring the voltage drop across the external MOSFET's drain-to-source (VDS) pins and enabling the gate drive. The reverse current flows from the output capacitor back to the input source, and transient pulse energy dissipates across the MOSFET.

Figure 3 shows the ISO 7637-2 Pulse 1 operation differences between a standard ideal diode and a TVS-less ideal diode solution.



- Input TVS diode D2 clamps ISO7637-2 Pulse 1 and dissipates pulse energy
- Peak ISO7637 pulse current flows from TVS diode as shown by red arrows
- External FET is operated as an active clamp element and dissipates ISO7637-2 Pulse 1 energy
- Reverse current flows from output capacitor, FET back to the input source
- Input is clamped at $-(V_{CLAMP} - V_{OUT})$

Figure 3. ISO 7637-2 Pulse 1 comparison between TVS and TVS-less operation.

TVS-less ideal diode: mode of operation and working principle

During VDS clamp operation, there is current conduction from the output capacitors back to the input source. This operation is acceptable during an ISO 7637-2 Pulse 1 transient event, where the output voltage holdup requirement is not mandatory given the long brownout duration of 200 ms. However, reverse-current protection is a critical feature needed in system tests, where the

supply interruptions are for short durations such as an input micro short (LV124-E10) as well as during AC superimposed testing (LV124-E06). The VDS clamp operation should not engage during these tests, ensuring reverse-current protection.

Figure 4 is a flow chart that can help you decide the VDS clamp threshold to ensure EMC performance across various test conditions.

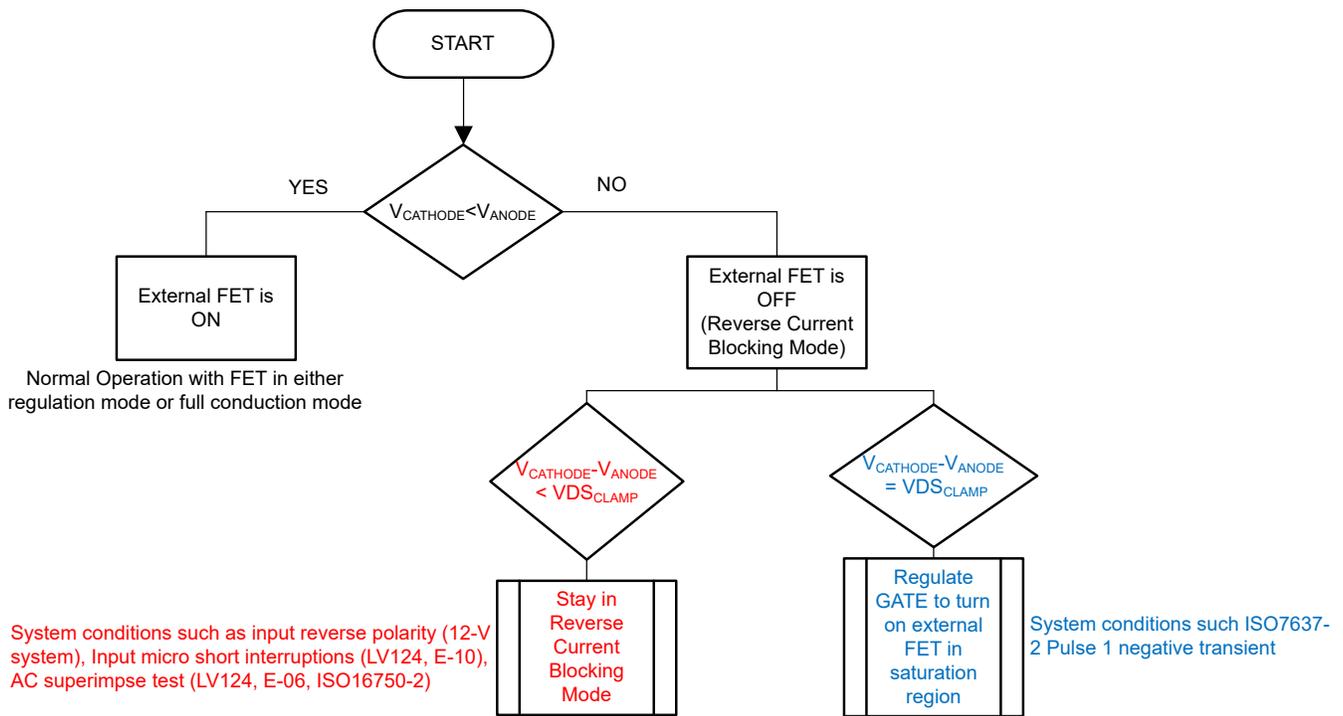


Figure 4. Algorithm for TVS-less ideal diode controller operation.

For a TVS-less ideal diode controller, when the input voltage is lower than the output voltage but has not reached the VDS clamp threshold, the ideal diode controller remains in reverse-current blocking mode and the external FET remains off, in order to ensure that the output voltage does not drop much from its nominal value. This mode of operation is preferable in system-level EMC tests with output-voltage holdup requirements such as input micro-short interruptions (LV124-E10, ISO 16750-2). When the voltage difference between the

output and input exceeds the VDS clamp threshold, such as in the case of an ISO 7637-2 Pulse 1 transient event, the ideal diode controller enables the gate drive and the external FET operates in the saturation region, acting as a current source. The output capacitor provides reverse energy back to the input source and the output voltage drops from its nominal value. Figure 5 shows the equivalent circuit of ideal diode controller TVS-less operation during an ISO 7637-2 Pulse 1 transient event.

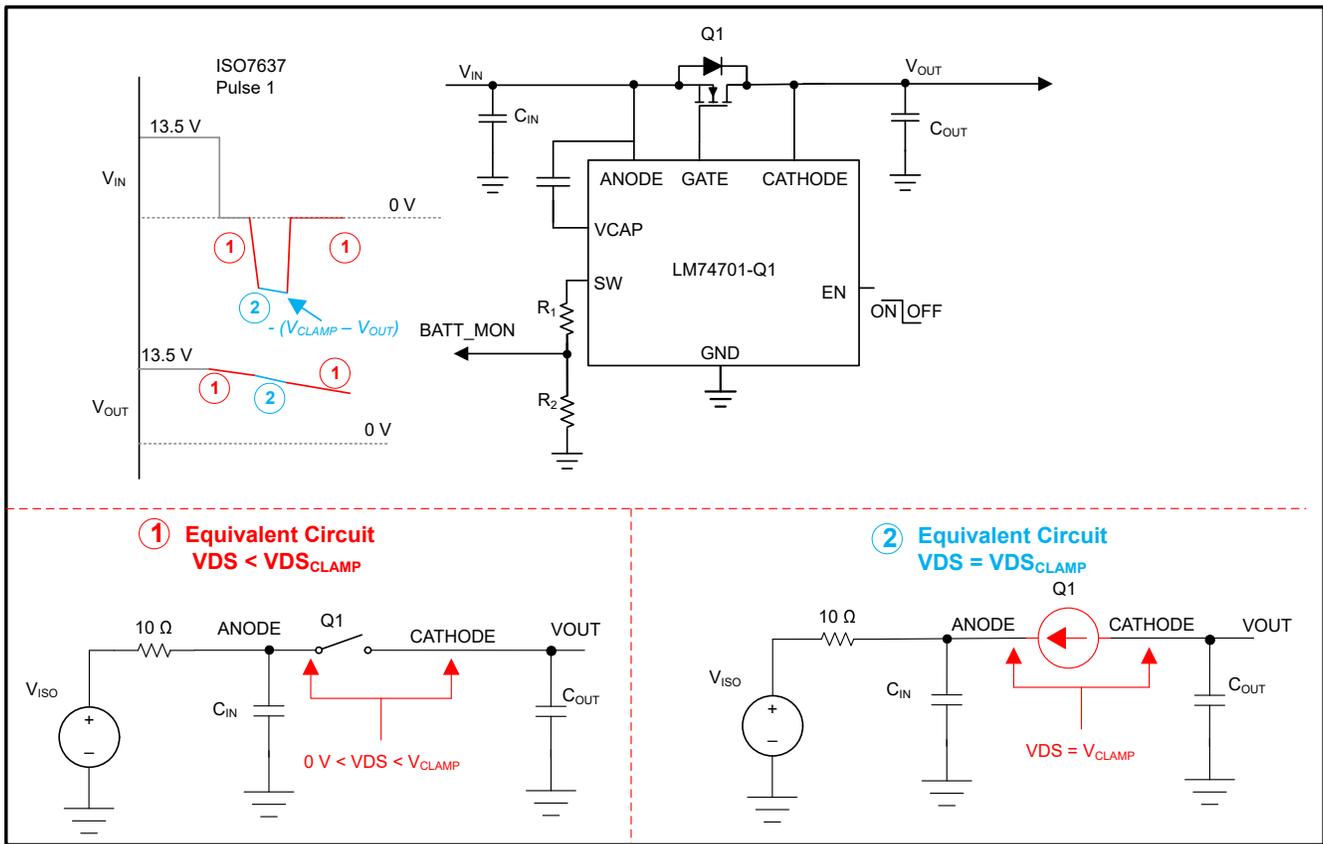


Figure 5. TVS-less ideal diode equivalent circuit during an ISO 7637-2 Pulse 1 transient event.

External MOSFET and Output Capacitor (C_{OUT})

discusses external component selection considerations.

External MOSFET

Select an external MOSFET that achieves the best trade-off between power dissipation, system-level performance (such as reverse-current blocking) and solution cost. A MOSFET that typically provides 30 mV to 50 mV of forward drop at a full load current is a good starting point.

Another important parameter is the MOSFET’s maximum VDS voltage rating. During the ISO 7637-2 Pulse 1 transient event, the maximum VDS seen by the external MOSFET Q1 is the VDS_CLAMP (max) detection threshold of an ideal diode controller. Equation 1 calculates the peak current flowing through the MOSFET during the ISO 7637-2 Pulse 1 transient event:

$$I_{ISO_PEAK} = \frac{(V_{ISO} + V_{OUT} - V_{DS_CLAMP(max)})}{R_S} \tag{1}$$

where:

V_{ISO} is the negative peak of ISO 7637-2 Pulse 1 transient event,

V_{OUT} is the initial level of the VBATT before applying the ISO 7637-2 Pulse 1,

V_{DS_CLAMP} is the maximum V_{CLAMP} threshold of the ideal diode controller and

R_S is the ISO 7637-2 pulse-generator input impedance (10 Ω).

Figure 6 shows the LM74701-Q1’s TVS-less performance during ISO 7637-2 Pulse 1 transient event, along with gate turn on behavior during VDS clamp operation, peak pulse current and power dissipation across the MOSFET.

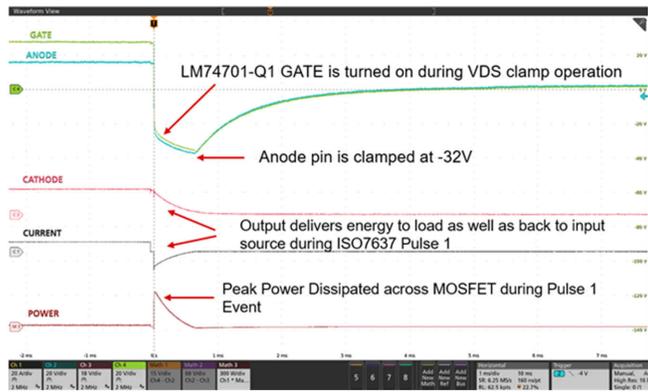


Figure 6. LM74701-Q1 ideal diode controller TVS-less performance.

The average current during an ISO 7637-2 pulse can be approximated as one-third the peak current, or $(I_{ISO_PEAK}/3)$. So **Equation 2** calculates the average power dissipated across the external MOSFET:

$$P_{D_ISO_AVG} = \frac{V_{DS_CLAMP(max)} \times I_{ISO_PEAK}}{3} \quad (2)$$

An ISO 7637-2 Pulse 1 transient event lasts for typically 2 ms, and the external MOSFET operates in active clamp mode for about 1 ms. Selecting a MOSFET with safe operating area (SoA) characteristics – with the load line corresponding to the VDS of $V_{DS_CLAMP(max)}$ and drain current (I_D) greater than $(I_{ISO_PEAK}/2)$ for 1 ms is a suitable option.

Figure 7 shows typical SoA characteristics and example selection criteria for the MOSFET.

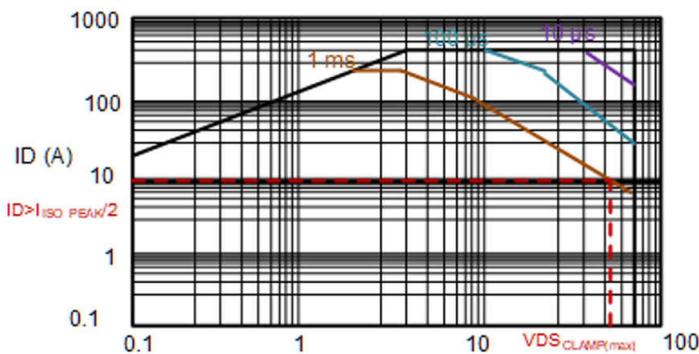


Figure 7. Example MOSFET SoA selection curve.

Output Capacitor (C_{OUT})

During an ISO7637-2 Pulse 1 event with a TVS-less ideal diode controller, current flows from the output capacitor back to the input source, discharging the output voltage. The output voltage can swing negative if the output capacitor is not large enough to hold the voltage above 0 V. An ideal diode controller such as the LM74701-Q1 is capable of handling negative voltages on the output (the cathode pin) and can work with lower-output capacitors. However, if the loads connected at the output of an ideal diode controller – such as DC/DC converters, audio amplifiers and voltage regulators – are not capable of handling a negative input voltage, then you must scale the output capacitor such that the output voltage does not go below 0 V during an ISO 7637-2 Pulse 1 transient event.

Equation 3 calculates the minimum required output capacitor during an ISO 7637-2 Pulse 1 event to ensure that the output does not swing negative:

$$C_{OUT} = \frac{(I_{LOAD} + I_{ISO_AVG}) \times 1\text{ ms}}{\Delta V_{OUT}} \quad (3)$$

where, ΔV_{OUT} is the difference between V_{OUT} at the start and end of the ISO 7637-2 Pulse 1 transient event.

TVS-less ideal diode controller EMC performance

Figure 8 illustrates the system-level performance of the LM74701-Q1 under:

- Input micro-short interruptions (LV124-E10 test) and AC superimposed frequency (LV124-E06) requiring a reverse-current blocking feature to hold up the output voltage. An ideal diode controller is not expected to engage VDS clamp operation.
- An ISO 7637-2 Pulse 1 transient event (a -100-V transient) where the ideal diode controller engages into VDS clamp operation and energy dissipates across the MOSFET to achieve TVS-less operation.
- ISO 7637-2 Pulses 2A and 2B transient events.

- ISO 16750-2 Pulse 5B suppressed load dump event (with a suppressed load dump of 35 V).
- ISO 7637-2 Pulses 3A and 3B, short-duration transient events filtered by input and output capacitors that do not affect device performance nor output voltage levels.

Certain automotive ECU designs consist of loads that are always powered on and demand overall low system quiescent current during active operation. For TVS-less input reverse-polarity protection of always-on systems, the LM74721-Q1 ideal diode controller has a typical active quiescent current of 25 μ A.

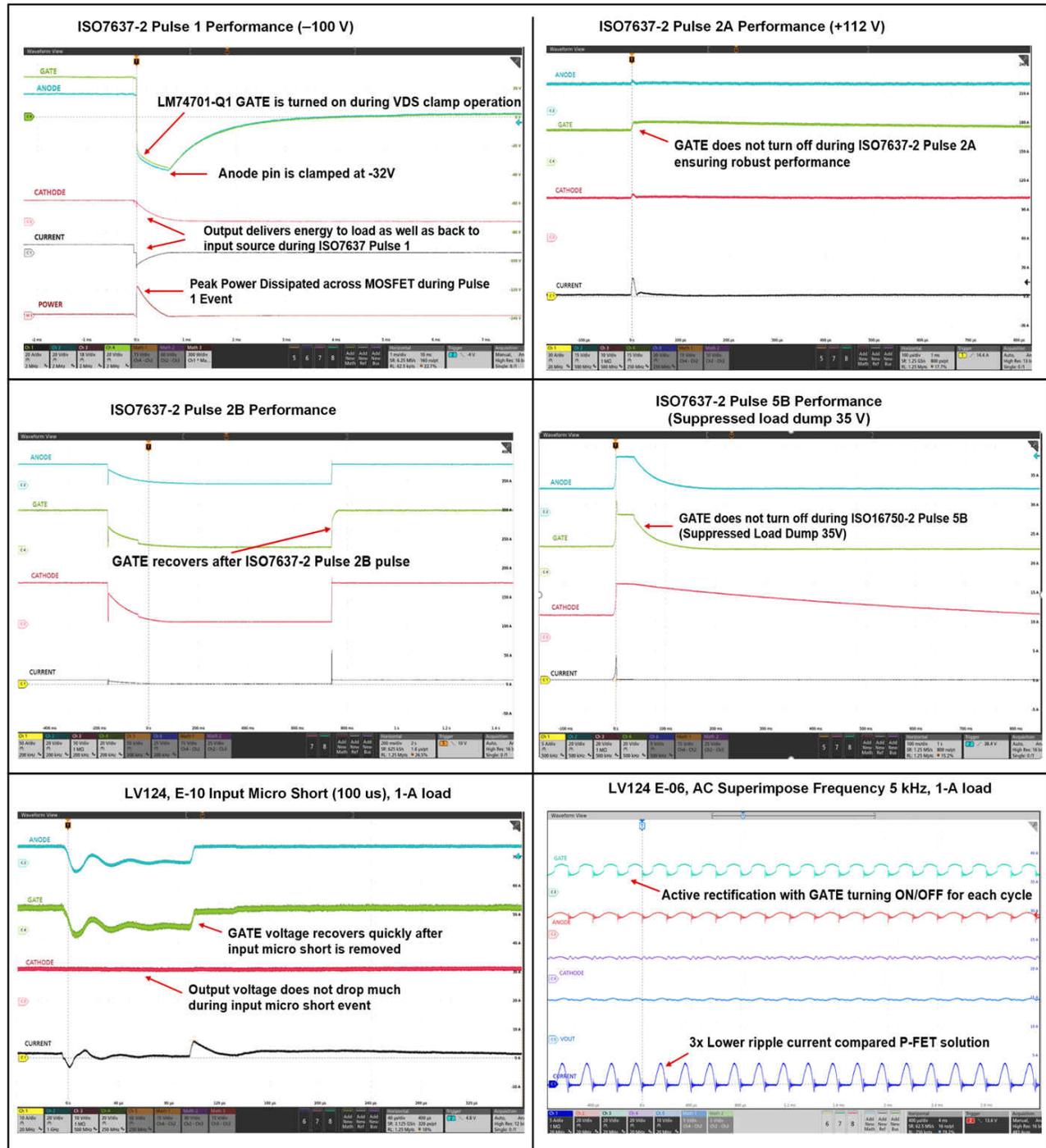


Figure 8. TVS-less ideal diode controller system-level EMC performance.

Conclusion

The rise in processing power levels and miniaturized electronic system sizes increases the demand for high efficiency and high power density designs. This poses new challenges for system designers particularly in designing automotive front-end power systems. The front-end reverse battery protection system directly impacts the reliability of overall system design. An ideal diode controller with an integrated VDS clamp enables an input-side, TVS-less automotive reverse-polarity protection solution resulting in reduced system cost, 70 percent smaller solution size and increased system reliability.

Related Websites

- [LM74701-Q1](#)
- [LM74721-Q1](#)

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