E-breaker and overvoltage protection

Introduction

Electronics functions are increasingly present in everyday life, including the industrial, appliance, consumer, and automotive segments, driven by the development of electrification and a focus on driver assistance.

Power electrical functions require safety protection against overcurrent or short circuits in the load.

Traditionally, this protection has been implemented using thermal materials, such as fuses or breakers, and mechanical relays with electromagnetic or thermomagnetic systems.

E-breakers are now constructed with power electronic switches, offering advantages such as very fast opening, prevention of arcing, accurate current turn-off values, and the ability to retest short-circuit conditions to confirm overcurrent or short-circuit events. Several power switches can be used in parallel to compensate for the limitations of switch-off capability. These switches are generally MOSFETs. In the case of parasitic or load inductance, an overvoltage is generated during turn-off, and the absolute maximum rating (AMR) of the drain-source voltage can be exceeded, potentially damaging the MOSFET.

Protection is therefore mandatory. Transient voltage suppressor (TVS) devices clamp overvoltages and ensure the MOSFETs operate safely.

Some types of loads or electronic functions with high-energy turn-off require very low clamping voltage. In such cases, other protection topologies are needed, combining TVS and silicon-controlled rectifiers (SCR) for e-breakers.

After a brief introduction to TVS and SCR, this application note discusses different solutions to protect switches, such as MOSFETs, against overvoltage during turn-off.

1 TVS basics

A TVS is a solid-state, monolithic PN junction device. TVS devices are used in sensitive semiconductors for parallel protection against electrical overstress (EOS) or electrostatic discharge (ESD) (see Figure 1). A TVS clamps any overvoltage above its breakdown voltage (V_{BR}). TVS devices can be unidirectional or bidirectional (see Figure 2).

Figure 1. **TVS in parallel protection schematic against electrical overstress (EOS) or ESD**

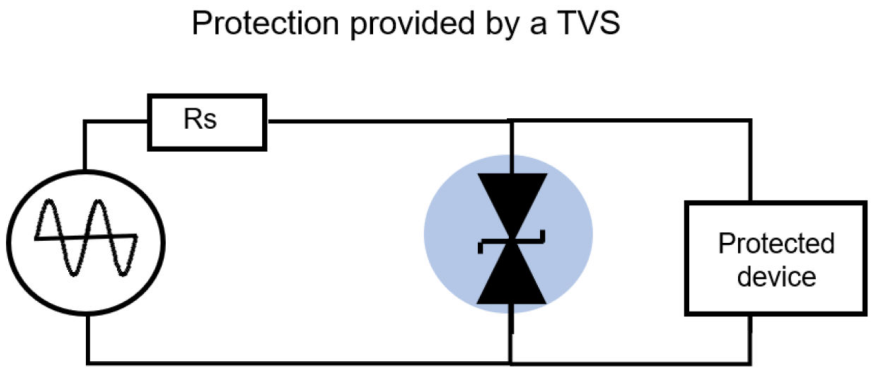
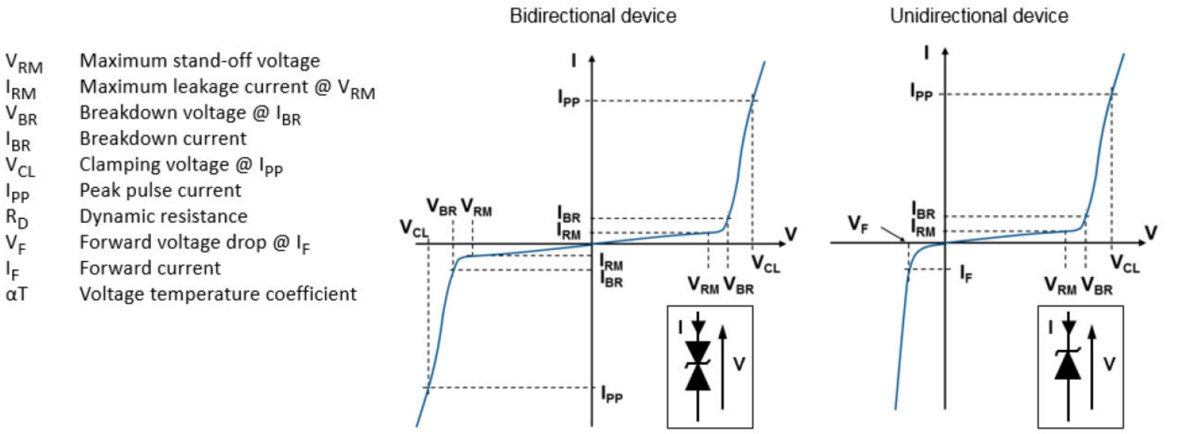
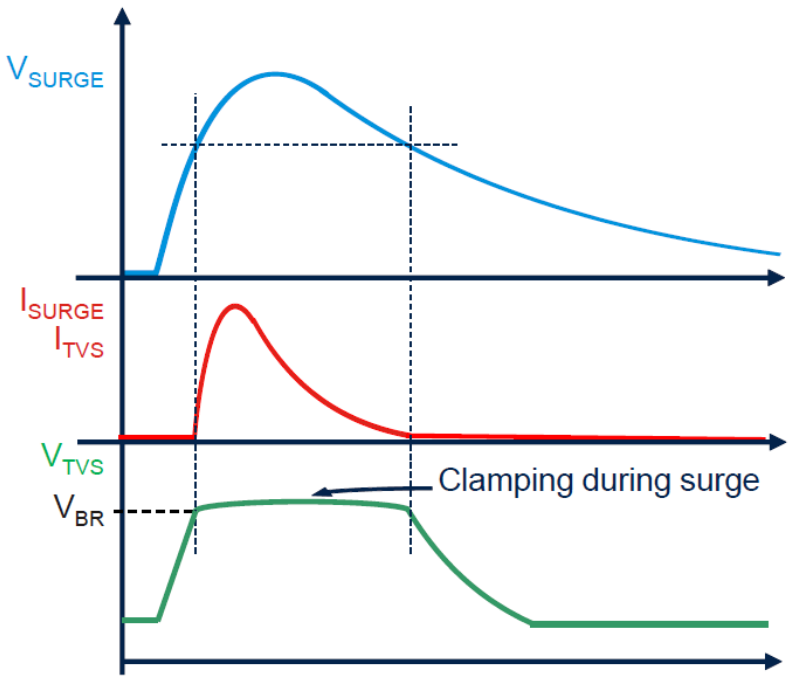


Figure 2. **Electrical characteristics–parameter definitions**



In its active state, the TVS becomes a low-impedance device. It clamps the surge voltage by absorbing the surge current, thereby limiting the surge voltage. Ideally, the TVS clamping voltage (V_{CL}) equals V_{BR}. However, in practice, the clamping voltage (V_{CL}) varies according to the surge current (see Figure 3).

Figure 3. **Electrical behavior of the TVS**



For more information, you can refer to AN316 for full details.

2 SCR basics

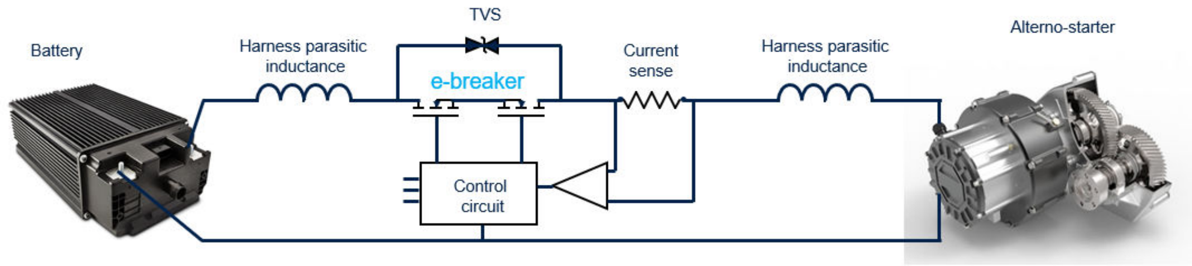
A silicon-controlled rectifier (SCR) is a type of semiconductor device used to control and switch high energy. It is a three-terminal device consisting of an anode (A), a cathode (K), and a gate (G). When no current is injected into the gate, the SCR remains in its off state, and no current flows from the anode to the cathode. If a small positive current is injected into the gate relative to the cathode, it triggers the SCR into its on state. This allows a large current to flow from the anode to the cathode with a low drop voltage (few volts). Once triggered, the SCR remains in the on state and continues to conduct current from the anode to the cathode, even if the gate current is removed. The device stays on until the current flowing through it drops below a given threshold (holding current). To turn off the SCR, the current flowing through it must be reduced below the holding current. This is typically achieved by reducing the load current using a commutation circuit or by inverting the current or voltage.

SCRs are commonly used in applications such as motor control, light dimming, and power regulation because they efficiently handle high voltages and currents.

3 E-breaker with TVS:

E-breaker is a series protection against overcurrent.

Figure 4. **Bidirectional e-breaker schematic example**

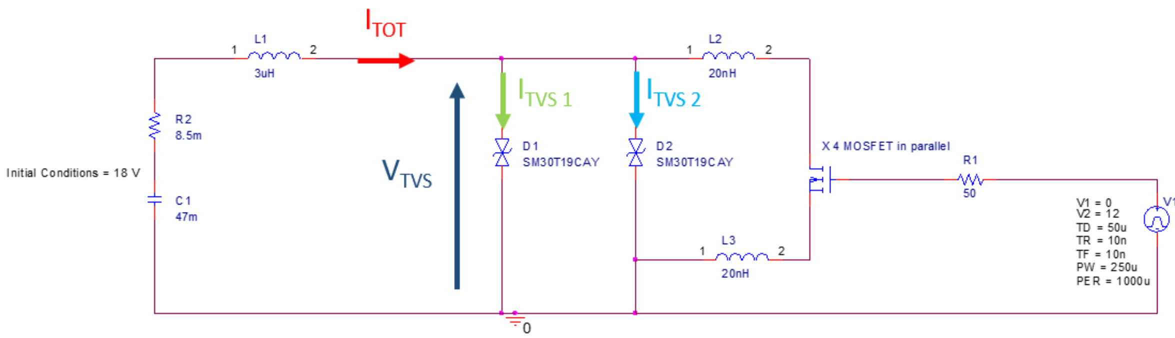


The e-breaker turns off in the event of a short circuit or overcurrent through the load. It also turns off if overcurrent is detected during the battery-charging operation. In this case, the e-breaker is bidirectional and must be protected against overvoltage in each current direction.

3.1 E-breaker protected by TVS between drain and source

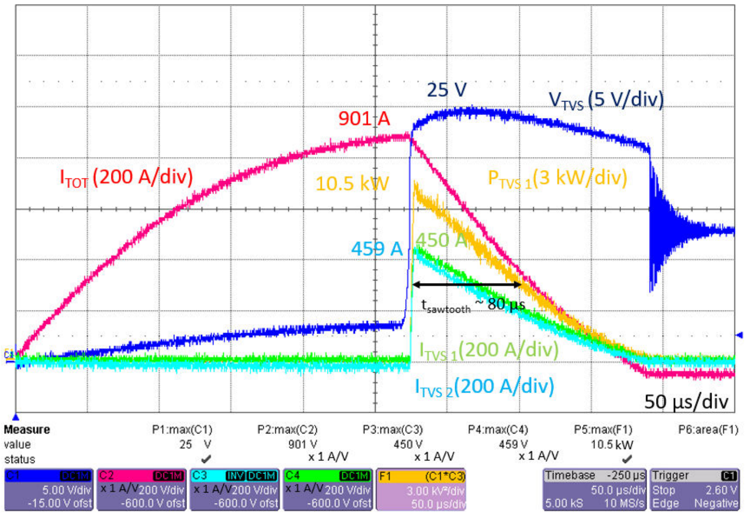
To simulate the e-breaker function, four MOSFETs in parallel are turned on for a few hundred microseconds to reach a high-level current, around 900 A. Then, these MOSFETs are turned off. Energy stored in inductance emulates the harness length (3 µH corresponds approximately to 3 meters), and creates an overvoltage clamped by two SM30T19CAY in parallel (see Figure 5).

Figure 5. **Schematic to emulate the e-breaker function**



Waveforms indicate that the TVS clamps overvoltage at V_{CL} = 25 V (see Figure 6).

Figure 6. Waveforms for e-breaker function with the clamping voltage blue waveform

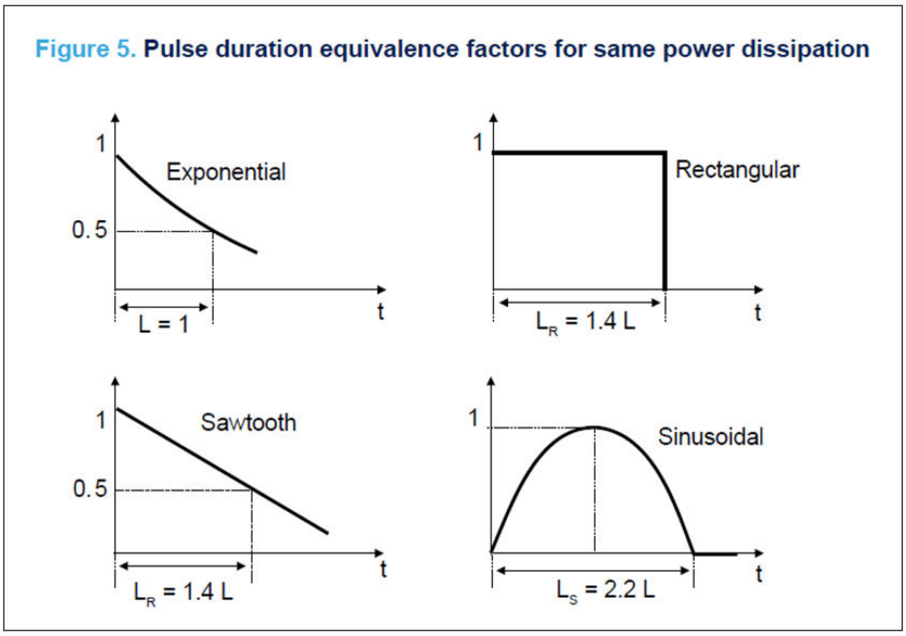


In the automotive segment with a 12 V battery system, the maximum voltage typically allowed by the switches of the e-breaker (MOSFET) is 40 V. In this configuration, a 25 V peak clamping voltage ensures correct operation in the event of a 900 A peak current turn-off with 3 µH parasitic inductance.

In addition to the clamping voltage, the transient voltage suppressor (TVS) power capability must be evaluated. The correct operation can be verified by using the sawtooth duration (inductance current discharge produces a sawtooth current waveform) on the power-measured orange waveform, calculated by multiplying the current and voltage waveforms. The peak power is approximately 10.5 kW, and the sawtooth duration ($t_{sawtooth}$) is 80 µs, measured at half of the peak power, as shown in Figure 6.

The sawtooth current waveform can then be transformed into an exponential waveform, as illustrated in Figure 7(figure 5 of application note AN316).

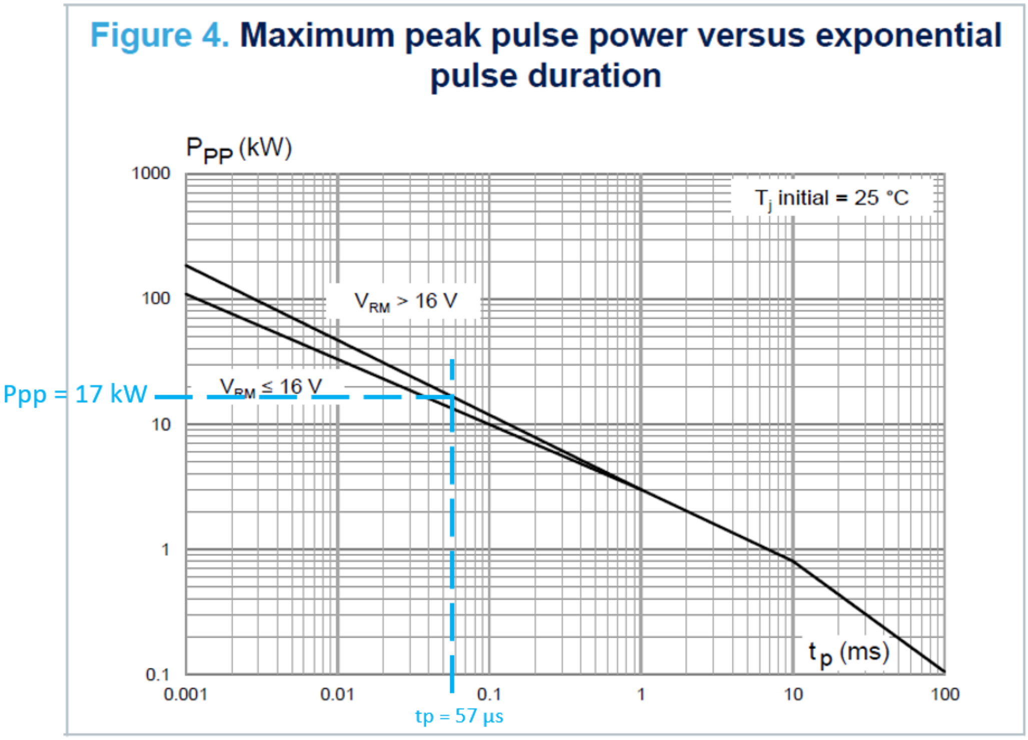
Figure 7. Pulse duration equivalence factors for same power dissipation



$$t_{pExponentiel} = \frac{t_{Sawtooth}}{1.4} = \frac{80\ \mu s}{1.4} = 57\ \mu s$$

The t_p exponential is calculated as 57 µs, and the peak power is measured as 10.5 kW. We can confirm that the SM30T19CAY is suitable because the maximum peak power allowed by the SM30T19CAY is 17 kW for t_p = 57 µs (from Figure 8 of SM30TY datasheet), which is higher than 10.5 kW.

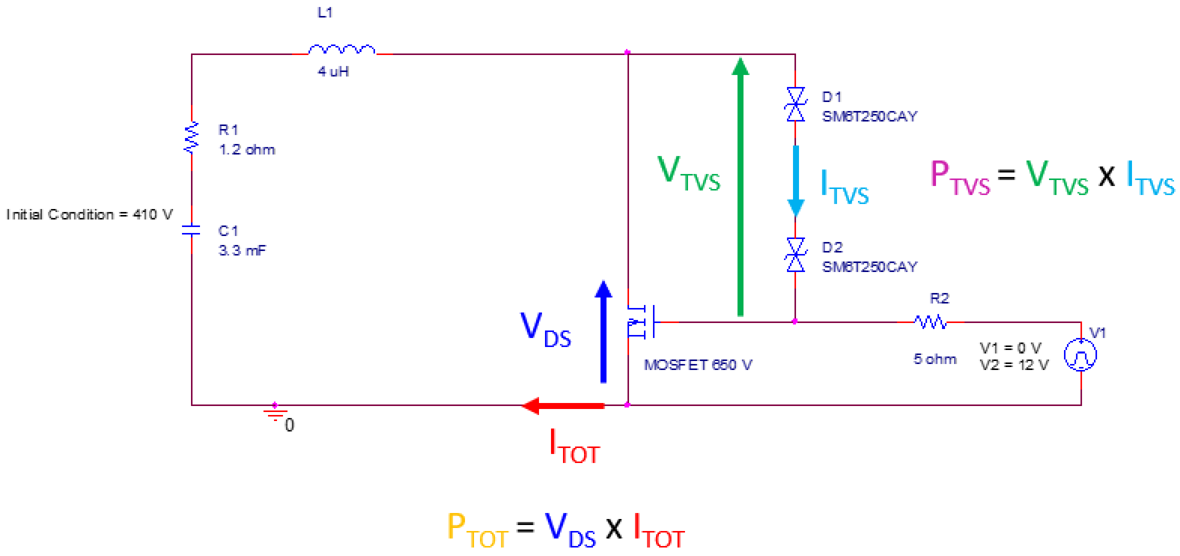
Figure 8. Maximum peak SM30TY pulse power versus exponential pulse duration (result for t_p = 57 µs)



3.2 E-breaker protected by TVS between Drain and Gate called active clamp protection

The previous example demonstrates that both transient voltage suppressors (TVSs) in the schematic are suitable for the specified conditions, such as peak current to turn off and parasitic inductance. If the peak power to dissipate is too high, particularly for high-voltage applications (400 V or higher), one solution is to add another TVS in parallel. Another solution is to use active clamp protection, as shown in Figure 9 below:

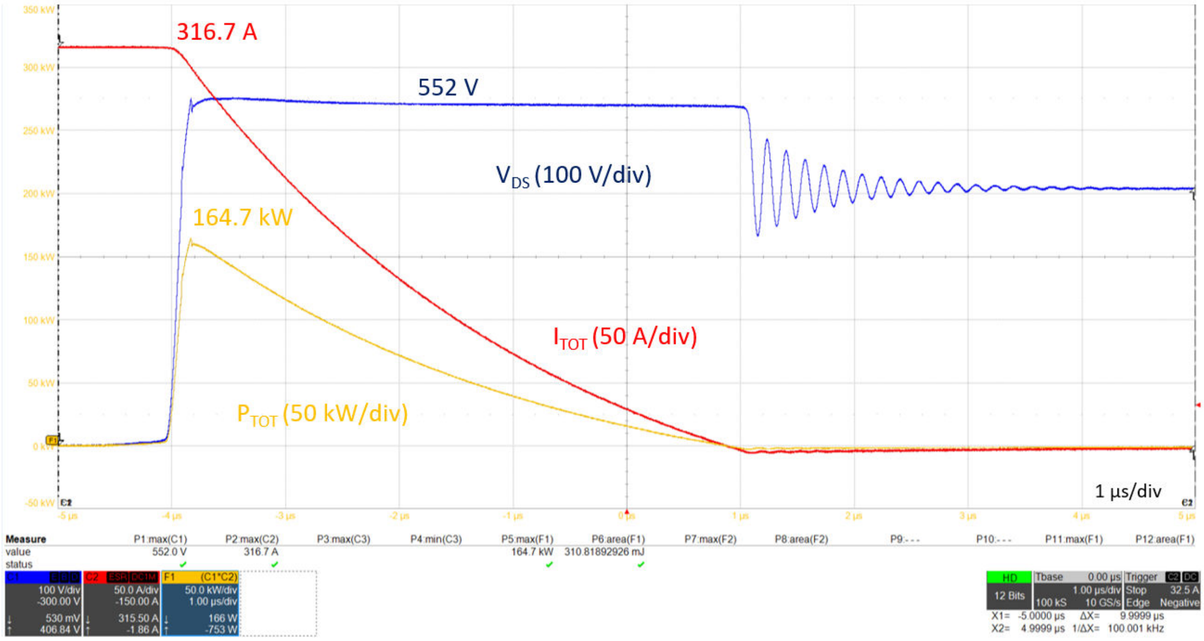
Figure 9. Active clamp protection schematic example



The 650 V MOSFET is used as an electronic breaker:

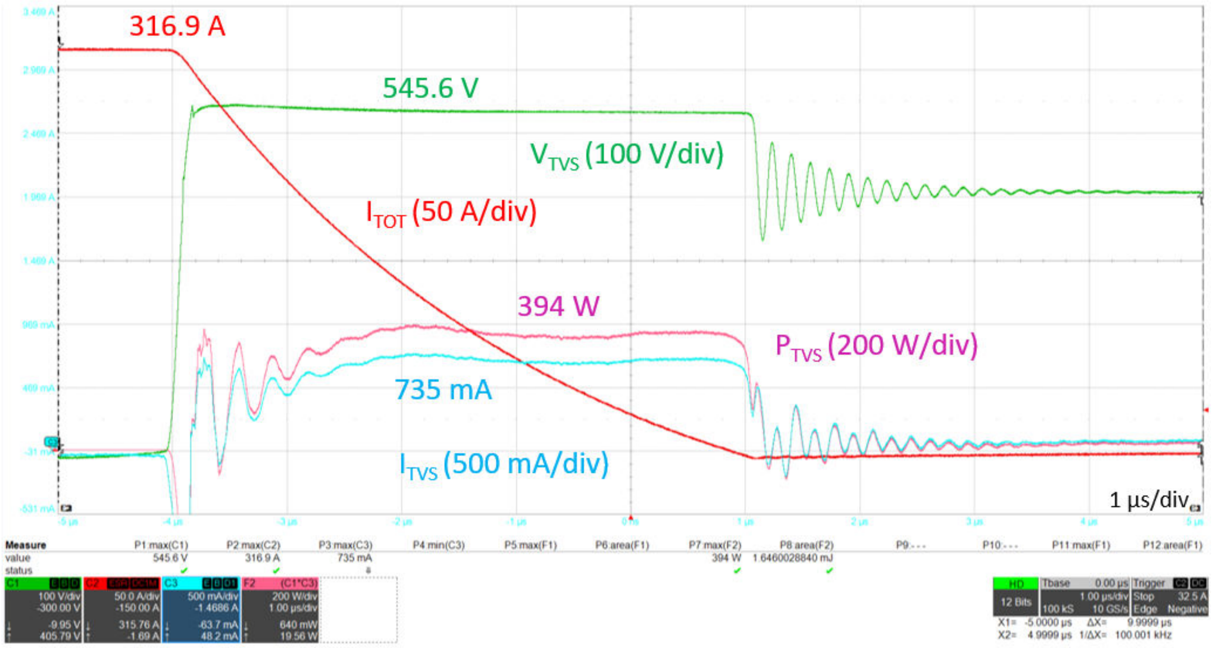
- During normal operation, the MOSFET is turned on (V1 = 12 V), and the electronic function operates correctly
- In the event of a short circuit or overcurrent detection through the load, the MOSFET turns off (V1 = 0 V), and an overvoltage appears due to the parasitic inductance (approximately 4 μH) across the MOSFET
- When the drain-source voltage exceeds the total breakdown voltage (V_{BR}) of the transient voltage suppressors (TVSs) (as shown in Figure 9 with two SM6T250CAY devices in series), the TVS conducts, and the gate-source voltage increases
- When the gate threshold voltage is sufficiently high, the MOSFET operates in linear mode, limiting the overvoltage
- Once the energy stored in the inductance is dissipated, the current through the TVS disappears, and the MOSFET turns off completely
- The advantage of this topology is that the MOSFET dissipates the energy stored in the inductor, while the power on the TVS remains low.

Figure 10. Active clamp protection waveforms (MOSFET)



Note: Drain-source voltage across a MOSFET: blue waveform, current through MOSFET and TVS: red waveform and power through MOSFET and TVS: orange waveform.

Figure 11. Active clamp protection waveforms (TVS)



Note: Voltage across both TVS: green waveform, current through TVS: light blue waveform and power through TVS: pink waveform

The maximum voltage (blue waveform in Figure 10) is clamped to approximately 550 V, which is 100 V lower than the maximum voltage allowed by the MOSFET (650 V). The red waveform illustrates the decrease in overcurrent after detection, primarily measured by the shunt, for example, through the MOSFET. Peak power compatibility must be verified for the MOSFET (safe area with the orange waveform and energy measurement) and also for the TVS. The power waveform (pink waveform, Figure 11) must be transformed into an exponential waveform (as previously shown, with the approximate pink waveform equivalent to a rectangular waveform). For the TVS, the peak power dissipated through each TVS can be estimated. The SM6T250CAY is rated for 600 W during a 1000 µs exponential waveform. From the pink waveform, the peak power for both TVSs is 394 W, which corresponds to approximately 200 W for each SM6T250CAY. This peak power is smaller than 600 W, and the duration is only a few microseconds, much shorter than 1000 µs. Therefore, the SM6T250CAY can withstand the power dissipated during the active clamping protection.

With a solution based on transient voltage suppressors (TVS) between the drain and source, the power capability of each SM6T250CAY device is evaluated as follows:

- In this configuration, during the overvoltage caused by the turn-off of the MOSFET, the entire current is bypassed by both SM6T250CAY devices in series. The total peak power is approximately 300 A × 550 V = 165 kW, and the total duration of the equivalent exponential waveform (red) is approximately 5 µs, as shown in Figure 10.
- For one SM6T250CAY device, the peak power is half of 165 kW, and the exponential pulse duration (tp) is approximately 1.8 µs at half of the peak current.
- After reviewing the *Peak pulse power versus exponential pulse duration* curve in the SM6T250CAY datasheet, for tp = 1.8 µs, the maximum peak power capability is approximately 15 kW, which is significantly lower than 165 kW / 2 = 82.5 kW.
- Therefore, with the drain and source protection topology and the conditions studied in this example, a minimum of 12 SM6T250CAY devices (as number must be even) are required to withstand the dissipated power. This is in comparison to the active clamp protection topology, which requires only 2 SM6T250CAY devices.

3.3 E-breaker protected by enhanced active clamp protection (ST patent)

Even with active clamp protection, in cases of significant energy dissipation (high voltage, high current variation, and high parasitic inductance), the power dissipated through the TVS might be excessive. By using the ST-patented schematic shown below, the TVS becomes suitable with reduced power dissipation.

Figure 12. Active clamp protection waveforms with NPN schematic patented

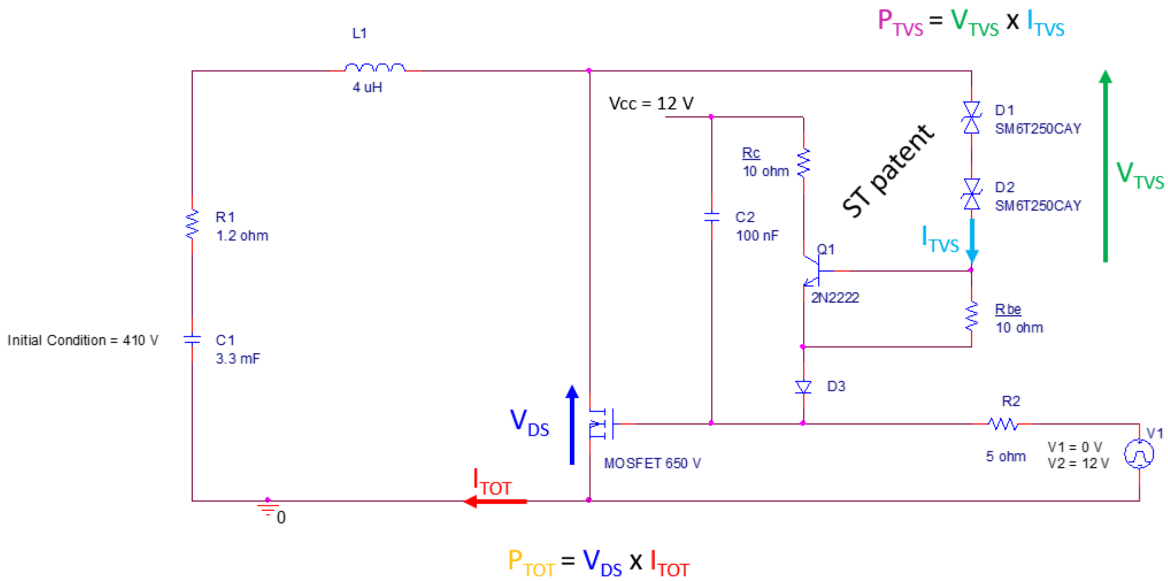
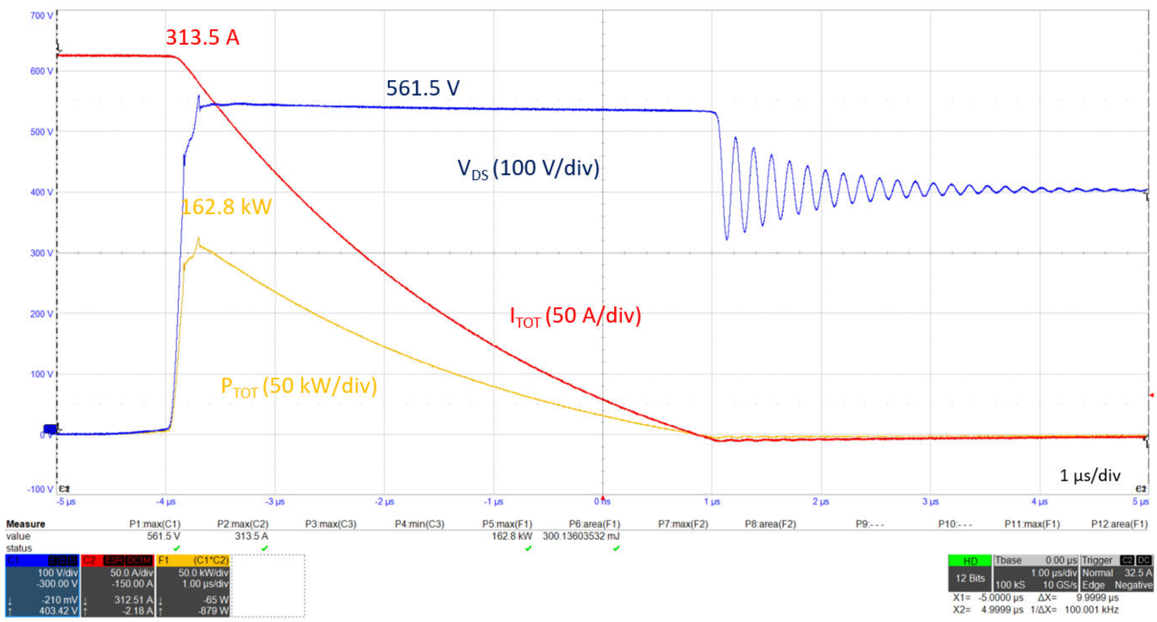
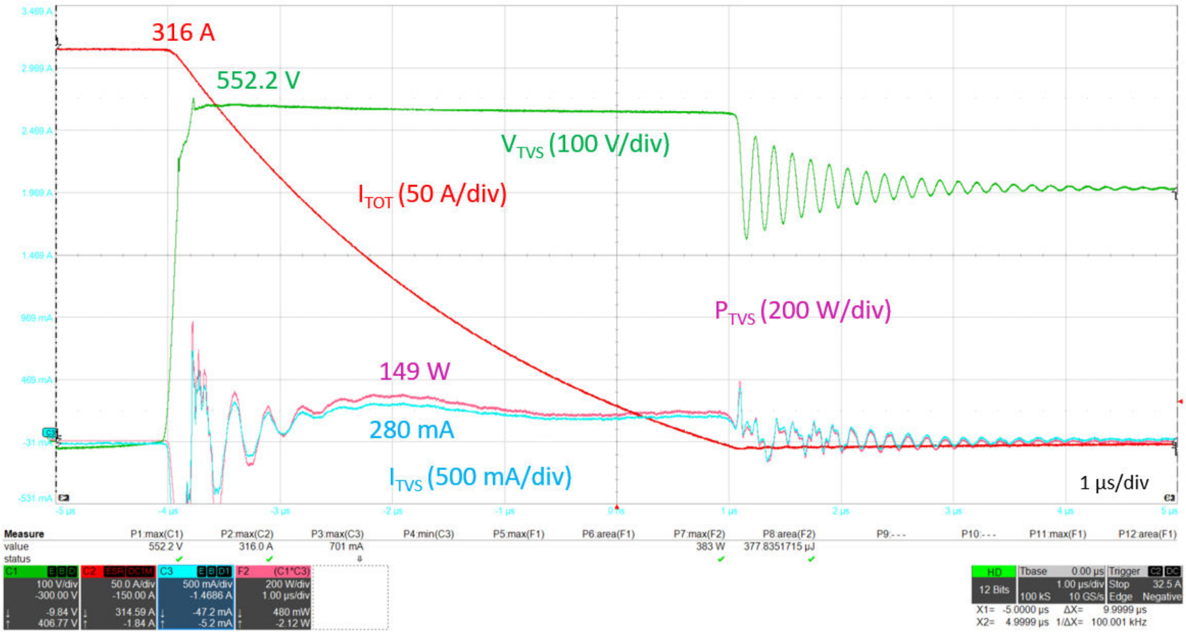


Figure 13. Active clamp protection waveforms with NPN patented schematic



Note: Drain-source voltage across a MOSFET: blue waveform, total current (mainly MOSFET): red waveform and total power (mainly MOSFET): orange waveform.

Figure 14. **Active clamp protection waveforms with NPN patented schematic**



Note: Voltage across both TVS: green waveform, current through TVS: light blue waveform and power through TVS: pink waveform.

The TVS dissipated power decreases by a factor of 2.5 with this schematic. The current required to balance the MOSFET during overvoltage originates from the supply. Only a portion of the current flows through the TVSs in series, which limits the power dissipated through them. The TVS power capability might also decrease.

3.4 E-breaker protected with SCR free-wheeling (ST patent)

Several cumulative constraints necessitate innovative solutions. In cases of high-current turn-off with very high parasitic inductance (up to 15 µH, as the maximum harness length is 15 m per automotive regulations) and specific loads (for example, a battery), traditional protection solutions are not feasible:

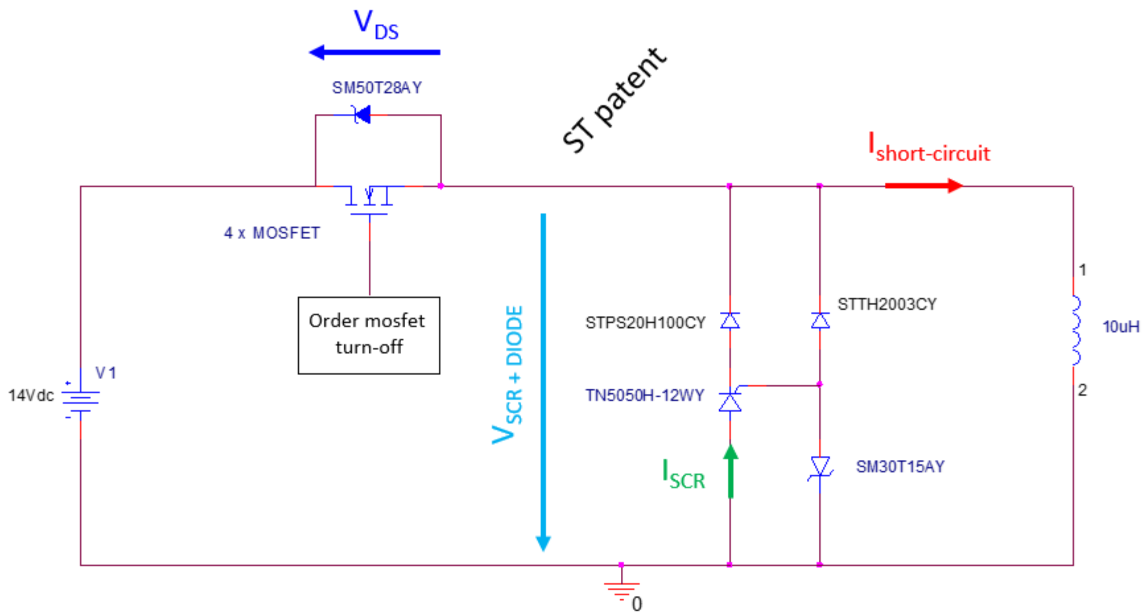
- Rectifier free-wheeling is not viable due to the risk of external reverse load (for example, a battery) connection
- Active clamp protection is unsuitable because of the energy that must be dissipated through the MOSFET
- The number of TVS diodes required in parallel with the switch is excessive.

ST has developed an SCR free-wheeling solution compatible with these conditions.

The SCR can function as an equivalent free-wheeling rectifier, triggered by a TVS with a breakdown voltage (V_{BR}) higher than 15 V (to ensure compatibility with a reverse load, such as a 12 V battery), as shown in Figure 15 below. In cases of significant di/dt during current turn-off, which generates overvoltage due to the inductor, the 15 V SM30T15AY TVS triggers the SCR to turn on and dissipate the energy stored in the inductor. The voltage across the latched SCR is low enough to protect the e-breaker (typically composed of several MOSFETs in parallel) as it turns off the current.

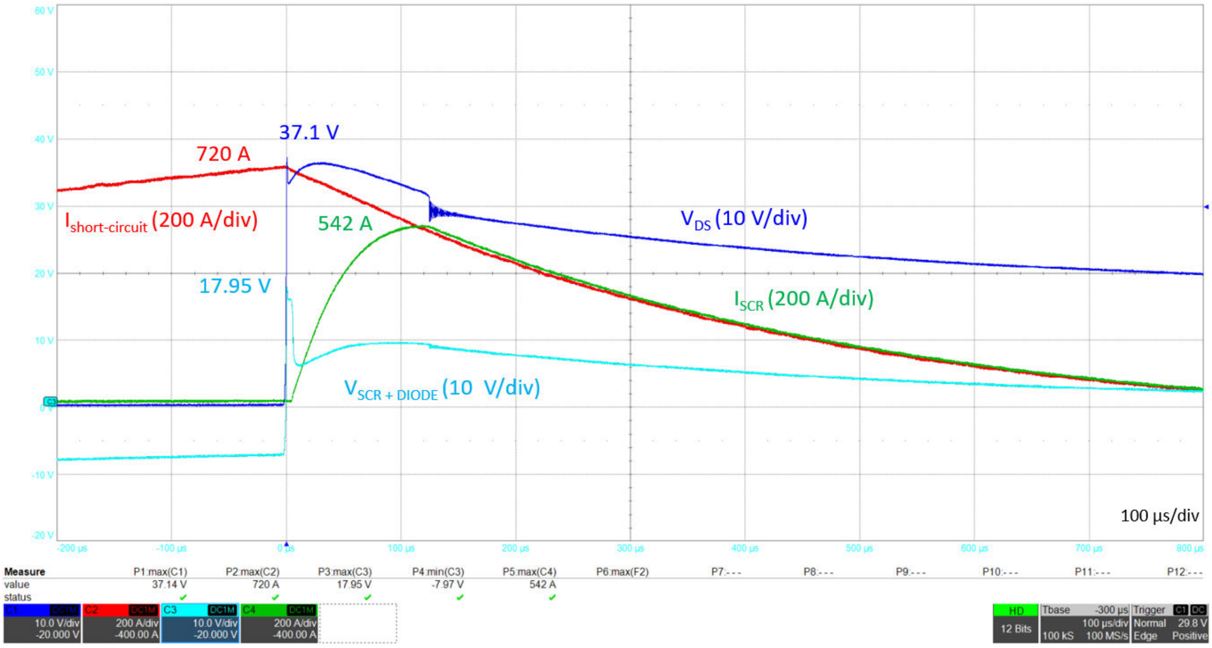
Additionally, a TVS can be placed between the MOSFET drain and source to mitigate parasitic spikes (caused by inductive bondings, pins, and tracks) and ensure that V_{DS} remains below the absolute maximum rating (AMR).

Figure 15. Free-wheeling SCR with SM50T28AY drain-source e-breaker MOSFET protection circuit



The Figure 16 below shows waveforms of this protection topology.

Figure 16. Free-wheeling SCR with SM50T28AY drain-source e-breaker MOSFET protection waveforms



The load current (red waveform Figure 16) is measured. In the case of a short circuit or overcurrent, as shown in Figure 15, the e-breaker with four MOSFETs in parallel is turned off. Due to the parasitic harness, 10 µH in this example, an overvoltage is applied across the e-breaker. The SCR turn-on current (green waveform) is not instantaneous, and the overcurrent is split between the TVS SM50T28AY and the SCR. The maximum overvoltage across the MOSFETs is limited to 37.1 V, which is lower than the maximum voltage authorized across the MOSFET (40 V AMR).

As explained previously, the TVS power capability must be checked, as well as the current capability through the SCR. Approximately, the current duration through the TN5050H-12WY is around 800 µs. The "Nonrepetitive surge peak on-state current for a sinusoidal pulse (tp < 10 ms)" curve in the TN5050H-12WY datasheet indicates that for this duration, the maximum current capability is equal to 1000 A, which is higher than the maximum current measured.

4 Conclusion

Power electronics integrate increasing functions and require protection to limit failures and ensure user safety.

ST transient voltage suppressors (TVS) efficiently protect MOSFETs and act as true companion chips for ST MOSFETs. In applications where the turn-off energy is very high, new protection solutions are available for customers. This application note provides examples of innovative solutions.

With the expertise and measurement capabilities of the ST application laboratory, the number of components can be reduced, as well as the printed circuit board (PCB) area required to protect e-breakers in cases of overvoltage.

Revision history

Table 1. **Document revision history**

Date	Revision	Changes
04-Aug-2025	1	Initial release.

Contents

List of figures