AN5704

Application note

Electro-thermal PSPICE models for transient voltage suppressor (TVS)

Introduction

Simulations in electronics circuits are fundamental to speed up time to final design. A field of electronics is the constraints linked to spikes, surges, pulses due to external perturbations (lighting, fast transients, …), inherent stress when the circuit is working (over-voltage due to parasitic inductances (harness, pins, …) or inductive loads such as motors, relays, …).

Accurate simulations allow to quickly choose the correct protection product, to check its suitability versus power dissipation, clamping voltage and the residual voltage which has to be lower than the protected circuit AMR (absolute maximum rating) values.

For this purpose, thermal effects have to be taken into account to get simulations results as close as possible to reality. The ambient temperature and the internal silicon heating (when current runs through electronic components) change the behavior of the circuit. This leads to more precise simulated voltage and current responses.

ST has developed electro-thermal TVS PSPICE models allowing to get better results and save development time.

This application note presents simulation comparisons between basic models (i.e. without heating effect) and electro-thermal models. Comparisons between measurements and simulations show advantages of electro-thermal models.

1 TVS basics

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

Figure 1. TVS in parallel protection schematic against Electrical Over Stress (EOS) or ESD

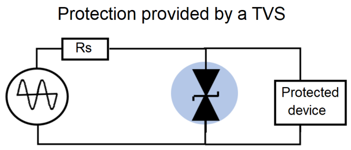
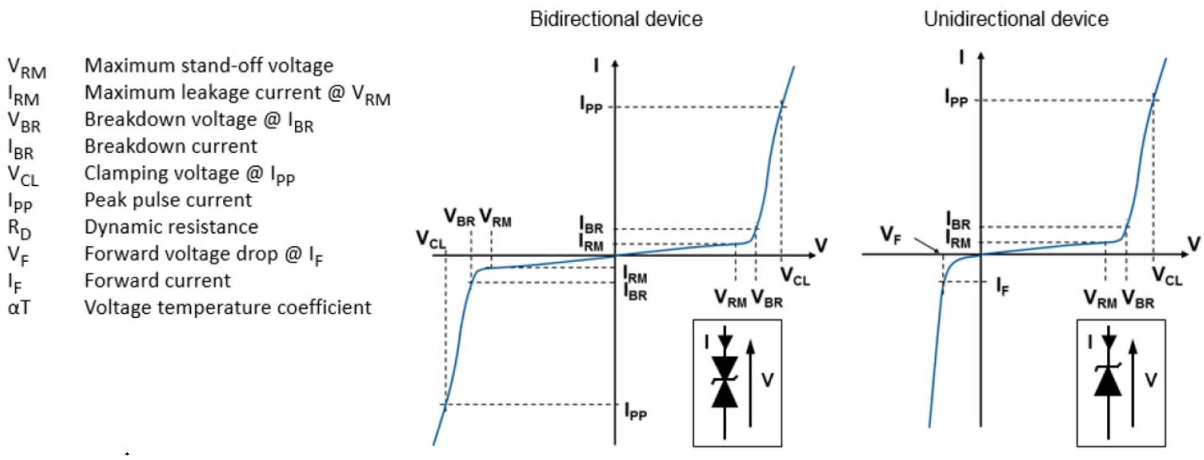
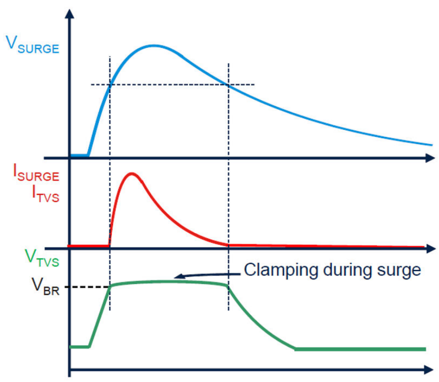


Figure 2. Electrical characteristics – parameter definitions



A TVS is used to protect an electronic device or circuit. The TVS is activated as soon as the surge voltage across the protected device reaches V_{BR}. In its active state, the TVS becomes a low impedance device. It clamps the surge voltage by absorbing the surge current, thereby clamping the surge voltage. Ideally, a TVS's clamping voltage (V_{CL}) is equal to V_{BR}, but in reality, the clamping voltage (V_{CL}) is varying according to the amplitude of the surge current (see Figure 3).

Figure 3. Electrical behavior of the TVS



Please see AN316 for full details.

2 Electro-thermal versus basic models, and comparison with measurements

To show the interest of electro-thermal models, simulation comparisons have been performed with pulses described by automotive standards but also with classical pulses. Both types of results will be compared with measurement waveforms. As electro-thermal models have accurate results, we can simulate different circuit topologies (series-parallel) and better anticipate the behavior with real process variation. For this, we will see waveform behavior for two TVS mounted in parallel with V_{BR} difference.

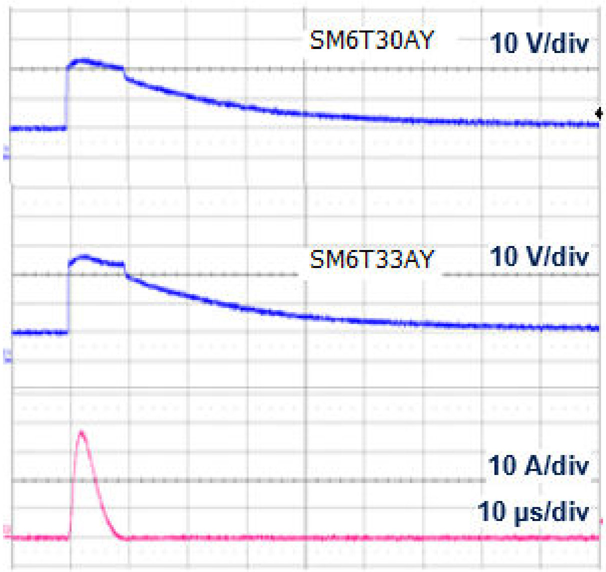
2.1 Automotive pulses

2.1.1 ISO7637-2 pulse 2a

2.1.1.1 Simulations and measurement waveforms comparison

ISO7637-2 is the automotive standard which defines the electrical transient conduction along supply lines in road vehicles. Several pulses are defined as over-voltage stress and TVSs are mandatory to protect electronics components and circuits. Pulse 2a is one of them and even if the voltage surge duration is short (50 µs at 10% of the peak voltage value), the peak current can be high due to the low series resistance of the generator (2 Ω): the silicon TVS is heating during the applied surge. The PSPICE simulation residual voltage can be only approximative if the thermal effect is not taken into account and if the dynamical performance is only simulated by a resistance value. As an example, each ST automotive TVS datasheet gives voltage and current waveforms with the different overvoltage pulses defined in ISO7637-2. The SM6TY datasheet shows the measurement of the pulse 2a response waveform for SM6T30AY and SM6T33AY (see Figure 4).

Figure 4. ISO7637-2 pulse 2a: Vs = +112 V with 12 V battery (extract of SM6TY datasheet)



We reproduced measured waveforms by simulating SM6T30AY and SM6T33AY TVS models (electro-thermal and basic) with pulse 2a generator. See Figure 5 and Figure 6.

Note: All simulation responses with thermal effect will be drawn in full line while basic model will be in dashed line.

Figure 5. ISO7637-2 pulse 2a PSPICE schematic with SM6T30AY or SM6T33AY

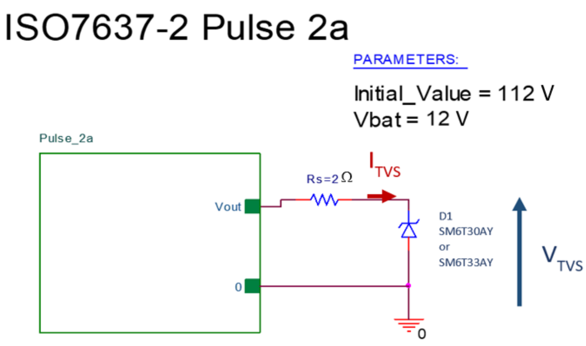
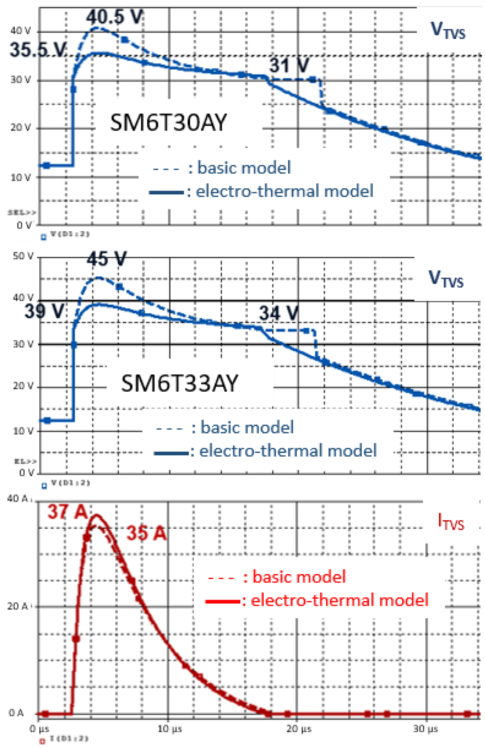


Figure 6. ISO7637-2 pulse 2a PSPICE simulation responses with SM6T30AY and SM6T33AY

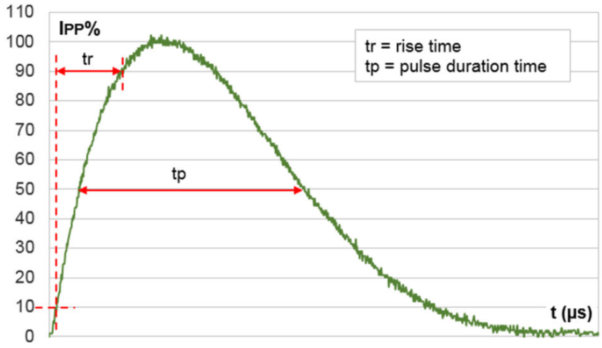


By comparing with Figure 4 the peak residual voltage waveform with electro-thermal SM6T30AY PSPICE model is more accurate (35.5 V) than with the basic model which is too pessimistic (40.5 V) versus the voltage measured (33.5 V). Similarly, the electro-thermal SM6T33AY PSPICE model is more accurate (39 V) than the basic model which is too pessimistic (45 V) versus the measured voltage (37 V).

2.1.1.2 *Power capability study (single pulse and repetitive surge)*

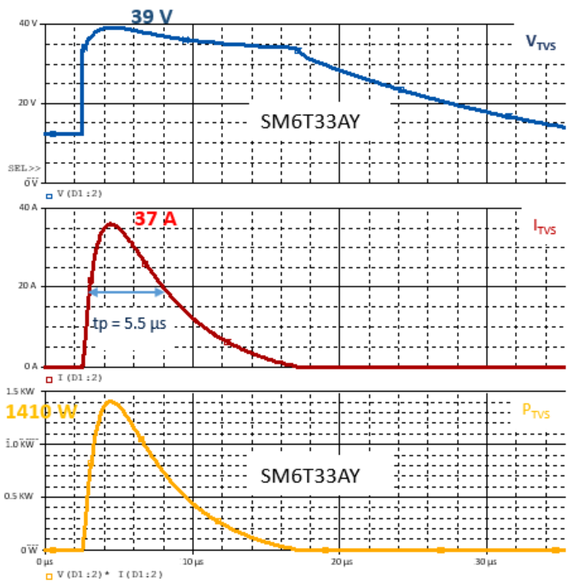
The power dissipation is important in the case of single pulse or repetitive surges. In both cases, we need to check the peak power dissipation versus t_P duration (t_P is defined as the pulse current duration through TVS at half of peak current, see Figure 7). In addition, in case of repetitive stress, we need to calculate the average power with surge frequency to get the junction temperature into the TVS die.

Figure 7. **Pulse duration definition for electrical characteristics**



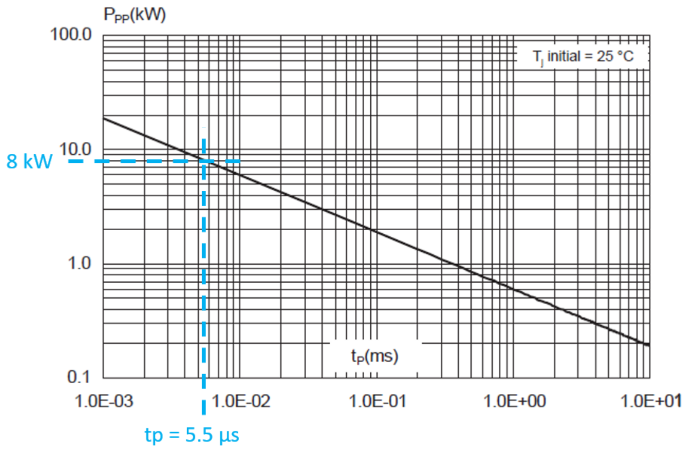
Thanks to accurate current and voltage simulated responses with electro-thermal ST TVS PSPICE models, we can get the maximum peak power and the tp value very easily. For example, from pulse 2a conditions given previously, PSPICE calculates SM6T33AY power waveform by TVS voltage and TVS current waveforms multiplication (see Figure 8):

Figure 8. **ISO7637-2 pulse 2a PSPICE voltage, current and power responses with SM6T33AY**



A figure "Maximum peak pulse power versus exponential pulse duration" is given on each datasheet. For instance, we can use the figure 4 of SM6TY datasheet and verify the power capability at tp = 5.5 µs (see Figure 9):

Figure 9. SM6TY “Maximum peak pulse power versus exponential pulse duration” extract of datasheet



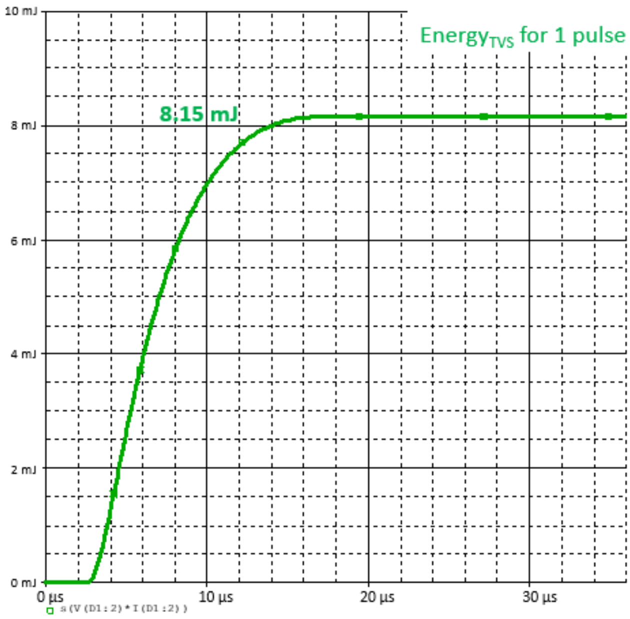
SM6TY TVS family has 8 kW power capability for t_P = 5.5 µs. As simulated peak power is 1410 W, SM6T33AY is suitable to clamp the over-voltage stress applied.

Pulse 2a is defined as a repetitive over-voltage stress with period between 0.2 s and 5 s. We will calculate the average power (P_{AV}) and then, obtain the junction temperature for the worst case (i.e. 0.2 s equivalent to 5 Hz).

Once again, very easily, we can obtain energy for 1 single pulse from PSPICE simulation with the integration of P_{PP} waveform (integration of previous orange curve):

SM6T33AY Energy = integral (V(D1:2) x I(D1:2)) = 8.15 mJ (see Figure 10).

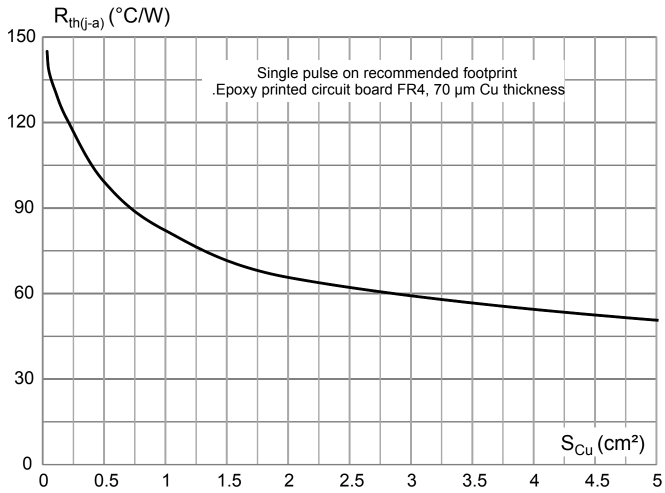
Figure 10. ISO7637-2 pulse 2a PSPICE SM6T33AY energy responses for 1 pulse (integration of power curve versus time)



Average power calculation: P_{AV} = Energy x frequency = 8.15 mJ x 5 Hz = 0.041 W

Every TVS family datasheet gives the value of junction to ambient thermal resistance $R_{th(j-a)}$ (usually with a curve “Thermal resistance junction to ambient versus copper area under each lead” see below Figure 11 for SM6TY), so we can calculate the increasing of the temperature (ΔT) due to average power dissipated: $\Delta T = P_{AV} \times R_{th(j-a)}$

Figure 11. "Thermal resistance junction to ambient versus copper area under each lead (SMB)” extract of SM6TY datasheet



$R_{th(j-a)}$ = 145°C/W with minimum copper area for packages, so ΔT = 0.041 W x 145 °C/W = 5.9°C

We can calculate the junction temperature T_j with this formula:

- $T_j = T_{amb} + P_{AV} \times R_{th(j-a)} = T_{amb} + \Delta T$

With T_{amb} = the ambient temperature.

For example, if T_{amb} = 85°C, T_j = 85°C + 5.9°C = 90.9°C

The maximum operating junction temperature admissible by TVS is given in each datasheet. For SM6T33AY, the maximum operating junction temperature is 150°C, higher than the calculated T_j (90.9°C). So the SM6T33AY is suitable for repetitive over-voltage stress in ISO7637-2 pulse 2a.

2.1.2 ISO16750-2 test A or formerly ISO7637-2 pulse 5a (load dump stress)

2.1.2.1 Simulations and measurement waveforms comparison

The ISO16750-2 standard includes the load dump pulses seen in the automotive environment. These pulses are the most stressful surge in the automotive ISO standards. Test A simulates load dump transient, caused by a highly stressful overvoltage upon battery disconnection while the alternator is providing current. For test A, the alternator is not auto-protected (test B is defined for auto-protected alternators).

The load dump protection LDP01Y TVS family has been developed by ST to protect circuits against the load dump pulse. Once again, simulations give accurate residual voltage allowing to check if this is compatible with devices to protect and the overall TVS capability.

Duration of the load dump surges is very long (from 40 ms up to 400 ms at the time point of 10% of peak voltage value) so, for sure, thermal effects have an impact on waveforms results.

Next example shows that simulated voltage waveform is completely different if thermal effect is taken into account or not. ISO7637-2 pulse 5a generator simulates the load dump stress (see Figure 12 and Figure 13).

Figure 12. ISO7637-2 pulse 5a PSPICE schematic with LDP01-30AY

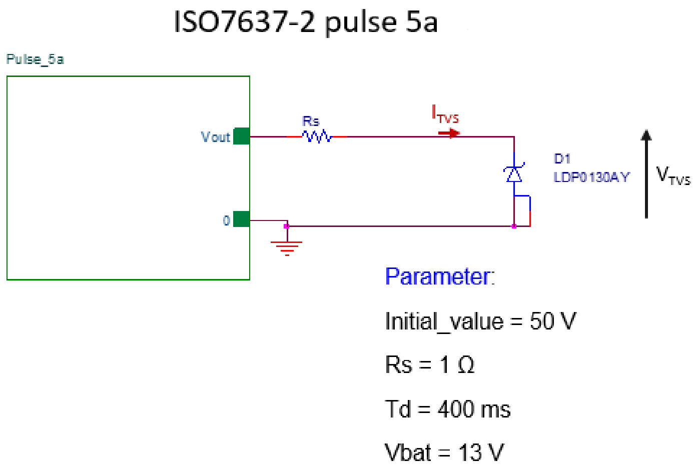
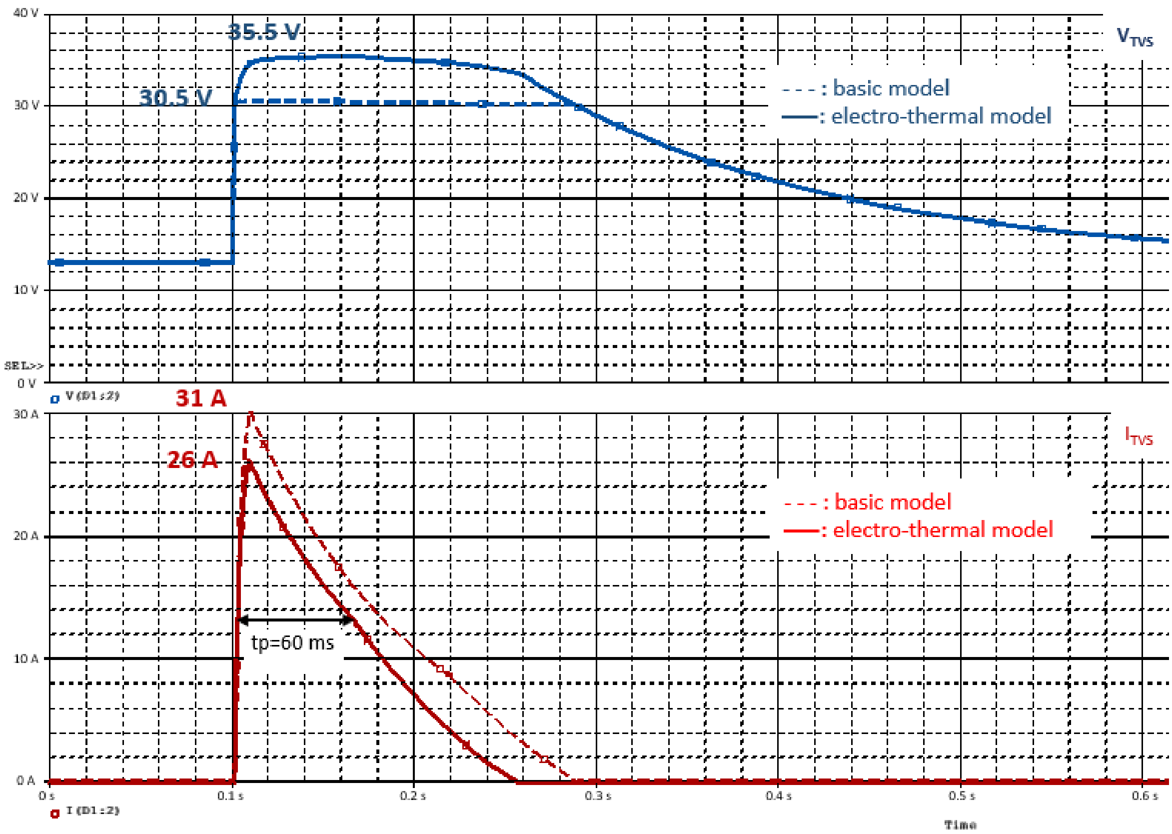
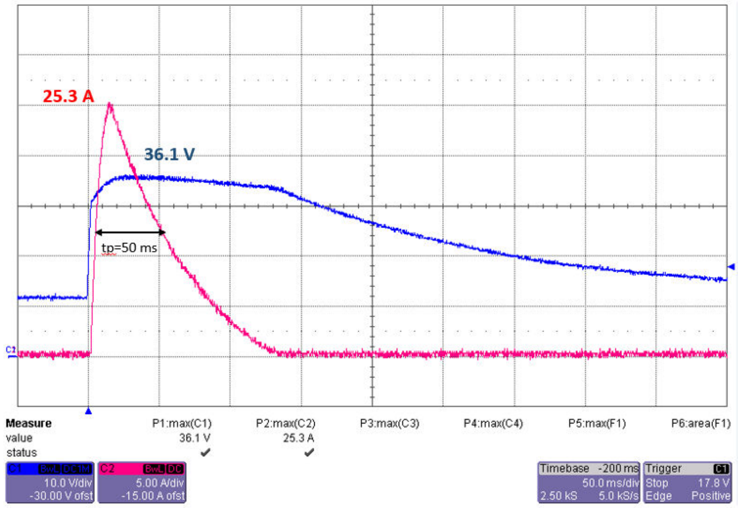


Figure 13. ISO16750-2 simulated test A PSPICE response with LDP01-30AY



When comparing simulations and measurements, it appears simulation done with electro-thermal PSPICE models are very close to real results on peak voltage, peak current and duration of current pulse (t_P) (see Figure 14).

Figure 14. **ISO16750-2 test A measurement**



There is 0.6 V difference between simulated and measured remaining voltage versus 5 V with the basic model. Knowing this remaining voltage is important to be compared to absolute maximum rating (AMR) voltage given in the datasheet of the circuit to be protected.

2.1.2.2 *Single pulse power capability study*

As already done with pulse 2a, we can check the power capability for pulse 5a. The approach is identical: from power simulated waveform and simulated current t_P duration (see Figure 15), we check the peak power limit given in LDP01Y datasheet versus the tp duration (see Figure 16).

Figure 15. **Peak power simulated waveform and t_P value**

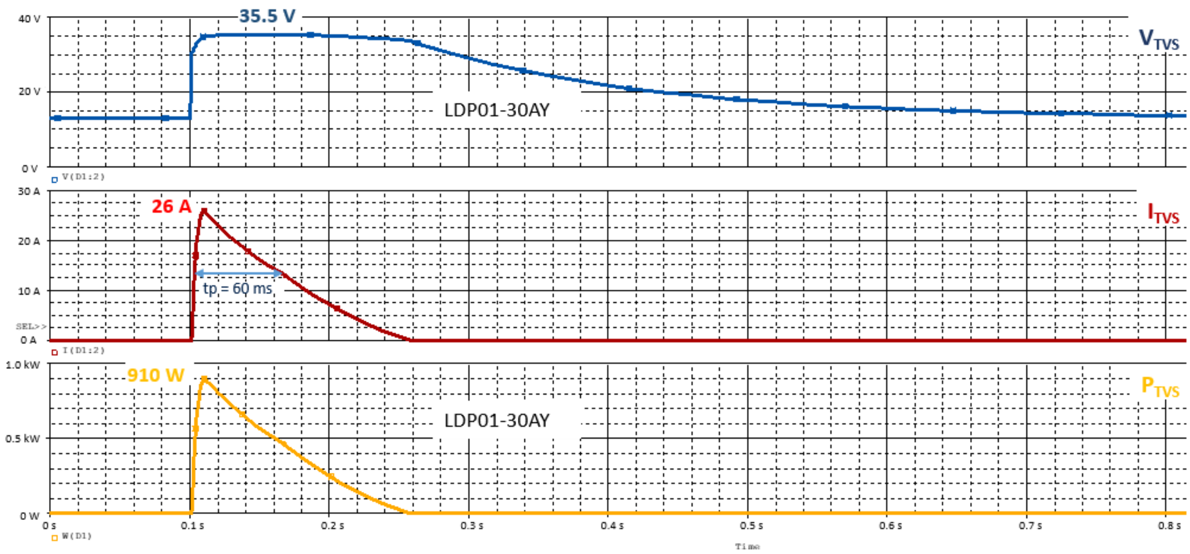
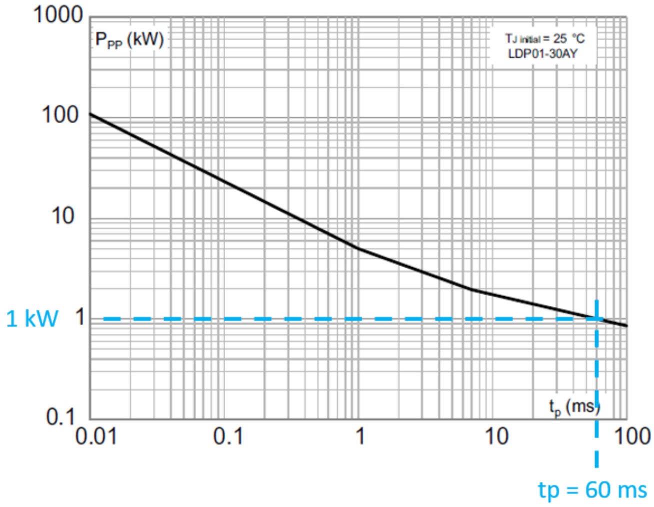


Figure 16. “Maximum peak pulse power versus exponential pulse duration” extract of LDP01Y datasheet



Power capability for t_P = 60 ms is 1 kW higher than the 910 W peak power simulated. LDP01-30AY is suitable for pulse 5a conditions given in Figure 12.

2.2 Standard pulses

TVS surge capability is always primarily specified with 10/1000 µs surges by all manufacturers. On top of this, STMicroelectronics is adding the 8/20 µs specification to be in line with IEC 61000-4-5. As we did for automotive waveforms, we can compare TVS PSPICE voltage (in particular, clamping voltage) and current waveforms with and without electro-thermal effects versus the measured waveforms.

2.2.1 8/20 µs standard study

From 1.2/50 µs - 8/20 µs PSPICE generator, set to 130 V with internal resistance equal to 2 Ω (see Figure 17), we study the difference between SM4T30AY measurement waveform (see Figure 18) and PSPICE simulated responses. Figure 19 shows simulation results, full line with electro-thermal behavior, dashed line without.

Figure 17. 1.2/50 µs – 8/20 µs generator with SM4T30AY

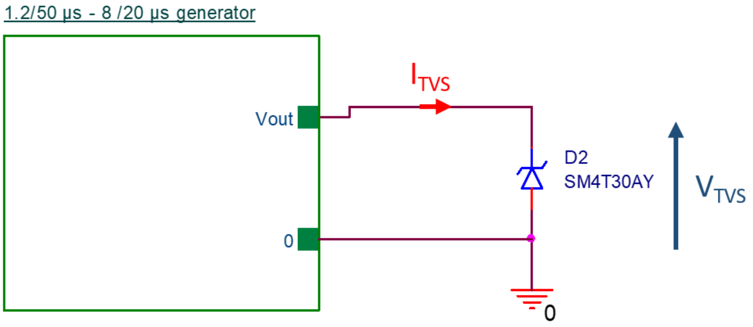


Figure 18. 1.2/50 µs – 8/20 µs SM4T30AY measurement

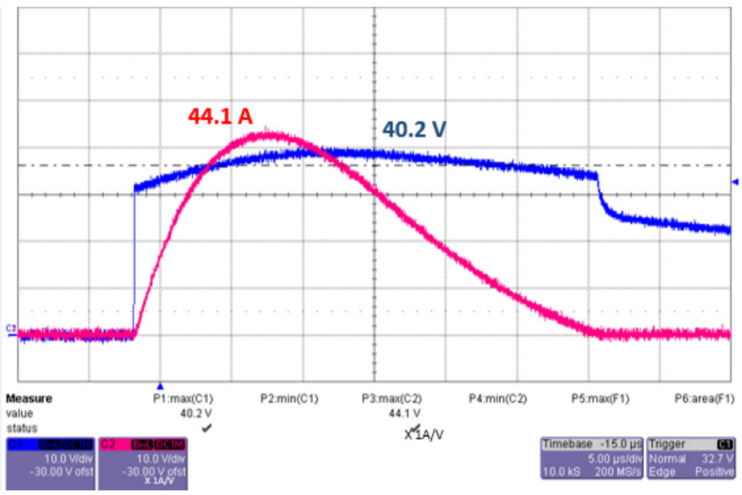
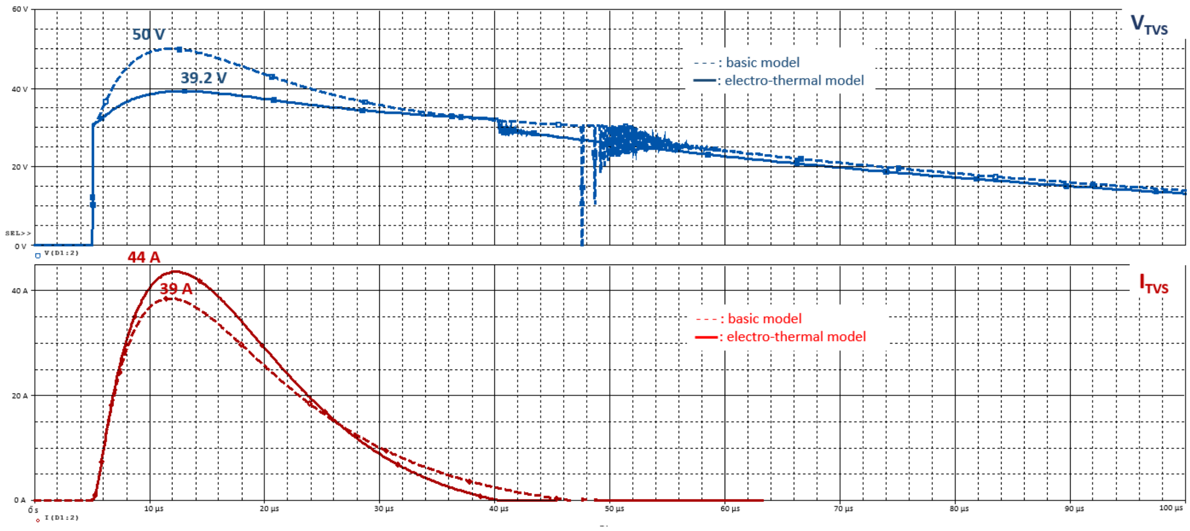


Figure 19. **1.2/50 µs – 8/20 µs SM4T30AY simulated responses**



Thermal effect PSPICE model fits with measurement waveforms and the difference with basic model is important. The main reason is not due to thermal effect but to the precision of the simulated internal TVS series resistance value, more accurate with thermal model.

2.2.2 10/1000 µs standard study

With the same approach, we can compare waveforms 10/1000 µs measurement (see Figure 21) and 10/1000 µs thermal or without thermal effect simulations (see Figure 22).

For PSPICE simulation, we use an 10/1000 µs STMicroelectronics labs design generator (see Figure 20). For this generator, voltage and current waveforms have the same rise time (10 µs) and same duration at 50% of peak pulse (1000 µs). This generator is set-up to 550 V with internal resistance equal to 10 Ω.

Figure 20. **10/1000 µs generator with SM15T30CAY**

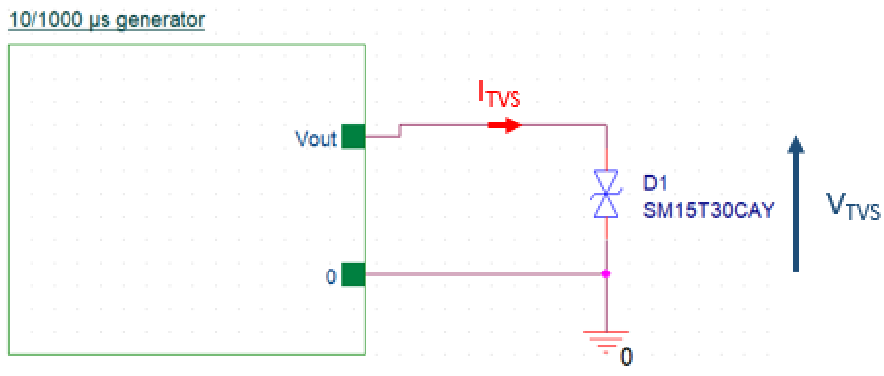


Figure 21. **10/1000 µs SM15T30CAY measurement**

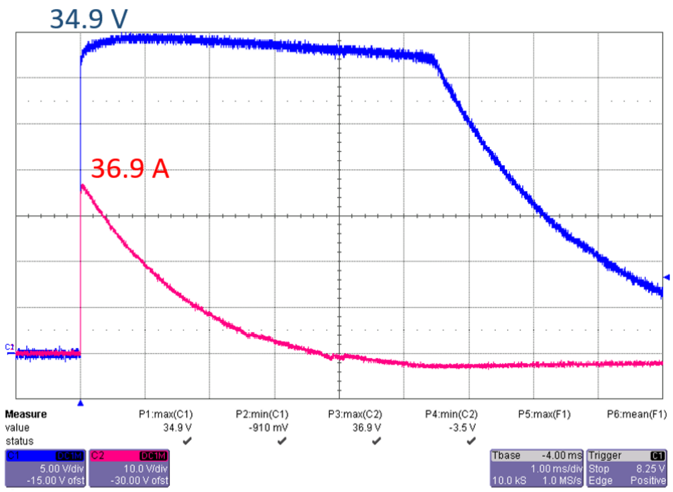
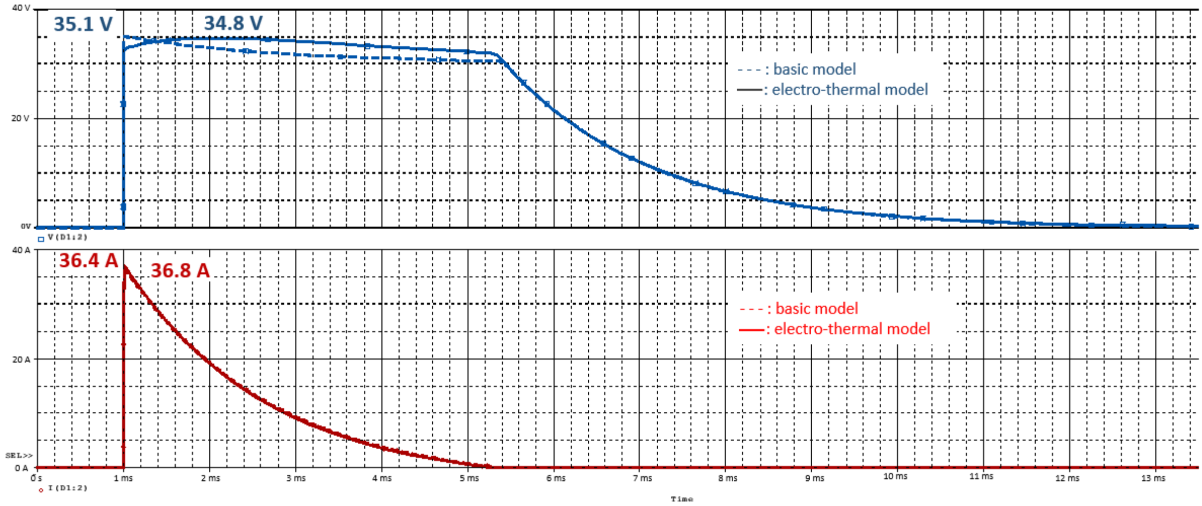


Figure 22. **10/1000 µs simulated pulse with SM15T30CAY**



The simulated behavior is completely different as the convex shape of the electrothermal model (full line) follows more closely the test waveform than the flat or concave shape of the basic model (dashed line). Indeed, thermal effect takes into account heating exchange time inertia before reaching external die and package interface. Electro-thermal simulation takes this effect and is really close to the real waveform measurements.

3 e-breaker circuit with TVS in parallel study

Standards are given for room temperature but in the automotive segment, ambient temperature variations can be large and different from room temperature. Electro-thermal components models are very interesting for this case. We will see an example with comparison between measurement and electro-thermal and no electro-thermal simulations, for room temperature and above room temperature. In a second part, we will study two TVSs mounted in parallel which are mismatched and see how this works out.

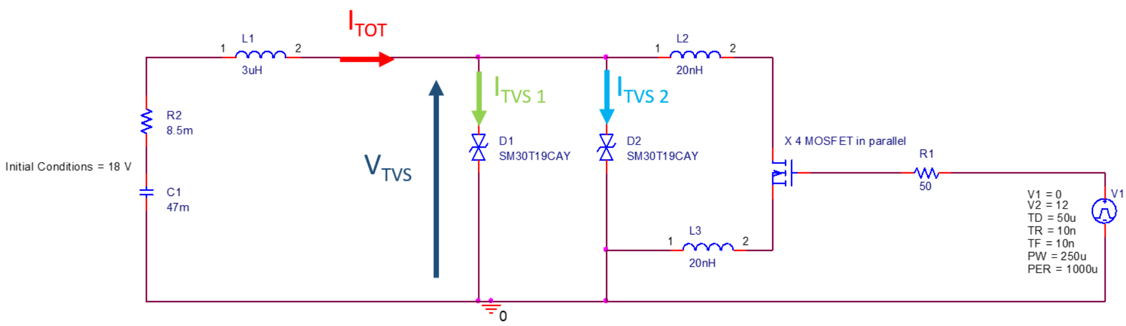
Electrical vehicles development generates more and more electronic functions. In particular, mechanical relays are replaced by e-breaker functions perfomed with MOSFETs. These MOSFETs switches are driven to open state in case of short-circuit or over-current detection. Due to stray inductance (harness), an over-voltage is applied across the MOSFET when the current is turned-off. The over-voltage can damage the MOSFET when the absolute maximum rating is exceeded: TVSs are mandatory to protect it. Once again, this e-breaker function can be simulated and the main point is to check if the residual voltage during pulse does not reach MOSFET absolute maximum rating (AMR). For this purpose, several TVSs can be used in series or parallel or series-parallel to get the best ratio V_{BR} / V_{CL}. Of course, ambient temperature has to be taken into account as this function can be placed in different car locations. Indeed, the ambient temperature impacts also waveform behavior.

Here is comparison between electro-thermal TVS e-breaker at room temperature and with ambient temperature equal to 115°C.

3.1 e-breaker at room temperature

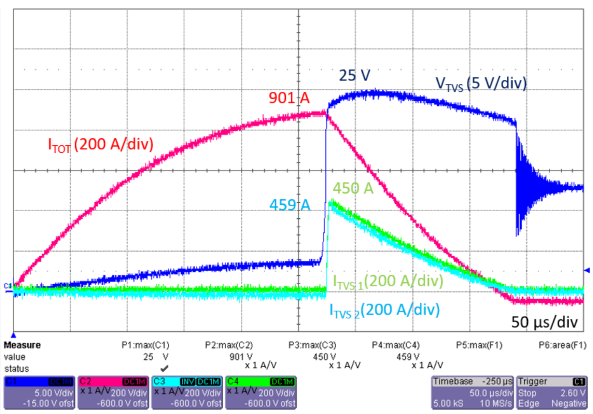
To simulate the e-breaker, 4 MOSFETs in parallel are turned on few hundred of microseconds to reach a high-level current, around 900 A. Then, these MOSFET are turned off. Energy stored in inductance emulates the harness length (3 µH corresponds approximately to 3 meters), and creates an over-voltage clamped by 2 SM30T19CAY in parallel. Here is the schematic (see Figure 23).

Figure 23. Schematic to emulate the e-breaker function



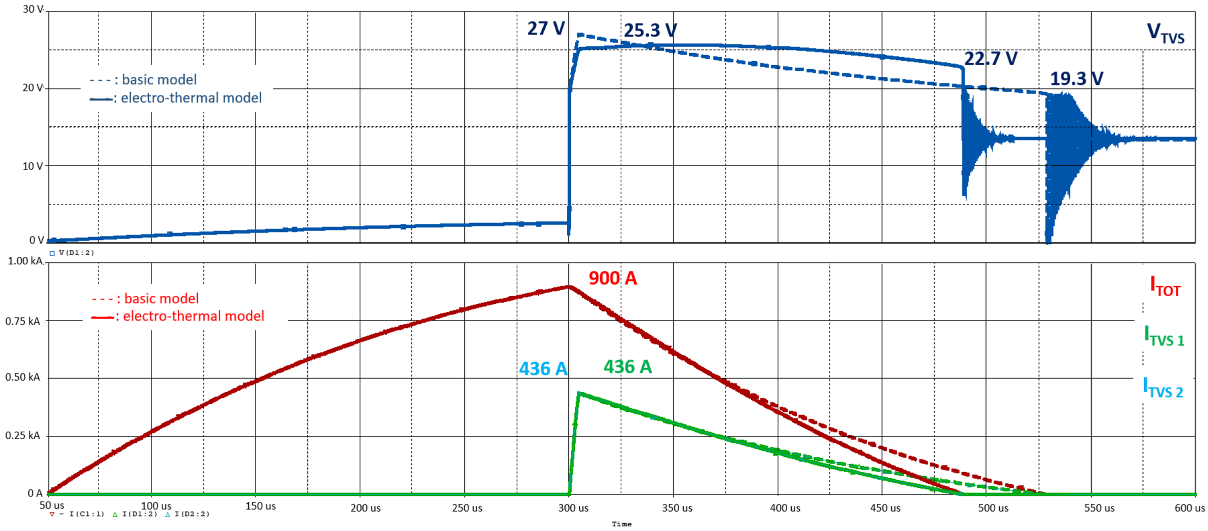
Waveforms at room temperature show that TVS clamp over-voltage at 25 V (see Figure 24).

Figure 24. Waveforms for e-breaker function with the blue waveform to show the clamping voltage



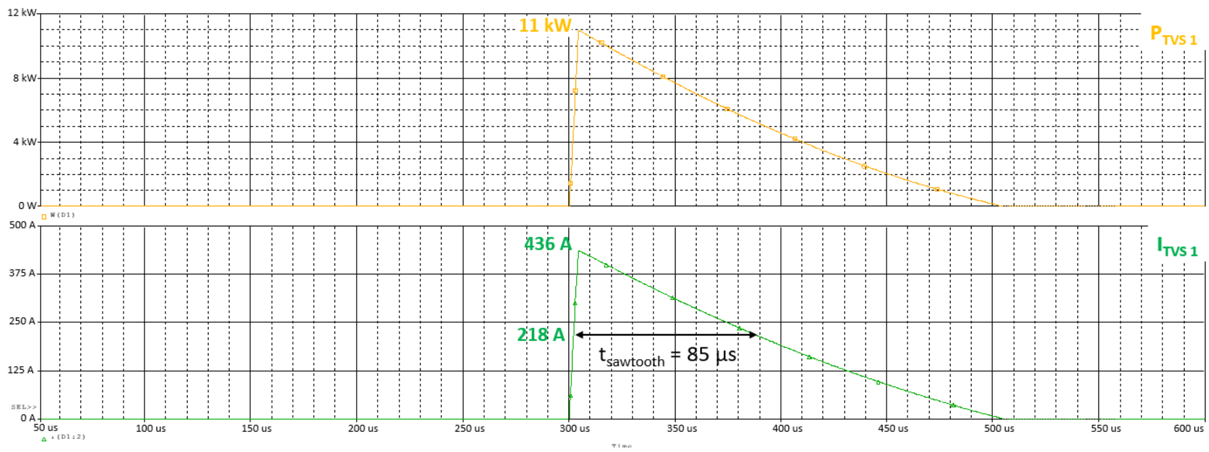
Simulations with electro-thermal SM30T19CAY models show equivalent results and behavior (full line) in comparison with basic models which gives a different clamping voltage waveforms (dashed line) (see Figure 25).

Figure 25. Simulated waveforms for e-breaker



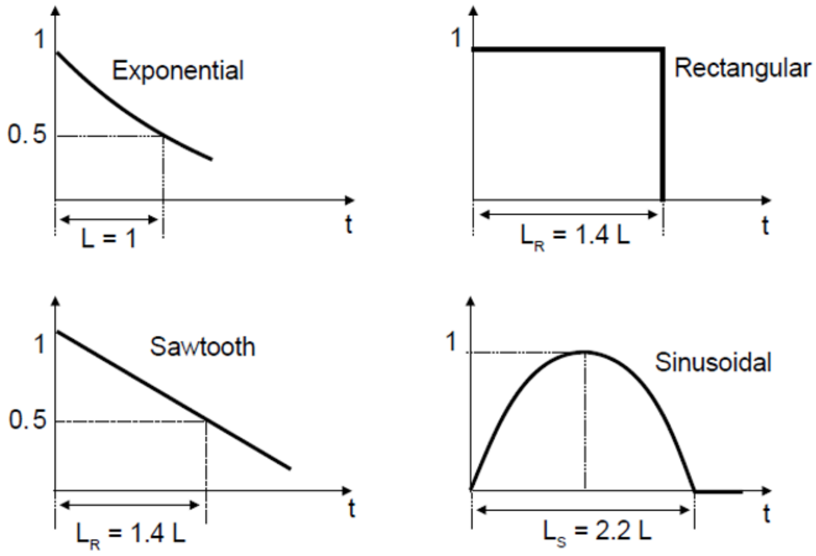
Once again with accurate simulations, we can check easily the power capability of the TVS, using the power waveform, and getting the tp value from sawtooth duration on current simulated waveform (inductance current discharge gives a sawtooth current waveform)(see Figure 26).

Figure 26. Simulated current and power waveforms for one of both SM30T19CAY (TVS 1 in schematic which correspond to D1 in simulation)



Then, we can transform the sawtooth current waveform to exponential waveform, thanks to figure 5 of AN316. (see Figure 27).

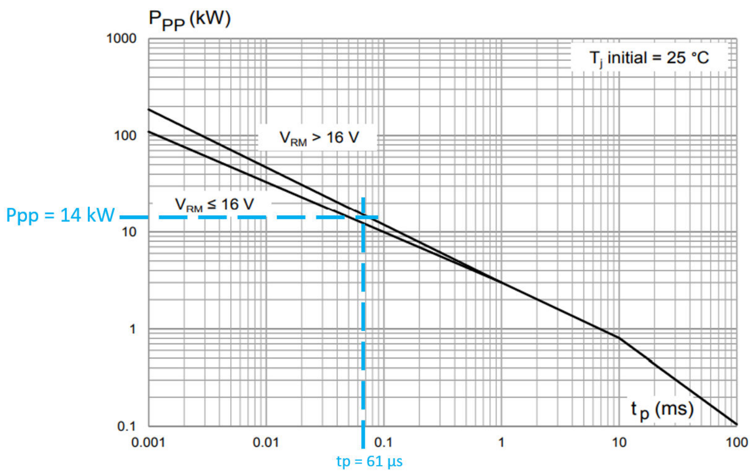
Figure 27. **Pulse duration equivalence factors for same power dissipation**



$$t_P exponential = \frac{t_{sawtooth}}{1.4} = \frac{85\ \mu s}{1.4} = 61\ \mu s \tag{1}$$

From figure 4 of SM30TY datasheet, t_P exponential calculated (61 µs) shows an admissible power of 14 kW (see Figure 28). The peak power from simulation being 11 kW, we can confirm that SM30T19CAY is suitable.

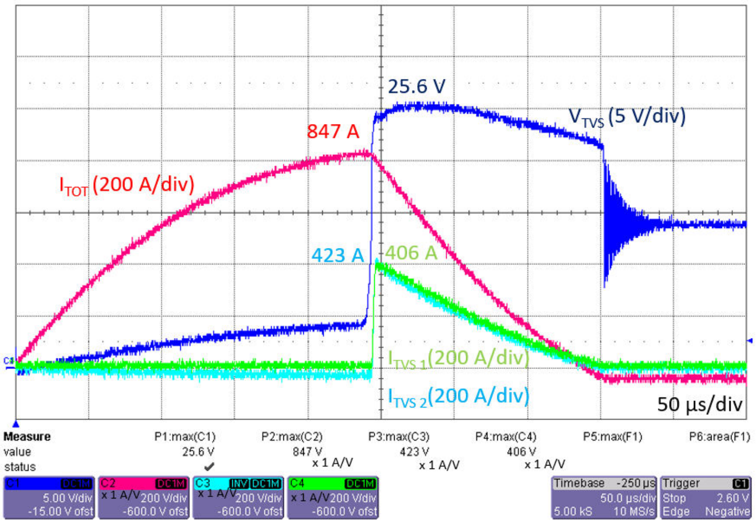
Figure 28. **SM30TY "Maximum peak pulse power versus exponential pulse duration" extract of datasheet**



3.2 Ambient temperature e-breaker

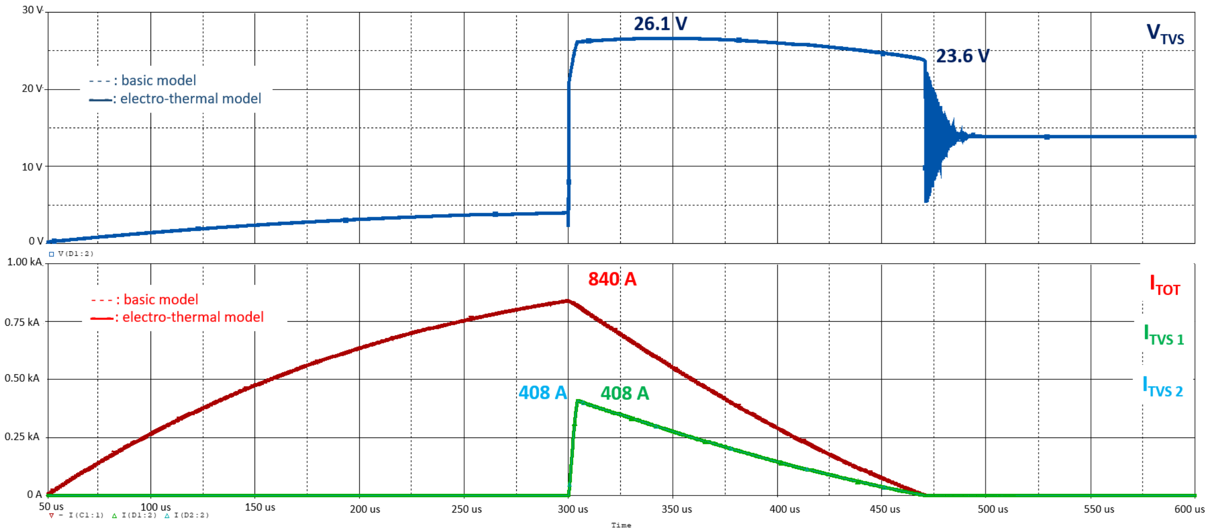
Ambient temperature is an important constraint in automotive and must be taken into account. The same measurement has been performed for T_{amb} = 115 °C. Here are waveforms (see Figure 29) for same schematic given in Figure 23 above: clamping voltage has increased as breakdown voltage has a positive thermal temperature coefficient. (ie for SM30T19CAY, the maximum $\alpha T = +8.8.10^{-4}$/°C given in SM30TY table 2 datasheet).

Figure 29. Waveforms for e-breaker function at ambient temperature equal to 115 °C



Simulations results for e-breaker function at 115 °C (see Figure 30) give an equivalent clamping voltage value and waveform, when using with electro-thermal SM30T19CAY PSPICE models.

Figure 30. Simulated waveforms for e-breaker function at 115°C ambient temperature



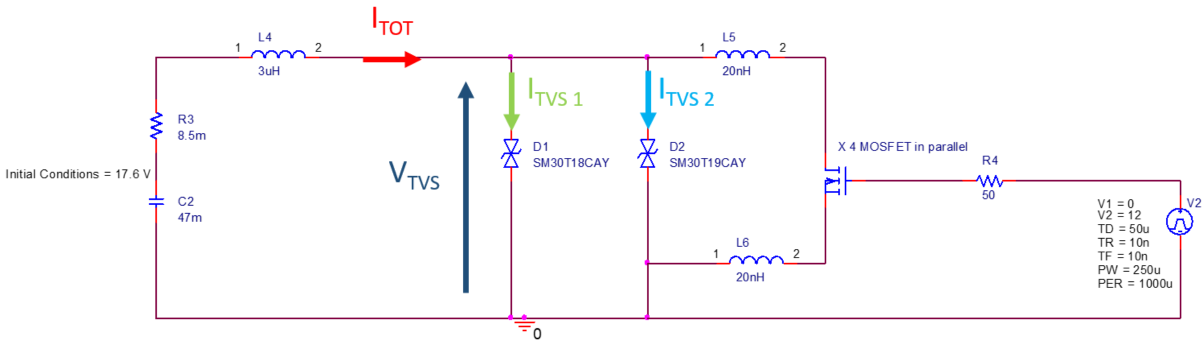
3.3 Process dispersion

When TVSs are in parallel, one question is the behavior when their breakdown voltages are not strictly identical. This difference is due to process and lot dispersions. Here, with the previous test schematic, we have the possibility to change one of SM30T19CAY to a SM30T18CAY to simulate dispersion:

- SM30T19CAY V_{BR} value is 18.5 V (curve tracer measured), very close to typical V_{BR} given in SM30T19CAY datasheet
- SM30T18CAY V_{BR} value is 17.6 V (curve tracer measured), almost equivalent to minimum V_{BR} given in SM30T19CAY datasheet

We can then perform same test with this schematic (see Figure 31).

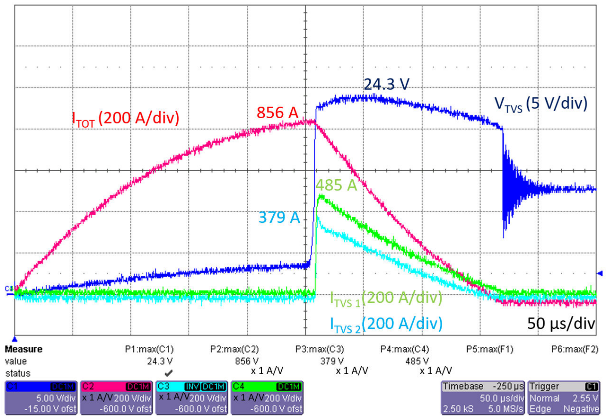
Figure 31. Schematic to emulate the e-breaker function with TVSs showing a V_{BR} difference



Experimental waveforms (see Figure 32) show the behavior:

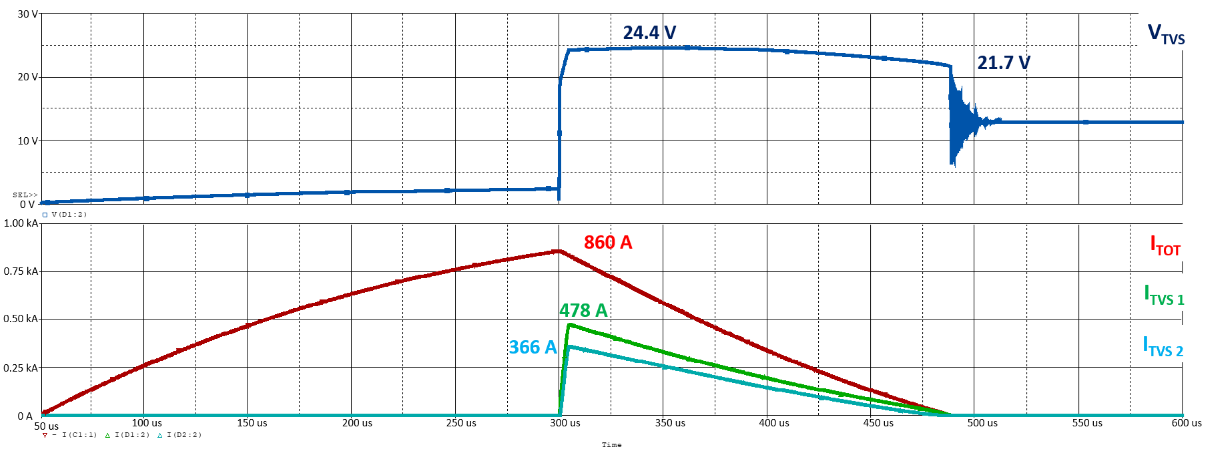
first, the lowest TVS V_{BR} value (D1: SM30T18CAY, green current waveform) is beginning to clamp. As thermal coefficient is positive, V_{BR} value increases and reaches very quickly the second V_{BR} TVS value (D2: SM30T19CAY, light blue waveform). The second TVS starts to conduct in addition to the first one. With electro-thermal TVS PSPICE models, it is possible to reproduce this behavior and then, study the power capability for each TVS, very easily.

Figure 32. Waveforms at room temperature for e-breaker with V_{BR} TVS difference



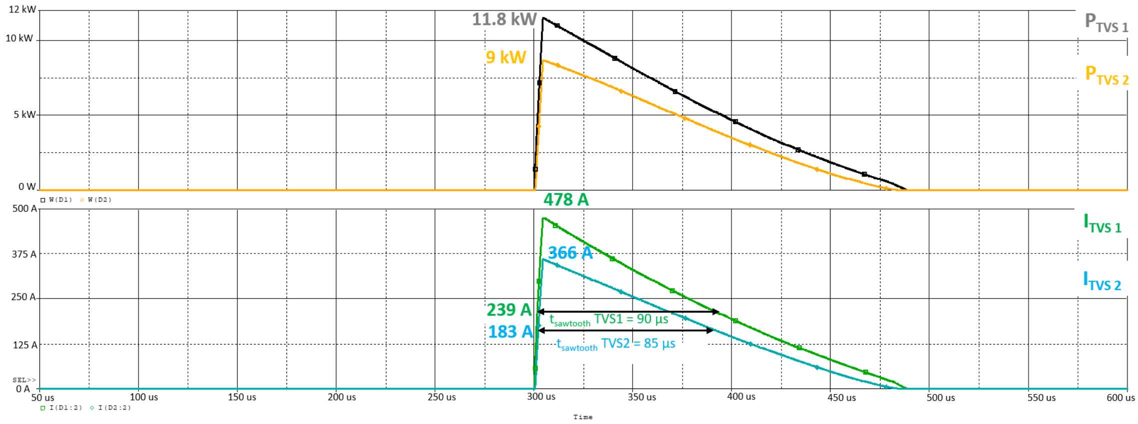
Electro-thermal simulations show same behavior (see Figure 33).

Figure 33. Simulated waveforms with V_{BR} TVS difference for e-breaker at ambient temperature (27 °C)



We can extract the power waveform for each TVS (see Figure 34) and check as done previously the power capability for the worse case: TVS 1 with lower V_{BR} value and with $t_{sawtooth}$ = 90 µs.

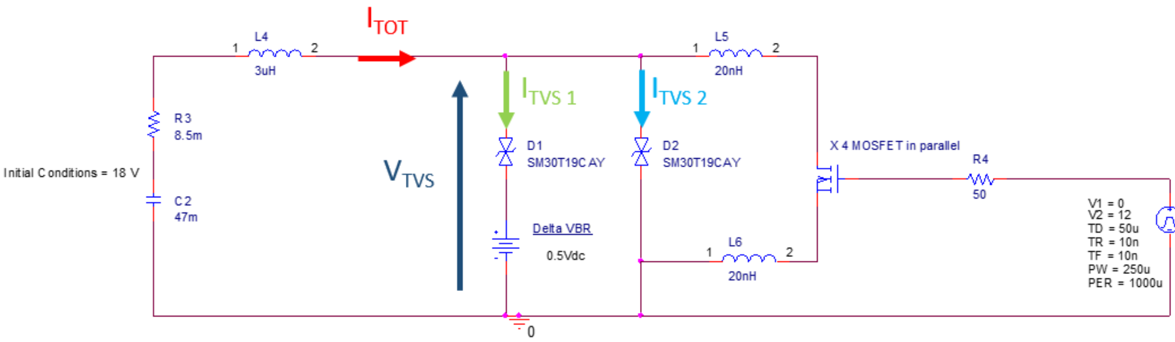
Figure 34. Simulated current and power waveforms for both TVS with V_{BR} difference



Sawtooth current waveform duration is transformed to exponential waveform thanks to figure 5 of AN316 (see Figure 27): we calculate t_P = 64 µs. With the maximum peak SM30TY pulse power versus exponential pulse duration curve (see Figure 28), we can check for t_P = 64 µs that TVS is able to withstand around 13 kW of dissipated power which is higher than the simulated power (11.8 kW).

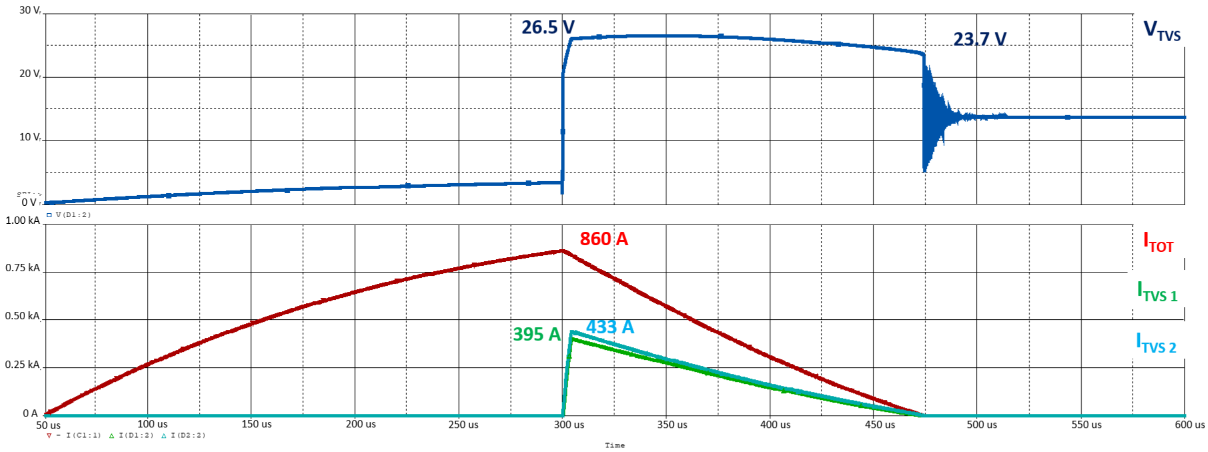
Here, with SM30T19CAY and SM30T18CAY electro-thermal PSPICE models, we simulated accurate behavior and electrical values with 1 V of breakdown voltage dispersion. Same simulations can be done with lower or higher breakdown voltage with DC voltage generator in series with one of TVS, as shown in the schematic below (see Figure 35) and this, at room temperature or other ambient temperature.

Figure 35. Simulated schematic with V_{BR} difference added with V_{DC} voltage generator (delta V_{BR})



For example, with a breakdown voltage higher of 0.5 V, we get the simulation waveforms at 85 °C ambient temperature (see Figure 36):

Figure 36. **Simulated waveforms with V_{BR} TVS difference of 0.5 V (DC voltage added in series with one of TVS) for e-breaker function at 85 °C ambient temperature**



Thanks to electro-thermal PSPICE TVS models, electrical simulated current and voltage waveforms are more accurate and we give a higher confidence in the results for a first approach before real tests.

4 Conclusion

This application note demonstrates that electro-thermal STMicroelectronics TVS PSPICE models, designed and fine-tuned for our planar technology, significantly improve accuracy compared to basic PSPICE models. This has been shown through various simulations and measurements with different pulse stresses, including automotive and standard exponential pulses, at different ambient temperatures and for various applications.

These electro-thermal models enable designers to verify TVS suitability, such as residual voltage and power capability, for parallel or series topologies, to check variation taking into account V_{BR} dispersion for example.

With accurate simulated results, designers can quickly and easily select the appropriate TVS for their application requirements, saving both time and money.

Appendix A

A.1 Limitations of the models

Models presented here trade off accuracy with simplicity and simulation convergence and so, present some limitations:

- For some TVS family, leakage current value is not fully compliant with datasheet in particular for breakdown voltage (V_{BR}) higher than 30 V. Leakage current remains below than 1 µA at 25°C
- In some TVS topologies (series, parallel) and complex schematic, simulation divergence could happen. Different solutions can be applied:
  - “Maximum step size“ has to be fixed with a value
  - Fix only one ambient temperature (if simulations diverge with several ambient temperatures)
  - “Auto-convergence” option can be used
- Simulated breakdown voltage (V_{BR}) is the typical value given in datasheet, but using a DC voltage generator in series, simulation can be performed to:
  - Emulate the maximum or minimum V_{BR} given in datasheet
  - Mismatch V_{BR} in case of series-parallel topologies
- Clamping voltage is limited and remains at a constant value when silicon temperature reaches outlier due to excessively high electrical stresses and/or ambient temperature

Although simulation is a very important tool to evaluate the device’s performance, the exact device’s behavior in all situations is not predictable, therefore the final laboratory test is necessary.

PSpice models describe the characteristics of typical devices and don't guarantee the absolute representation of product specifications and operating characteristics; the datasheet is the only document providing product specifications.

Revision history

Table 1. Document revision history

Date	Revision	Changes
22-Oct-2021	1	Initial release.
16-Nov-2023	2	Updated Figure 24, Figure 26, Figure 28, Figure 30, Figure 33, Figure 34, and Figure 36.

Contents

List of figures