AN6379

Application note

Correlation between rectangular and triangular power pulses in the thermal and electrical behavior of power MOSFETs

Introduction

This application note presents a comprehensive analysis of the thermal and electrical behavior of power MOSFETs subjected to rectangular and triangular power pulses, representative of typical industrial and automotive applications. The study focuses on the Safe Operating Area (SOA) and thermal instability phenomena, highlighting the significant impact of pulse shape on thermal stress and device robustness. Through experimental measurements and SIMetrix simulations, the work outlines the differences in power dissipation profiles, peak junction temperatures, and failure current thresholds between the two types of pulses. The practical implications are discussed with reference to two main application systems like airbags, where rectangular pulses are mainly used, and hot-swap circuits, typically characterized by triangular pulses.

The note aims to provide a clear understanding of the SOA and the various stresses encountered in different applications. Bench tests and simulations help correlate datasheet parameters with actual operating conditions, supporting accurate device selection, thermal management, and optimized MOSFET sizing.

Power MOSFETs are widely used in modern electronics for switching applications thanks to their high efficiency, fast switching speed and ease of control. To meet these targets, the latest MOSFET technologies are based on trench structure and are characterized by extremely low $R_{DS(on)}$, high cell density, die shrinking and hence very low FOMs. These features guarantee outstanding performance in high power and high frequency switching converters increasing the overall efficiency.

However, die shrinking reduces power capability, which can be critical during linear mode operation, where high-power dissipation occurs due to the overlap of drain current (I_D) and drain-source voltage (V_{DS}). Insufficient ruggedness may lead to thermal runaway and device failure.

Many applications operate MOSFETs in linear mode, from fan controllers to hot-swap devices, in both automotive and industrial segments. During switching transients, the device also operates shortly in linear mode, with power dissipation increasing proportionally to transient duration. Therefore, a wide SOA is essential to ensure MOSFET robustness and reliable operation under high-power dissipation conditions.

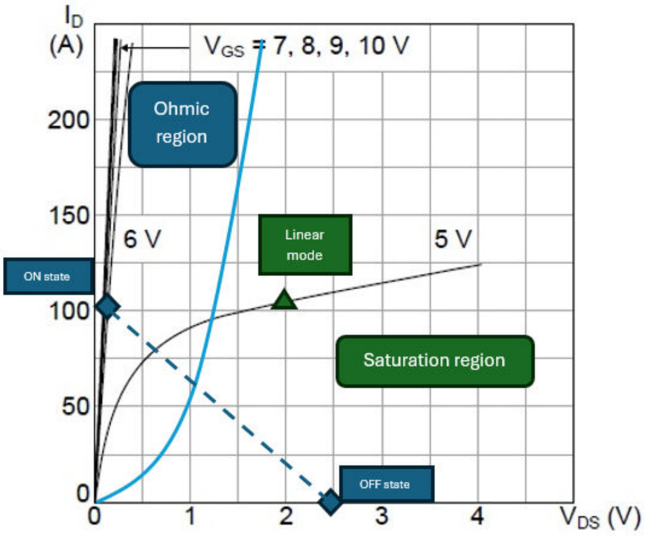
1 Power MOSFET operating modes

When a Power MOSFET device is conducting current (ON state), it can work in two different operating modes:

- Ohmic (or $R_{DS(on)}$) region: the device works as voltage-controlled resistor and there is a linear relationship between drain current (I_D) and drain-source voltage drop (V_{DS}) $\left(I_D = \frac{V_{DS}}{R_{DS(on)}}\right)$. In this condition, the gate-source voltage is at a high level (>7 V) while the drain-source voltage drop is extremely low (V_{DSon}).
- Saturation (or linear) region: the drain current is controlled only by the gate-source voltage (V_{GS}) and is independent on drain-source voltage (V_{DS}). So, the device acts as a gate-controlled current generator $\left(I_D = k \cdot (V_{GS} - V_T)^2\right)$. Linear mode operation is characterized by relatively low V_{GS} level ($3\ V < V_{GS} < 5\ V$) while the drain source voltage is typically high.

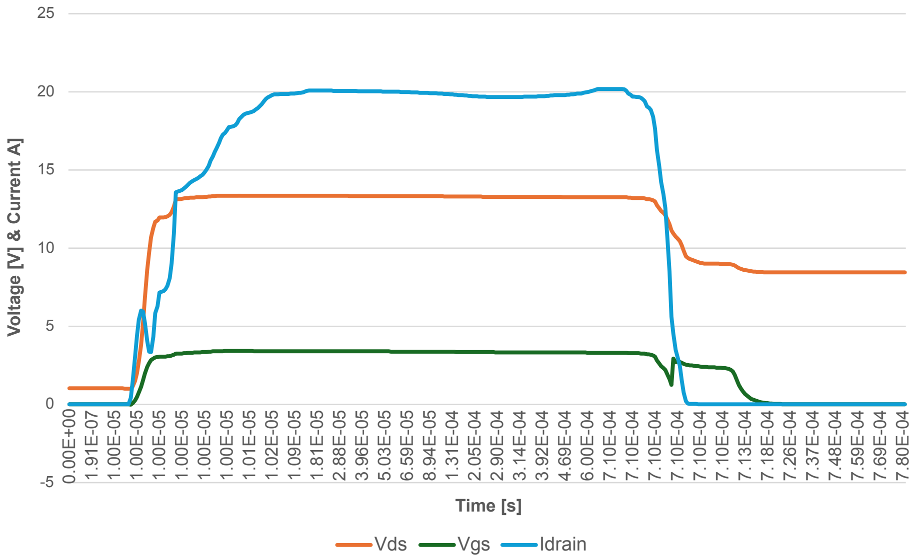
Output transfer curves show drain current (I_D)-drain-source voltage (V_{DS}) relationship at different gate-source voltage (V_{GS}) levels (see the following figure).

Figure 1. Example of MOSFET output characteristics



Ohmic region is characterized by very low V_{DS} level and high drain currents ($V_{DS} << V_{GS} - V_{GS(th)}$) while overlap of drain current (I_D) and drain-source voltage (V_{DS}) is present during saturation (linear) mode. In Figure 1. Example of MOSFET output characteristics, are shown blue rhombus (switching mode operating point) and green triangle (linear mode operating point). In switching mode, the device moves from OFF-state (I_D=0, V_{GS}<<$V_{GS(th)}$) to ON-state (V_{GS}>>$V_{GS(th)}$, high I_D); during this transition, it passes into linear mode. If the switching time is relatively fast (that is, low external gate resistance), the device does not dissipate high power and it is able to manage the linear mode operation. Vice versa, if the transition is longer or if the application requires it, the device works in linear mode for extended pulse durations, and it must be rugged and able to withstand the power pulse (see Figure 2. Typical waveforms for linear mode operation). In linear mode, the devices must work inside the SOA (safe operating area) for a fixed pulse and case temperature; moreover, good thermal management and low total thermal resistance are needed.

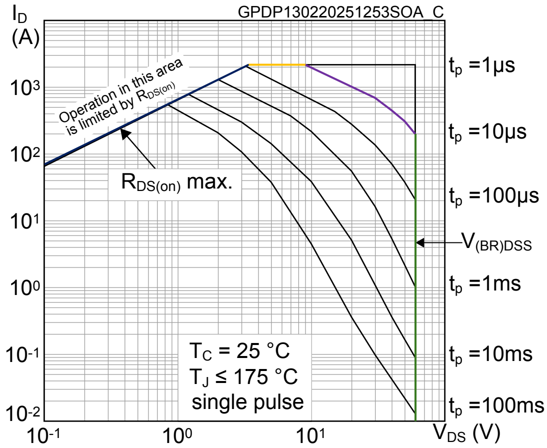
Figure 2. **Typical waveforms for linear mode operation**



2 Safe operating area of a MOSFET device and thermal instability description

For a Power MOSFET device, a safe operating area (SOA) is a two-dimension chart that defines the voltage and current levels that the device can sustain without failing (see the following figure).

Figure 3. Safe operating area for a 60 V Power MOSFET device



X-axis reports drain-source voltage values, while in the y-axis the drain current levels are shown. SOA is defined for a fixed single power pulse (t_p) and case temperature (T_c = 25 °C). The single pulse ($V_{DS} \cdot I_D$) applied to the device has a rectangular shape; a different pulse shape (that is, triangular) or higher temperature needs SOA derating. Safe operating area is important for three kinds of reasons:

- Reliability: it ensures that the device operates safely without damage.
- Design: it helps engineers select the right device and design protection circuits.
- Protection: it prevents failure modes such as thermal runaway or breakdown.

Considering Figure 3. Safe operating area for a 60 V Power MOSFET device, SOA can be divided into different zones:

- $R_{DS(on)}$ limit (blue line): there is a linear correlation between drain-source voltage (V_{DS}) and drain current. The slope is given by the device $R_{DS(on)}$ at maximum junction temperature (depending on datasheet values):

$$I_D = \frac{V_{DS}}{R_{DS(on)@T_{Jmax}, V_{GS} = 10V}} \tag{1}$$

  From Eq. (1), this limit is higher at lower T_J as $R_{DS(on)}$ value decreases with junction temperature.
- Orange line: it is the maximum current that the device can manage. It mainly depends on the device die size.
- Breakdown voltage limit (green line): it is given by the maximum drain-source applicable voltage (BV_{DSS} as reported in the datasheet). MOSFET breakdown voltage is dependent on junction temperature: the lower T_J the lower BV_{DSS}.
- Maximum power dissipation limit (purple line): it defines the maximum amount of power that MOSFET can safely manage without exceeding its maximum junction temperature. This limit is critical because excessive power dissipation causes the MOSFET's junction temperature to rise, potentially leading to thermal runaway or permanent damage. The maximum power dissipation is given by:

$$P_{max} = V_{DS} \cdot I_D = \frac{T_{J,max} - T_C}{R_{thJC}} \tag{2}$$

Where R_{thJC} is the junction-to-case thermal impedance. As reported in the previous formula, the power dissipation limit is affected by case and temperature values; moreover, longer pulse duration reduces this limit reflecting higher thermal impedance values.

The maximum power dissipation limit is valid when the device can dissipate all the electric power generated (thermal equilibrium):

$$P_{GEN} = P_{DISS} \tag{3}$$

If the power generation increase rate is higher than power dissipation one, the thermal equilibrium ends, and the device is in the so-called thermal instability zone. In the SOA graph, this point corresponds to a change in the slope (Figure 3. Safe operating area for a 60 V Power MOSFET device, see the purple circle):

$$\frac{\partial P_{GEN}}{\partial T} > \frac{\partial P_{DISS}}{\partial T} \tag{4}$$

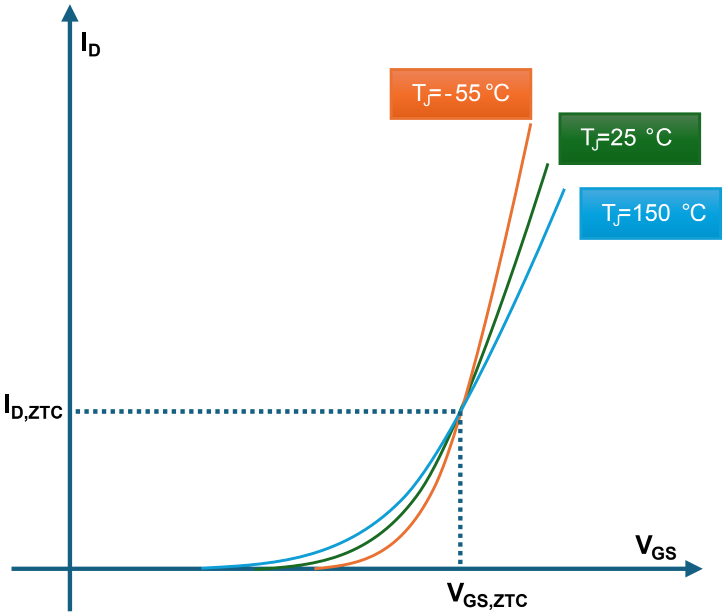
Considering Eq. (2) and Eq. (4) can be written as:

$$V_{DS} \cdot \frac{\partial I_D}{\partial T} > \frac{1}{R_{thJC}} \tag{5}$$

$$\frac{\partial I_D}{\partial T} > \frac{1}{V_{DS} \cdot R_{thJC}} \tag{6}$$

Eq. (6) gives the mathematical condition for thermal instability, linked to V_{DS} and thermal impedance R_{thJC}; $\frac{\partial I_D}{\partial T}$ is the thermal coefficient of drain current. Positive values of this parameter mean that the device is working inside the thermal instability zone. To highlight how the I_D thermal coefficient can affect the device behavior, the following figure shows the transfer characteristics (drain current as function of gate-source voltage) at three different temperatures (-55 °C, 25 °C and 150 °C).

Figure 4. **Transfer curves @ -55 °C, 25 °C, 150 °C**



Power MOSFET threshold voltage ($V_{GS(th)}$) has a negative thermal coefficient ($dV_{GS(th)}/dT < 0$), the higher the temperature the lower $V_{GS(th)}$. The three transfer curves intersect at “zero temperature coefficient” point (or “zero tempco”, ZTC); considering the gate-source driving voltage, three different scenarios can happen:

1. $V_{GS} = V_{GS,ZTC}$: the device current is stable with the temperature.
2. $V_{GS} > V_{GS,ZTC}$: the device current decreases when the temperature rises (negative I_D thermal coefficient), reaching the thermal equilibrium.

3. $V_{GS} < V_{GS,ZTC}$: the device current increases with the temperature (positive I_D thermal coefficient). In these conditions, when a small die part becomes hotter than the adjacent area, it conducts more drain current creating more heat. Therefore, due to negative $V_{GS(th)}$ thermal coefficient, more current will flow in this area and finally a huge amount of current is limited to a very small die zone pushing the device to failure (thermal runaway).

So, MOSFETs with high $V_{GS,ZTC}$ and $I_{D,ZTC}$ values are more sensitive to thermal instability (bigger area with positive $\frac{\partial I_D}{\partial T}$) and vice versa. There is a strict relationship between ZTC and MOSFET transconductance (g_{fs}): the higher the transconductance the higher ZTC. This means that the MOSFET is more prone to thermal runaway. Modern MOSFET technologies are characterized by high g_{fs} values needed to work at high switching frequency with low switching losses improving system efficiency. So, these devices are less robust in linear zones and it is important to design the boundary operating conditions inside the safe operating area.

3 Typical applications working in linear mode

Several applications using Power MOSFETS working in linear mode benefit from several advantages:

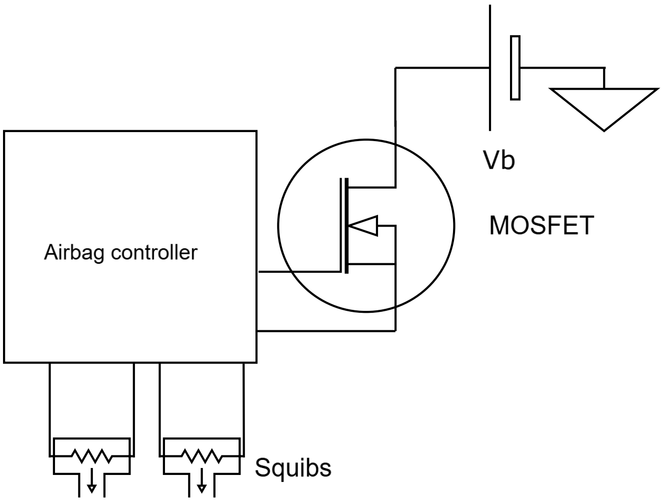
1. In linear mode, the MOSFET works as a gate-controlled current generator and it can ensure fine control of current flow by adjusting the gate voltage.
2. Linear mode enables gradual adjustment of power dissipation avoiding switching noise and EMI.
3. The MOSFET can replace mechanical or discrete variable resistor improving density and reliability of resistance in power systems.
4. As the MOSFET dissipates power continuously, thermal stress can be more predictable and thermal and heat-sink design can be simpler.

Therefore, linear mode is typically used where precise control and low switching noise are preferable than low efficiency.

3.1 Applications with rectangular pulses

A first class of applications with MOSFETs in linear mode is characterized by subjecting them to a rectangular power pulse, when drain-source voltage (V_{DS}) and drain current (I_D) are constant. A classic example is the airbag in automotive systems (see Figure 5. Airbag schematic). Here, the power switch is typically implemented using an N-channel power MOSFET arranged in a high-side configuration to precisely control the current flow to the squibs. This topology is preferred for its efficiency and ability to handle high current loads while maintaining low conduction losses. Squibs are pyrotechnic igniters—small, precisely engineered microexplosives—that, once electrically activated, initiate the rapid inflation of the airbag within a few microseconds. The ignition process is critical and must be executed with high reliability to ensure occupant safety.

Figure 5. **Airbag schematic**

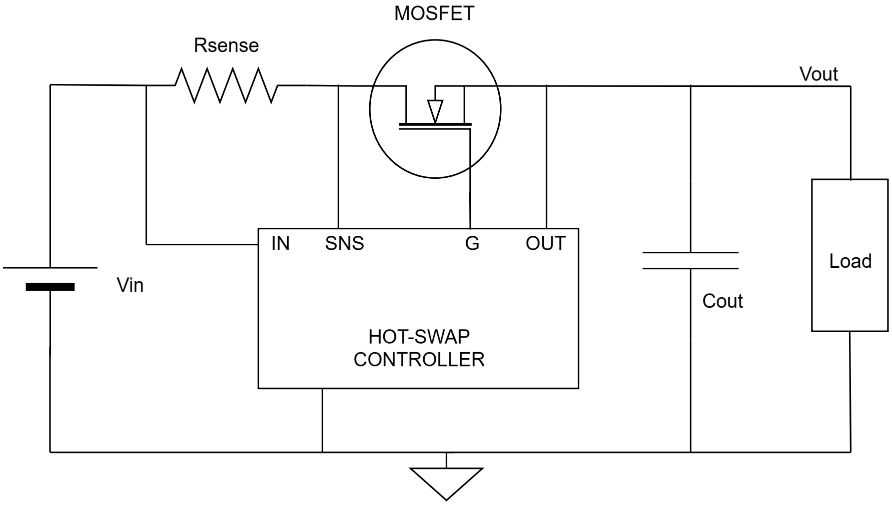


Proper ignition of the squibs requires a carefully controlled electrical pulse with well-defined parameters: voltage level, current magnitude, and pulse duration. These squibs function correctly and safely only if the voltage across and the current through each squib remain within tightly controlled specified ranges. This requirement implies that the power MOSFET must operate in its linear region during the ignition pulse, rather than simply switching fully on or off. By operating in linear mode, the MOSFET effectively regulates and limits both the current and voltage delivered to the squibs, ensuring that these parameters remain within the precise thresholds needed for proper ignition. Careful design considerations are essential to balance the MOSFET's linear operation for accurate current and voltage control with robust thermal management strategies. This includes selecting MOSFETs with appropriate power ratings, implementing effective heat sinking or thermal dissipation methods, and incorporating protective features such as thermal shutdown and current limiting within the driver IC. By maintaining the MOSFET within safe thermal and electrical operating limits during the ignition pulse, the system ensures reliable squib activation while preserving component integrity and overall system safety.

3.2 Applications with triangular pulses

In some other systems, MOSFET working in linear mode must manage triangular power pulses; classic examples are the inrush current limiter, soft-start or hot-swap circuits (See Figure 6. Hot-swap (single device) circuit schematic). The power switch is typically a single or dual (back-to-back) N-channel Power MOSFET configured in a high-side position to control the current magnitude during the transient turn-on. The transient turn-on control allows controlled charging of output capacitances, preventing voltage spikes and ringing that could otherwise damage the system or cause electromagnetic interference. After the transient phase, the power switch is fully turned on, operating in the ohmic region with a minimal voltage drop, ensuring efficient conduction and low-power dissipation. During the transient phase, the MOSFET operates in saturation mode for a fixed duration, effectively limiting the current magnitude until the output voltage reaches its nominal value, ensuring smooth and safe power-up behavior. This controlled current charging phase is critical when driving large capacitive loads or complex systems where the input capacitances must be charged gradually to the nominal bus voltage. By maintaining a constant current during pre-charging, the system avoids inrush currents that could stress components or cause voltage dips in the power supply network.

Figure 6. Hot-swap (single device) circuit schematic



Unlike applications with rectangular power pulses (such as airbag deployment systems), the power pulse in this pre-charging phase exhibits a triangular shape. This is because the MOSFET limits the current to a constant value while charging the output capacitances. As these capacitors charge, the drain-to-source voltage (V_{DS}) decreases gradually from a high initial value down to a low value close to the MOSFET's on-resistance voltage drop ($R_{DS(on)} \cdot I$). This dynamic voltage transition results in a triangular current waveform rather than a rectangular one, reflecting the continuous change in V_{DS} during the charging process. Given the triangular nature of the power pulse — where V_{DS} decreases linearly while the current Ids remains constant — the instantaneous power dissipation ($P = V_{DS} \cdot I_D$) also follows a triangular profile. Consequently, the maximum junction temperature is reached during the early phase of the transient, when power dissipation is at its peak. After this initial peak, the junction temperature tends to decrease as the power dissipates reduce over time.

3.3 Correlation between rectangular and triangular power pulses in MOSFET linear mode applications

It is important to establish a direct correlation between the rectangular pulse described in the datasheet and the triangular pulse, which can be derived from the former. This is because the data provided in the datasheet typically refers to conditions of rectangular pulses with constant voltage and current values. These data do not directly define the maximum current that a device can support for a given pulse duration (Tp) in the case of a triangular pulse.

To achieve this, we conducted experimental measurements to confirm the hypothesis. These measurements validate the correlation between the rectangular and triangular pulses and support the analysis of the MOSFET's behavior under real operating conditions.

A critical aspect in assessing the thermal behavior and safe operating area (SOA) of MOSFETs operating in linear mode is the accurate correlation between rectangular and triangular power pulses. Datasheets typically provide SOA data for rectangular pulses, while many applications feature triangular power pulses.

Recent experimental and modeling work has demonstrated that, even under electro-thermal instability conditions, the maximum allowable current for a triangular pulse is approximately twice that of a rectangular pulse of equivalent duration.

This empirical relationship:

$I_{Dtriangular} \approx 2I_{Drectangular}$

It has been validated across a broad range of MOSFET devices with varying package types, blocking voltages, die sizes, and trench technologies.

Supporting this finding, advanced thermal models and SPICE simulations accurately predict junction temperature dynamics under triangular pulses, including hotspot formation and cumulative thermal effects during pulse trains.

This correlation enables designers to leverage existing rectangular pulse SOA data for robust evaluation of MOSFET performance under triangular power dissipation profiles, simplifying design verification and accelerating time-to-market. This approach is particularly valuable in automotive applications where thermal management and reliability are paramount.

4 Test results

Experimental tests and related spice simulations can provide a complete understanding of the device behavior when subjected to rectangular and triangular power pulse. Moreover, through electrical simulations, it is possible to monitor the junction temperature and its trend in the two above mentioned application types. To improve the correlation between bench tests and simulations, an RC thermal network is set up as close as possible to the real testing boards. A 40 V Power MOSFET is selected as device under test.

Figure 7. Clamping circuit schematic

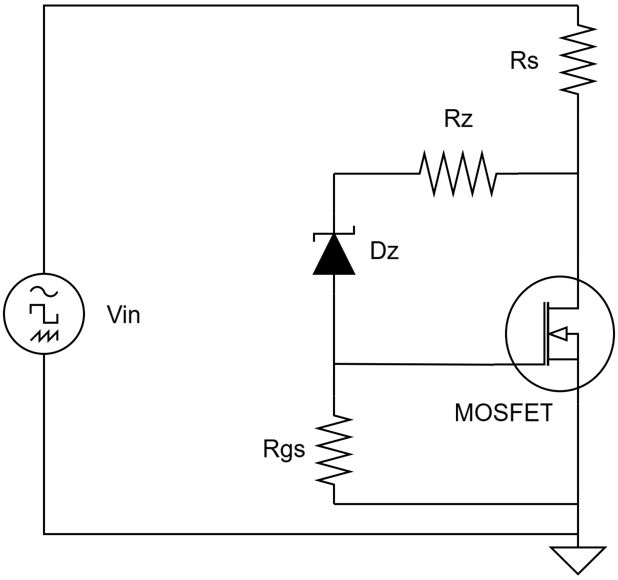
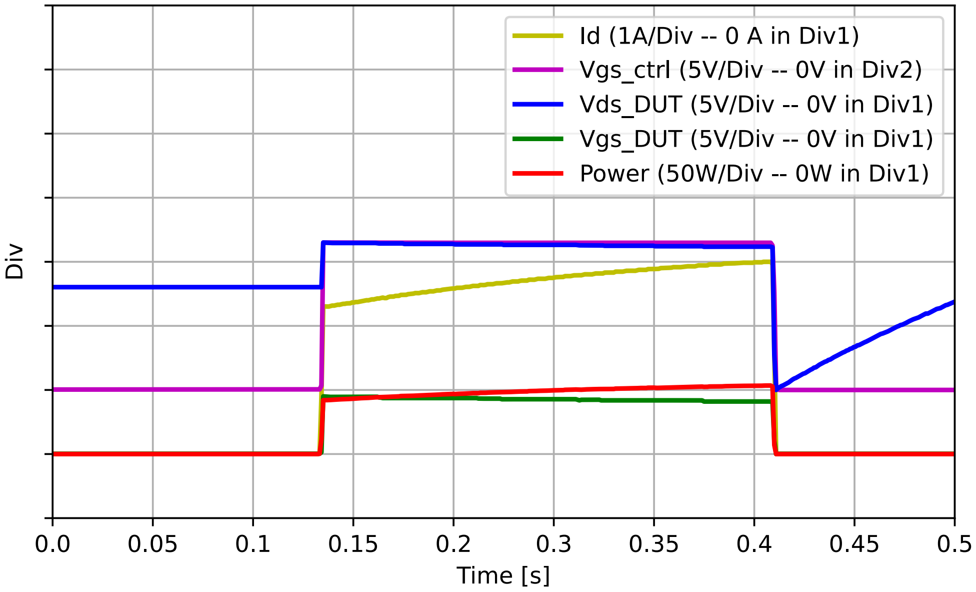


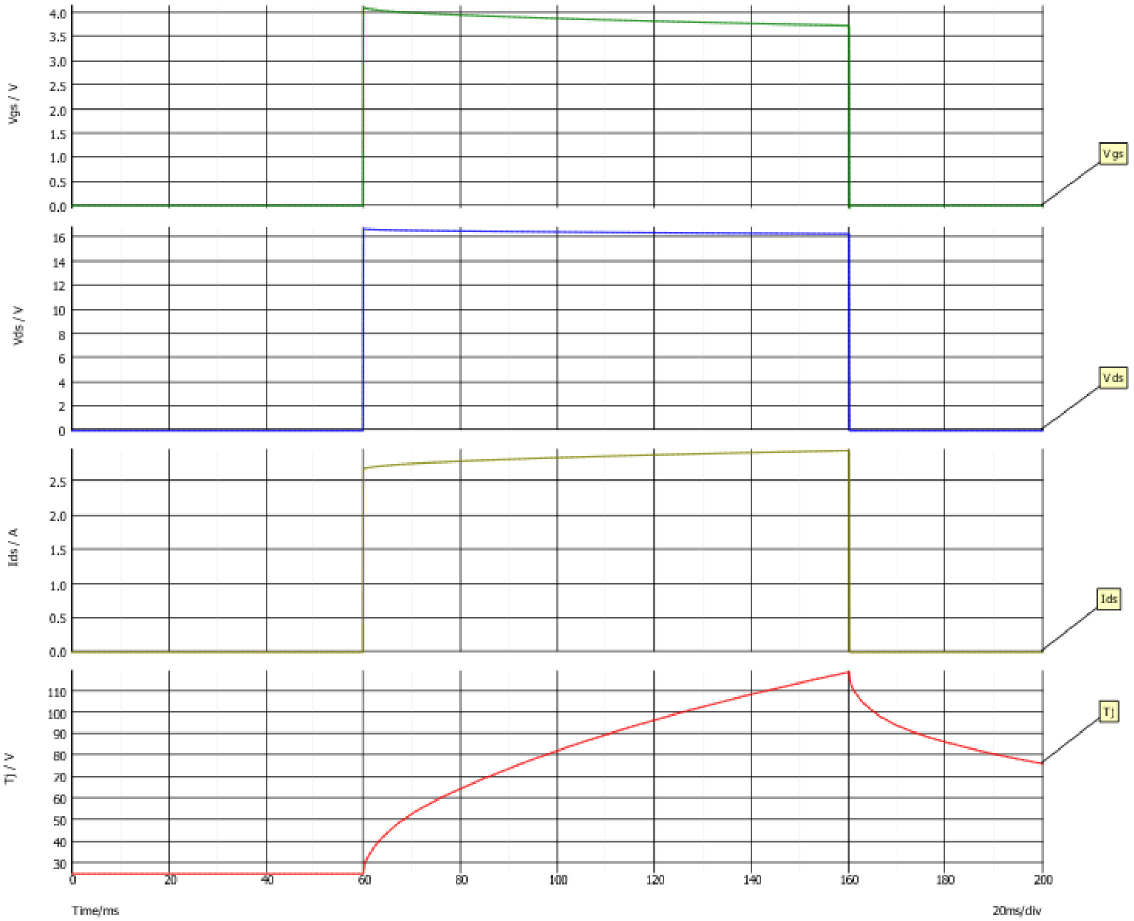
Figure 7. Clamping circuit schematic represents the testing circuit to apply rectangular pulse to the device under test. The input voltage is a pulsed generator setting the power pulse duration. With a proper selection of the Zener diode D_Z, MOSFET is biased in linear mode ($V_{DS} = V_Z + V_{GS}$, $V_{GS} \approx 3$ V - 4 V) while the device current is fixed by adjusting the input voltage value. Next figure shows the relevant waveforms for a 100 ms pulse (V_{DS} = 16 V, I_D = 3 A).

Figure 8. Waveforms @ 100 ms, 16 V, 3 A (rectangular pulse)



V_{DS} is constant during the pulse, while the gate-source voltage is enough to get 3 A as drain current. Considering the thermal effect, power dissipation is slightly increasing during the pulse reaching the maximum value at the end of the pulse. Hence, junction temperature should have the same trend making the final part of the pulse more critical; here, current focusing phenomena could start and bring the device close to the failure. The results from electrical simulations fully confirm the experimental ones (see the following figure).

Figure 9. **Simulation waveforms @ 100 ms, 16 V, 3 A (rectangular pulse)**



At the end of the pulse, there is the maximum junction temperature even if it is well below the maximum ratings. The device can dissipate all the generated power avoiding any risk of thermal runaway. If the power dissipation increases (that is, higher drain current), the device is no longer in thermal equilibrium and the generated power cannot be easily dissipated.

Figure 10. **Waveforms @ 100 ms, 16 V, 3 A (triangular pulse)**

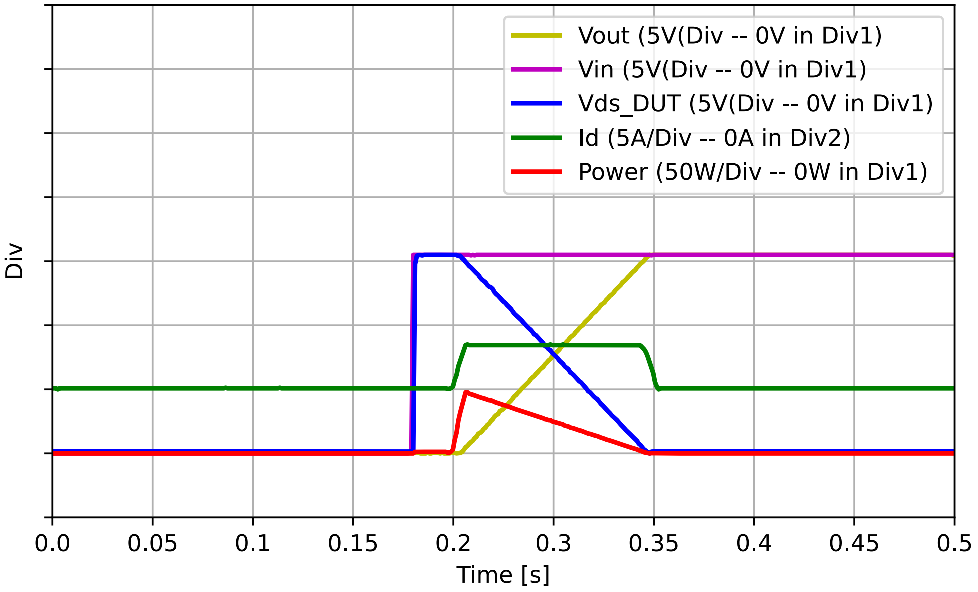


Figure 10. Waveforms @ 100 ms, 16 V, 3 A (triangular pulse) and Figure 11. Simulation waveforms @ 100 ms, 16 V, 3 A (triangular pulse) show the results from experimental tests and electrical simulations performed on a basing replicating hot-swap function (see Figure 12. Linear charge of capacitor – basic schematic).

Figure 11. **Simulation waveforms @ 100 ms, 16 V, 3 A (triangular pulse)**

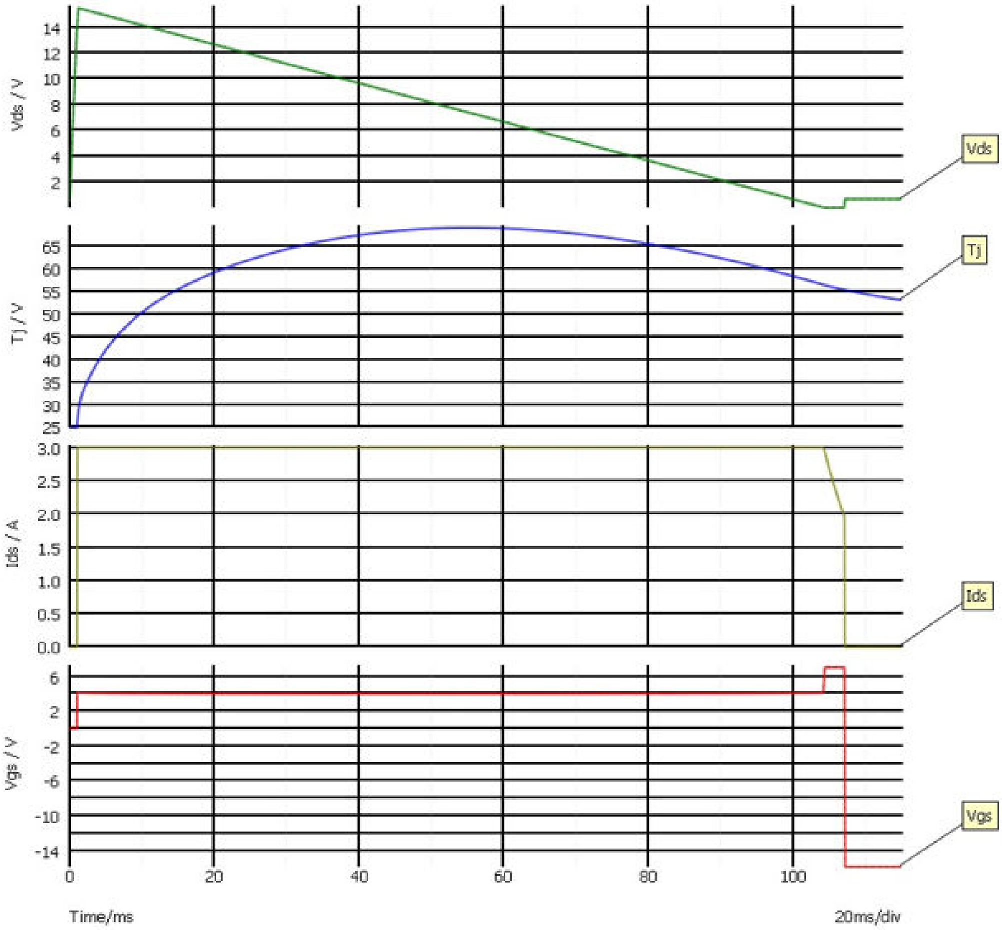
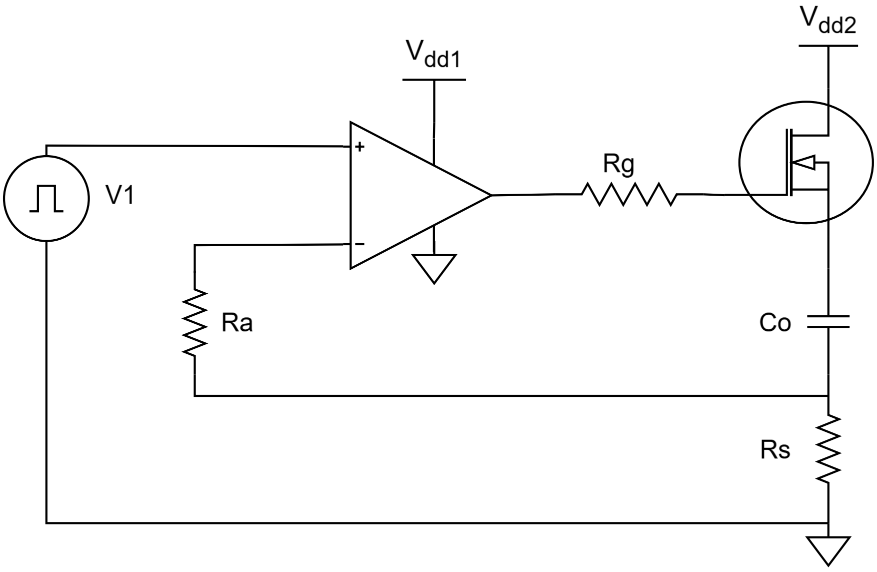


Figure 12. **Linear charge of capacitor – basic schematic**



As reported in Figure 10. Waveforms @ 100 ms, 16 V, 3 A (triangular pulse) and Figure 11. Simulation waveforms @ 100 ms, 16 V, 3 A (triangular pulse), with a triangular pulse, the instantaneous power being dissipated by the MOSFET ($P_{INST} = V_{DS}(t) \cdot I_D(t)$) rapidly increases at the beginning of the pulse as both V_{DS} and I_D are at high levels. So, the device dissipates the maximum power in the first tens of milliseconds. Then, during linear charge of the output capacitor, the drain-source voltage is reducing; in this way, the device is moving towards safer operating conditions (lower V_{DS} and power dissipation). Comparing the figure Figure 8. Waveforms @ 100 ms, 16 V, 3 A (rectangular pulse) and Figure 9. Simulation waveforms @ 100 ms, 16 V, 3 A (rectangular pulse) with Figure 9. Simulation waveforms @ 100 ms, 16 V, 3 A (rectangular pulse) and Figure 10. Waveforms @ 100 ms, 16 V, 3 A (triangular pulse), some important considerations can be made:

1. A rectangular pulse biasing the device with constant V_{DS}, I_D and P_D is more stressful for the device under test than a triangular one.
   a. At the same pulse condition (V_{DS}= 16 V, I_D= 3 A, t_p= 100 ms), the average power dissipation with a rectangular pulse (44 W) is 90% higher than that with a triangular one (23 W).
2. The maximum junction temperature ($T_{J,max(triang)}$≈85 °C, see Figure 8. Waveforms @ 100 ms, 16 V, 3 A (rectangular pulse)) is reached in the first tens of milliseconds when the device is subjected to triangular pulse. Vice versa, with constant V_{DS} and I_D, the device reaches the maximum T_J ($T_{J,max(rect)}$≈110 °C) at the end of the pulse. Consequently, the maximum current and hence the power the device can manage is higher in the first condition.

Figure 13. **Failed device waveforms (rectangular pulse)**

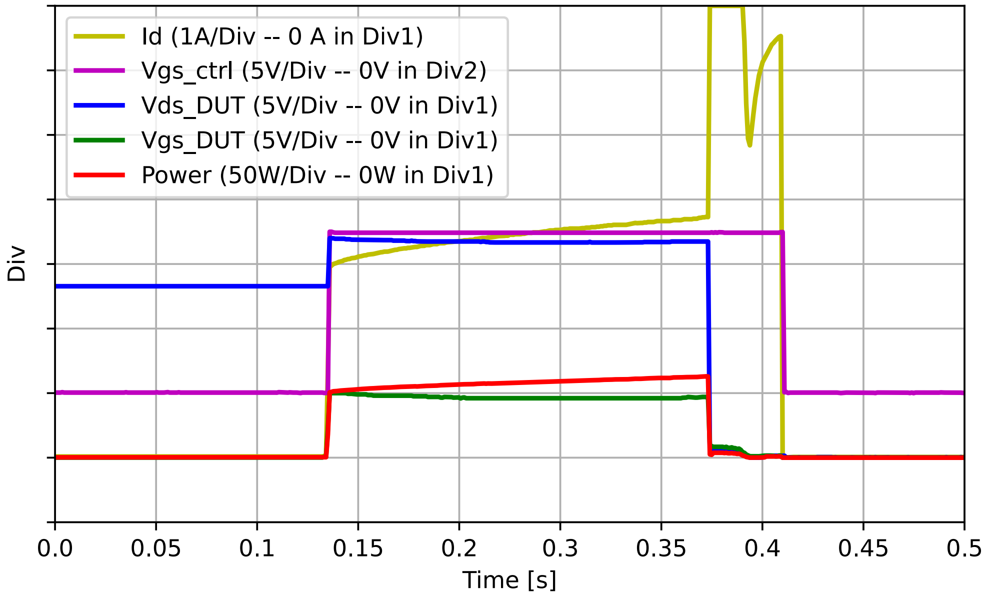
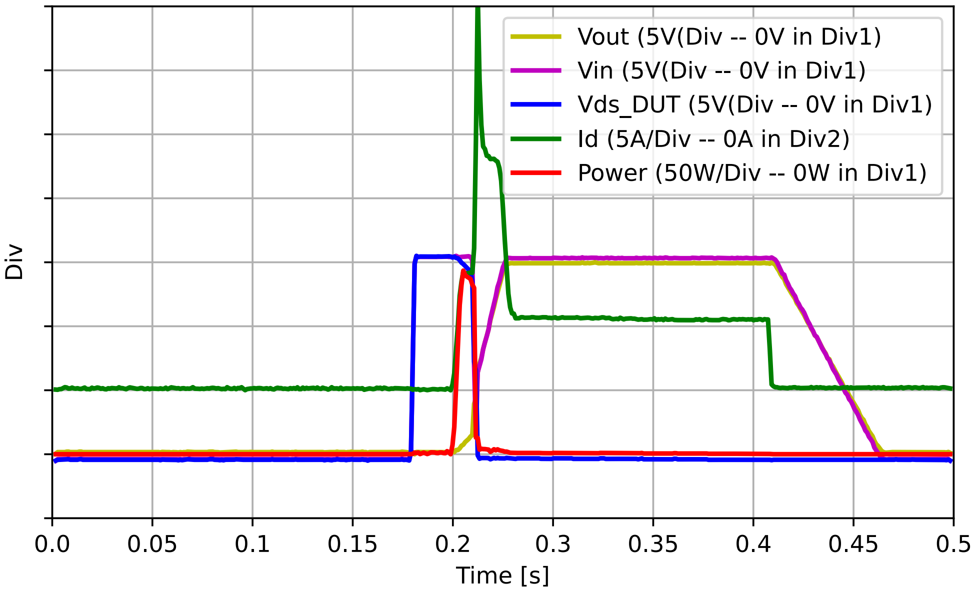


Figure 13. Failed device waveforms (rectangular pulse) and Figure 14. Failed device waveforms (triangular pulse) show the real waveforms when the devices fail. As clearly highlighted, the device subjected to triangular pulse has higher failure current ($I_{D,FAIL}$ ≈ 8 A) and can manage bigger power dissipation than rectangular pulse before failing. Due to different T_J trends, the failure happens nearly at the beginning of the triangular pulse, due to higher power dissipation. In Figure 13. Failed device waveforms (rectangular pulse), the device under test enters in thermal runaway at the end of the pulse, as it is not in thermal equilibrium and cannot manage the generated power.

Figure 14. **Failed device waveforms (triangular pulse)**



5 Conclusions

This application note has presented a thorough analysis of the thermal and electrical behavior of power MOSFETs subjected to rectangular and triangular power pulses, typical of various industrial and automotive applications. Experimental results and electrical simulations highlighted how the pulse shape significantly affects thermal stress and device robustness.

Specifically, it has been demonstrated that:

- Rectangular pulses, characterized by constant voltage and current values, generate significantly higher average power dissipation compared to triangular pulses of the same duration and peak current, thus imposing greater stress on the MOSFET.
- The maximum junction temperature in the case of triangular pulses is reached rapidly within the first tens of milliseconds and then gradually decreases, whereas in rectangular pulses the temperature continuously rises until the end of the pulse, increasing the risk of thermal instability and failure.
- The device can sustain higher current levels with triangular pulses than with rectangular ones, confirming the empirical correlation:
  $I_{Dtriangular} \approx 2I_{Drectangular}$
- Tests and simulations have been conducted to validate this empirical relationship, confirming the theoretical analysis and providing a reliable basis for device evaluation under specific operating conditions.
- A detailed understanding of the safe operating area (SOA) and thermal instability phenomena is essential for proper device selection, effective thermal management, and reliable design, especially in critical applications such as airbags and hot-swap circuits.

These findings provide practical and theoretical guidance for designers, enabling correlation of datasheet parameters with actual operating conditions and optimizing MOSFET sizing according to specific application requirements. The proposed methodology, based on experimental measurements and advanced simulations, represents a valuable tool to enhance the reliability and safety of electronic systems operating in linear mode.

Revision history

Table 1. **Document revision history**

Date	Revision	Changes
10-Dec-2025	1	Initial release.

Contents

List of figures

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