ESD307-U1-02N ESD311-U1-02N

Efficient Surge/ESD protection for charging lines in mobile devices

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Page	**Subjects (major changes since last revision)**
16	Chapter 5 added, general update

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1 Customized Surge and ESD Protection for USB V_{BUS} Line

Over the last years, enormous amount of mobile devices, Set-Top-Boxes and Smart-TVs have been brought into the market. Most such devices support USB2.0/3.0 as Data Exchange Interface. Most mobile devices such as mobile phones, phablets, tablets, navigators and smart-watches use USB Interface to provide connectivity to other electronic devices and for charging purposes. Generally for all plug-in/plug-out electronic interfaces, electrostatic discharge (ESD) and surge discharge are widespread threats. An overvoltage failure caused by such a strike can hit the interface connectors directly or hit the internal electronic circuits via the user interface. This interface can be a keypad, touch screen, LC-display or LAN-Cables connected to the desktop stations.

The effect of these ESD/Surge strikes can be permanent performance degradation or even a destruction of the interface circuit, resulting in a failure of the entire electronic device. Therefore a reliable combination of ESD and surge protection is obligatory and should be taken into account from the very beginning of the electronic device's design phase.

ESD protection is integrated inside the IC too – but only for device handling protection. To protect the equipment in the field, a smart ESD/Surge protection approach distributes the failure current between a tailored external ESD/Surge protection circuit and the small ESD protection in the IC. The internal ESD protection structure can be very small because it has to handle only weak ESD strikes e.g. (2kV HBM), which may occur during manufacturing and board assembly (refer to Figure 1).

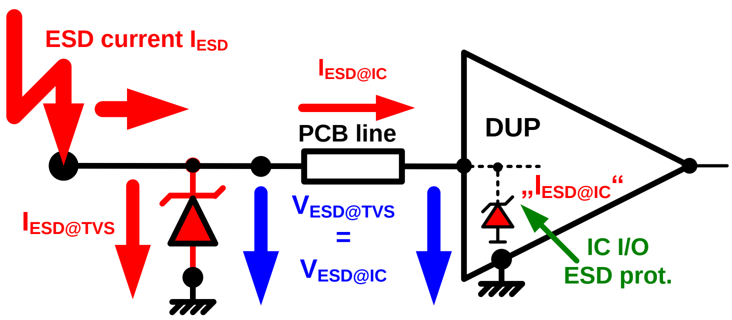


Figure 1 ESD/surge current distribution via ESD/surge diode and IC based ESD protection

Moving forward in miniaturization of semiconductor structures, ESD/Surge handling capability of miniaturized semiconductor structures is reduced accordingly. Today, I/Os are tailored to be 2kV ESD safe according to HBM (Human Body Model - JEDEC standard JS-001.). Safety margin is reduced more and more moving forward from one technology node to the other.

To achieve SURGE protection capability, a combination of external ESD/surge protection is mandatory anyway to handle the huge dissipated energy generated by the surge strike impact. An IC with built-in surge handling capability would require an extension of expensive IC chip area. Finally, chip area to realize basic functionality would be the minor one.

The combination of external ESD/surge diode with internal ESD handling protection keeps the high required ESD/Surge protection capability alive. The required ESD/Surge structure on the die is minimized. Furthermore this two-step ESD/Surge approach enables the designer to pass high system level ESD/Surge requirements according to IEC61000-4-2 and IEC61000-4-5. Various applications demand different ESD/Surge protection devices. So the selection of the right ESD/surge diode is tailored to the application and to the internal IC based ESD protection circuit.

2 Over-voltage protection in a mobile device extended with a Surge protection TVS diode

2.1 Surge Transients

Commonly a surge discharge is an unwanted electrical transient, transmitting high amount of energy and can show an amplitude of several hundred volts. For device characterization, a dedicated reference surge pulse waveform is postulated providing a similar energy as the real transients hiding the device (e.g. USB VBUS line).

For the so called “short circuit 8µs/20µs” reference surge pulse, we are facing an entire pulse duration of less than 100µs. Other norm surge pulses show a “5µs/360µs” and a “10µs/700µs” characteristic and provide much higher energy to the subsequent device.

In the following discussion we are discussing about the “short circuit 8µs/20µs” surge strike stated in IEC61000-4-5.

The surge, also known as glitch, can have either positive or negative polarity. Significant overshoot and / or undershoot in reverse polarity is also possible. Such voltage surges often occur in unstable power networks between building networks. Furthermore, surges on the Vcc line can be generated in case of load alternation. Surge transients can damage, destroy and cause malfunction of any personal, commercial electronic as well as any industrial facilitiy.

A basic origin of a surge is power switching between the electrical units inside facilities or buildings such as household appliances or their switch mode power supply (SMPS). Power switching of electrical loads (On/Off-State) may not result in a surge of enormous energy but due to their frequent presence, they may damage the equipment over some period of time. Common sources of surge from the outside networks are, lightning events and power surges on the LAN cables and their transformer units. Most of the recent high-end mobile phones use a wall-plug USB-adapter **to charge/fast-charge/ultra-fast-charge** their battery cells. Plug-in and plug-out of the USB cable in the USB-adapter results in power switching (load alternation) in the DC/DC converter module followed by a surge on the VBUS-Line.

2.2 What is OVP and how does it work?

For a mobile device, the Over-Voltage-Protection (OVP) is a mandatory feature. The OVP functionality can be implemented in a dedicated OVP IC, direct at the Vbus input, or integrated in the charger IC or in the Power-Management-Unit (PMU). The job of the OVP is to separate the subsequent low voltage section e.g. charger unit, or PMU in case of an overvoltage on Vbus.

Such an OVP basically consists of a Field-Effect-Transistor (FET) connected in series and a built-in control unit (comparator) which senses the input voltage and controls the gate region of the transistor. In case the input voltage rises above the adjusted threshold, the control unit switches the FET in open state to turn the subsequent circuit structure (e.g. PMU) into unpowered mode and protect it from the overvoltage transient on the USB VBUS Line.

Optionally OVPs protect battery cell from unintentional discharge by blocking any reverse-current from a battery cell.

Limitation of input voltage for the OVP functionality is based on the semiconductor process used. In typical designs, often a maximum input voltage $V_{IN\text{-}max}$ of about 25V…30V is stated. Exceeding this range, the OVP block will be damaged (Figure 2).

In case of a surge event, charging voltage on the Vbus line rapidly rises and the FET is switched off. Finally the transient voltage on the Vbus line exceeds $V_{IN\text{-}max}$ and will damage the OVP section. Furthermore the internal FET can move into conducting mode and the surge is transferred to the subsequent PMU. The PMU is not designed to withstand any voltage higher than the charging voltage and will be damaged immediately as well.

Therefore it is highly recommended to use an appropriate surge Protection mechanism in USB Charging Chain consisting of a TVS Diode in addition to the OVP Unit. As a result of having a TVS Diode connected in front of the OVP function block to GND, the surge pulse is facing NO open-circuit (provided by the serial MOSFET) any more. The surge energy is shunted to GND. The surge clamping voltage @ the OVP input is controlled by the TVS diode characteristic and MUST not exceed the maximum working voltage of the OVP.

Specification of the surge TVS diode is given for the “8µs/20µs” use-case. For a stated maximum peak surge current, peak clamping voltage should be minimized.

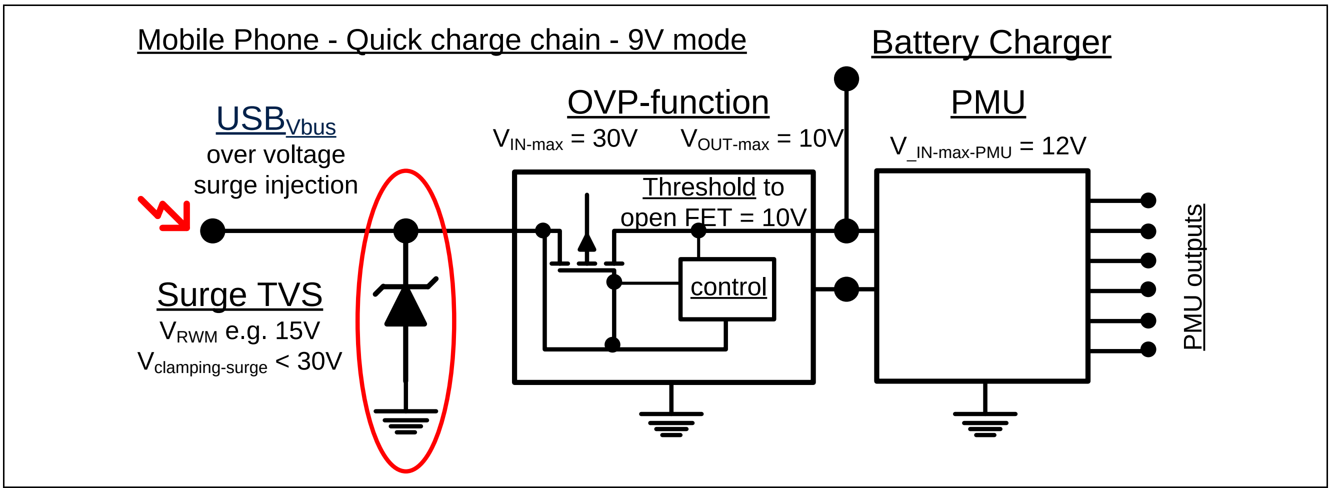


Figure 2 USB charging chain in the Mobile Phone for the Quick Charge 9V mode

Maximum required working voltage of the surge TVS depends on the application. From system point of view the TVS diode characteristic is defined in this way:

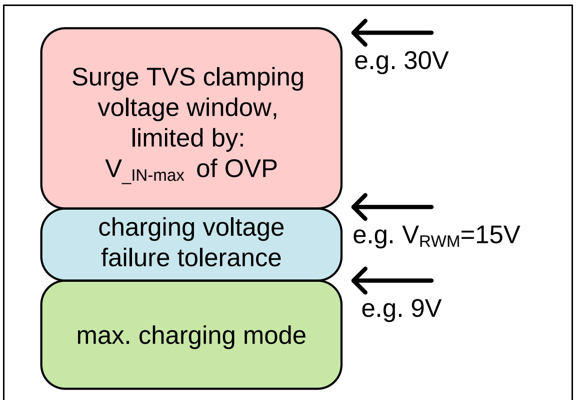
1. Maximum TVS surge clamping voltage V_{peak_max} @ requ. surge current I_{peak} < $V_{in\text{-}max}$ of the OVP
2. Maximum working voltage V_{RWM} of TVS > max charging voltage / maximum threshold voltage of OVP

Charging voltage is defined according the charging mode

- Standard: 5V, 0.5A typ. up to 1.5A
- Quick-Charge 1.0/2.0: 5V/9V/12V/20V (Notebook), up to 5A
- USB-Power Delivery (PD): 5V/9V/12V/20V (Notebook), up to 5A

The TVS diode is a device to protect the OVP function regarding short transient e.g. ESD, surge strikes, but is not able to handle a faulty charger DC voltage. This job is served by the OVP function up to maximum input voltage of the OVP ($V_{in\text{-}max}$).

Taking a certain DC charging voltage failure on the V_{bus} line into account (OVP and TVS are in isolating mode), maximum working voltage of the TVS (V_{RWM}) should be considerably higher than the nominal maximum charging voltage, BUT surge clamping voltage must be lower than the stated $V_{IN\text{-}max}$ of the OVP unit to avoid any destruction of the OVP (requirement #1)



Example:
For a standard 5V charging, V_{RWM} should be about 10V…12V (ESD307).

In case of fast charging, V_{RWM} of the Surge TVS diode has to be adjusted above the highest threshold voltage of the OVP, defined by the highest fast-charging mode.

For a 9V quick charge mode the ESD311 fits perfect.

Figure 3 Correlation between charging mode and TVS characteristic

3 Uni-directional TVS diode ESD307-U1-02N and ESD311-U1-02N

These **uni-**directional TVS diodes are designed for a wanted signal between ~0 V and their “maximum working voltage”. The ESD protection capability is granted for a **uni**-directional diode for positive **AND** negative ESD strikes in the same way. Most standard data signaling, Vcc supply, are unidirectional signals. As long as the signal is maintained between zero and its maximum voltage, the diode is switched off. By exceeding its value all signal line content, accordingly wanted signal plus failure current, are driven through the diode into ground. In case of a negative failure current, every signal with amplitude higher than 0.7 Volts is driven through the diode into ground.

3.1 Features of the ESD307-U1-02N

• ESD / Transient / Surge protection according to:
– IEC61000-4-2 (ESD): ±30 kV (air / contact discharge)
– IEC61000-4-4 (EFT): ±80 A (5/50 ns)
– IEC61000-4-5 (surge): ±34 A (8/20 µs)
• Uni-directional working voltage up to V_{RWM} = 10 V
• Low capacitance: C_L = 270 pF (typical)
• Low clamping voltage V_{CL} < 24 V
• Low leakage current I_R = < 100 nA (typical)
• Small and flat-profile SMD plastic package: 1.6 mm x 0.8 mm x 0.375 mm.
• Pb-free (RoHS compliant) and halogen free package

3.2 Features of the ESD311-U1-02N

• ESD / Transient / Surge protection according to:
– IEC61000-4-2 (ESD): ±30 kV (air / contact discharge)
– IEC61000-4-4 (EFT): ±4 kV / ±80 A (5/50 ns)
– IEC61000-4-5 (surge): ±28 A (8/20 µs)
• Uni-directional working voltage up to V_{RWM} = 15 V
• Low capacitance: C_L = 210 pF (typical)
• Low clamping voltage V_{CL} < 29 V at I_{PP} = 28 A
• Low leakage current I_R = < 100 nA (typical)
• Small and flat-profile SMD plastic package: 1.6 mm x 0.8 mm x 0.375 mm.
• Pb-free (RoHS compliant) and halogen free package

3.3 IEC61000-4-5 Surge and TLP characteristics of the ESD307 and ESD311

Below a 8µs/20µs “short circuit” and TLP discharge characteristic presented.

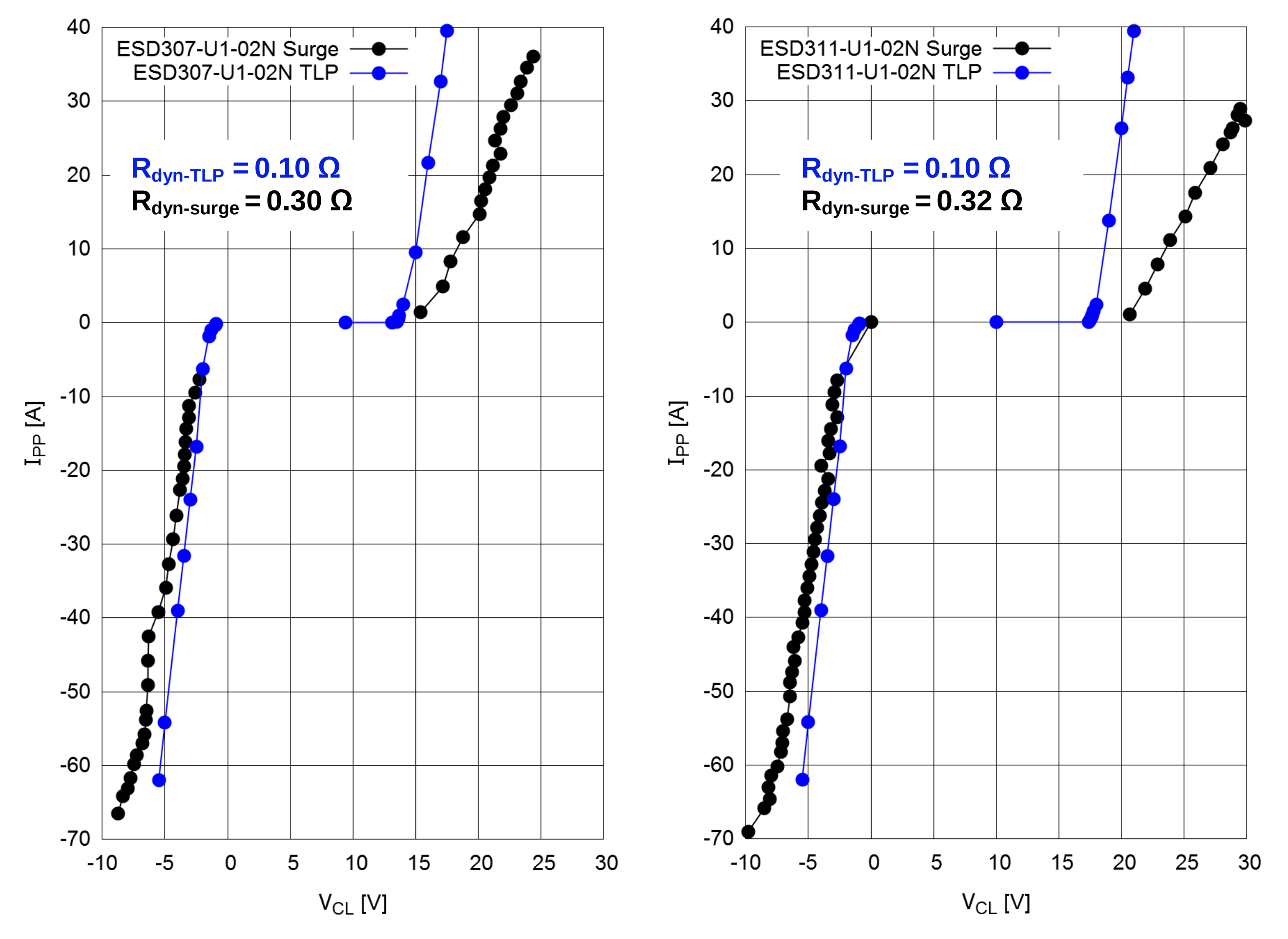


Figure 4 IEC61000-4-5 Surge and TLP characteristics of the ESD307-U1 and the ESD311-U1

The dynamic resistance $R_{dyn\text{-}surge}$ in case of IEC610004-5 8µs/20µs surge test is significant higher compared to the dynamic resistance evaluated in IEC61000-4-2 test or in the TLP test. The increase of $R_{dyn\text{-}surge}$ is caused by self heating effects of the TVS/surge diode because of the long surge pulse duration (according IEC61000-4-5). For an ESD strike according IEC61000-4-2 or an TLP pulse the generated heat is much lower (because dissipated energy of an ESD strike is much lower) and limited to a certain small chip area only. For surge testing, dissipated energy is spread inside the entire chip and is fed to the leads. The heating effect of the chip and especially the active chip area is much higher in case of a surge strike. For surge robustness a package showing low thermal resistance is very important.

4 Design of Experiment and Simulations

4.1 Simulation of IEC61000-4-5 “short circuit 8µs/20µs” Surge Current Discharge

The surge specification IEC61000-4-5 covers several different test scenarios. In one scenario, we have the surge tests working with a pulse length (pulse comes down to 50% of peak value) of 20µs (short circuit) and 50µs (open circuit). Another scenario shows a much longer ESD strike duration. Here the surge strike should emulate the effect of a lightning. The pulse length is 700µs (open circuit) and about 350µs (short circuit). The rise time of the “lightning” strike is up to 10µs. Based on their very long pulse duration the energy of such pulses is extremely high .

In this subsection, the working principle of the ESD source / -generator according IEC61000-4-5 “short circuit” 8µs/20µs is explained. The ESD test generator shown as a black box model, connected to the DUT (Device Under Test) is presented in the Figure 5. To judge the exact waveform of the surge strike, a 1 Ohm resistor is used for the DUT.

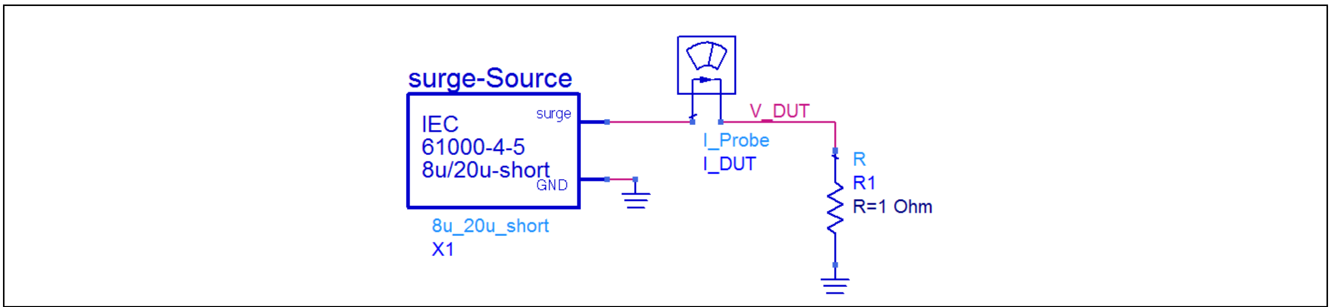


Figure 5 Schematics of the Surge Generator connected to the DUT (1Ohm resistor).

The electrical equivalent circuit of the IEC61000-4-5 combined surge generator for a short current waveform (8µs/20µs) and an open circuit waveform (1.2µs/50µs) is shown in Figure 6.

Internal and external wire connection adds about 0.5…1 Ohm serial resistance (R_cable) at the generator output. Taking this into account, the generator output resistor (in front of R_shunt) is about 2 Ohm. This fits exactly with the output resistance specification of an IEC61000-4-5 combined wave surge generator.

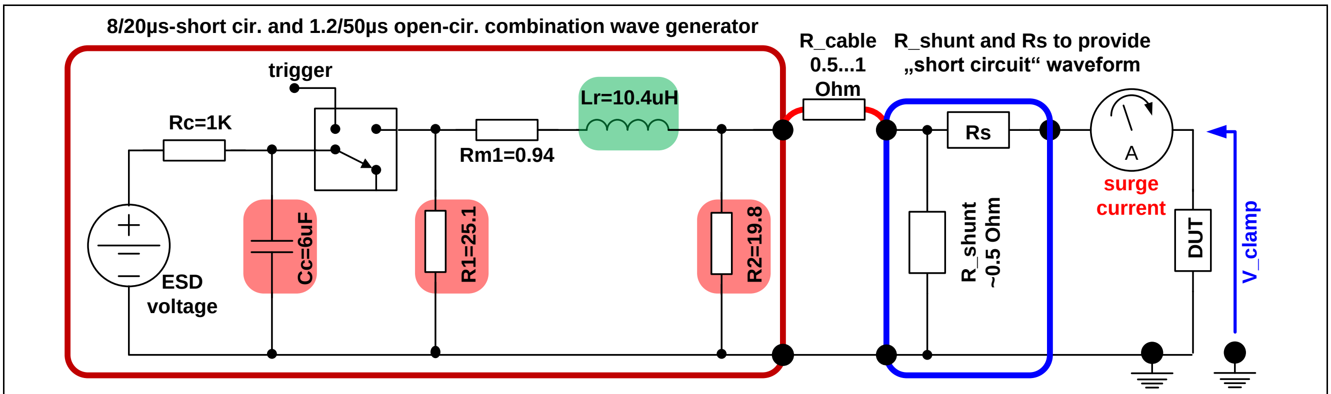


Figure 6 Functional structure of the 8/20us Surge Generator short circuit version.

To generate the exact waveform in “short circuit mode” an assisting “R_shunt” (~0.5 Ohm) is necessary to provide a “defined short” independent of the DUT impedance.

The lower the R_cable and the shunt resistance are, the higher the under-swing will be. In most real test-equipment, there is NO or only a minimum under-swing. An “under-swing” is not mandatory but possible up to 30% respective peak level in IEC61000-4-5 specification for 8µs/20µs “short circuit” surge strike.

To adjust the surge current to the required test range, a serial resistor is placed in front of the DUT. Furthermore the surge current into the DUT can be measured in an easy way via the serial resistor.

Finally the “short circuit” surge current waveform according IEC61000-4-5 is simulated and the dissipated power in the DUT caused by the (8µs/20µs) Surge pulse is presented. The dissipated power is presented in Watt and normalized to 1 Ohm DUT/Load resistance. The total energy of the ESD discharge is calculated and given in MILI-Joules. The simulated waveforms are illustrated in Figure 7. The voltage drop / clamping voltage across the DUT is monitored as well.

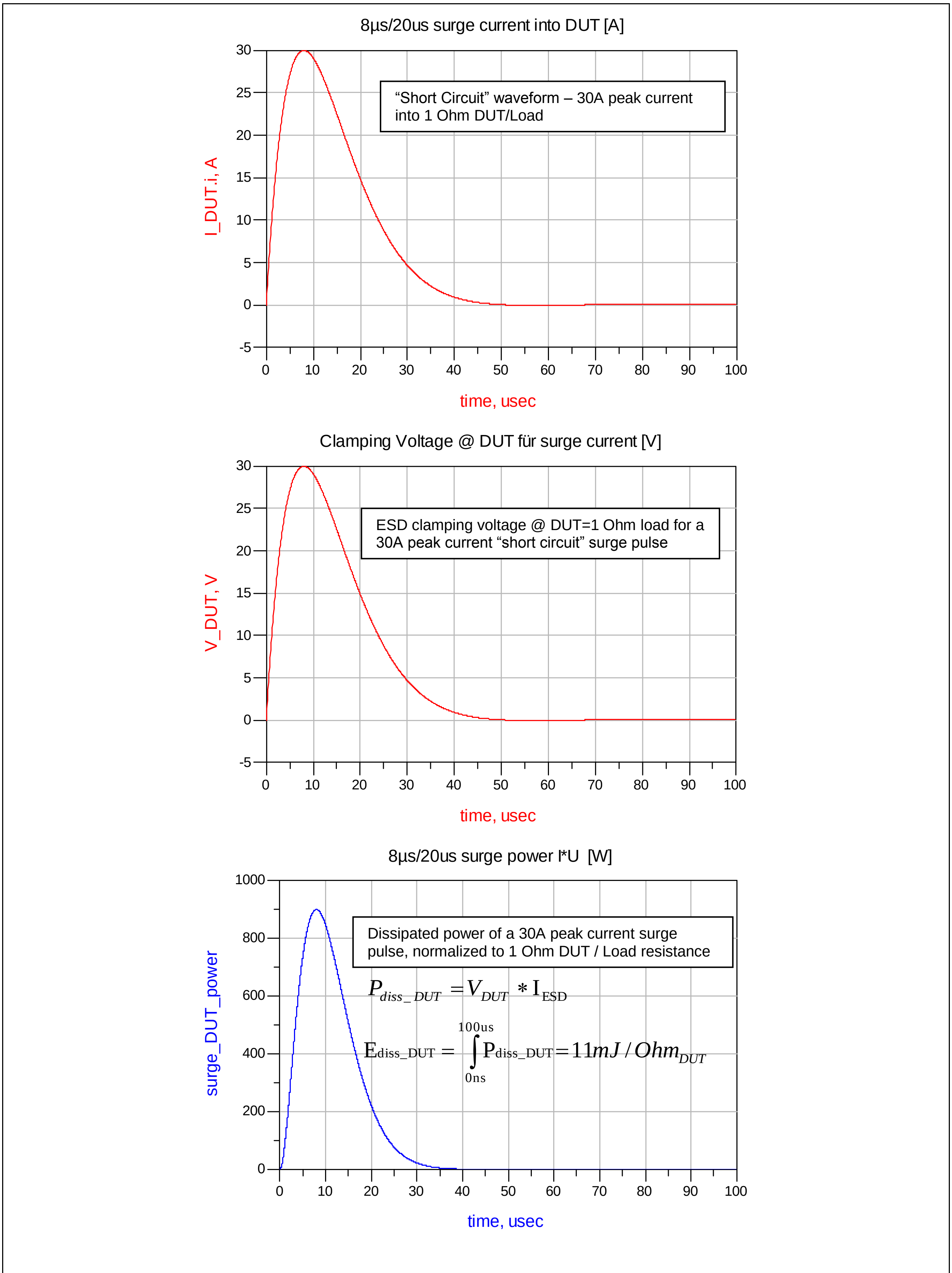


Figure 7 Surge current,- clamping voltage, dissipated power and energy simulated for a DUT of 1 Ohm

4.2 Simulation of the Surge clamping voltage across the TVS

The same procedure is done for the surge discharge.

In the next step the 1 Ohm DUT is replaced by the TVS/Surge Diode. The TVS/surge diode ($U_{breakdown}$=12V, $R_{dyn\text{-}surge}$=0.35 Ohm) was tested with an 8µs/20µs surge strike according IEC61000-4-5. Peak surge current was adjusted to 30A. Dissipated power of the surge strike in the TVS/surge diode was calculated. The total energy of the surge discharge was calculated and given in MICRO-Joule. The simulated waveforms are illustrated in Figure 8. The voltage drop / clamping voltage across the ESD/Surge diode is monitored as well.

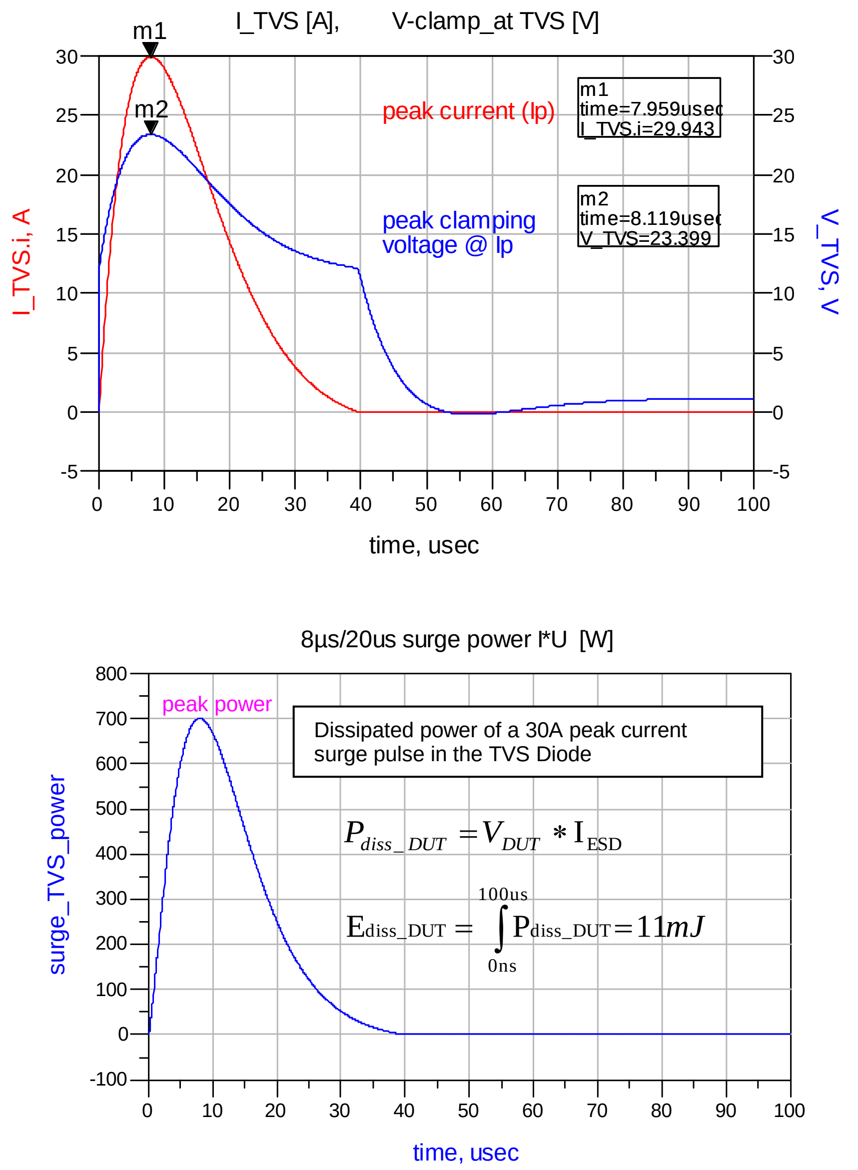


Figure 8 Surge current, Surge clamping voltage, dissipated power and energy simulated for a TVS diode affected with an 8µs/20µs surge strike according IEC61000-4-5

5 Surge Peak Power – the Mystery

As we learned, dissipated power for an ESD/surge diode (DUT) is related to ESD/surge current I_{ESD} through the protection device times clamping voltage (V_{DUT}) across the protection device.

$$P_{diss\_DUT} = V_{DUT} * I_{ESD}$$

Finally the dissipated energy E_{diss_DUT} is the integral of P_{diss_DUT} over time (duration of the surge strike)

$$E_{diss\_DUT} = \int_{0ns}^{100us} P_{diss\_DUT}$$

Peak power is simply the maximum current - I_{peak} - times maximum clamping voltage - V_{peak} –
Because the system is acting resistive, - I_{peak} – and - V_{peak} –are present at the same time (NO phase shift).

Maximum peak power is simply $P_{peak} = V_{peak\_clamp} * I_{peak}$

Comparing two diodes designed for the same working voltage (e.g. 12V). Both diodes can withstand a maximum peak current I_{p_max} of 30A.

- Diode-A is rated with a max. peak power (P_{peak_max}) of 900W,
  Maximum Peak clamping voltage $V_{p\_clamp\_max}$ for diode-A is 30V

  $$P_{peak\_max\_Diode-A} = V_{peak\_max\_Diode-A} * I_{peak\_max} = 30V * 30\,A = 900\ Watt$$

- Diode-B is rated with a max. peak power (P_{peak_max}) of 630W
  Maximum Peak clamping voltage $V_{p\_clamp\_max}$ for diode-B is 23V

  $$P_{peak\_max\_Diode-B} = V_{peak\_max\_Diode-B} * I_{peak\_max} = 23V * 30\,A = 690\ Watt$$

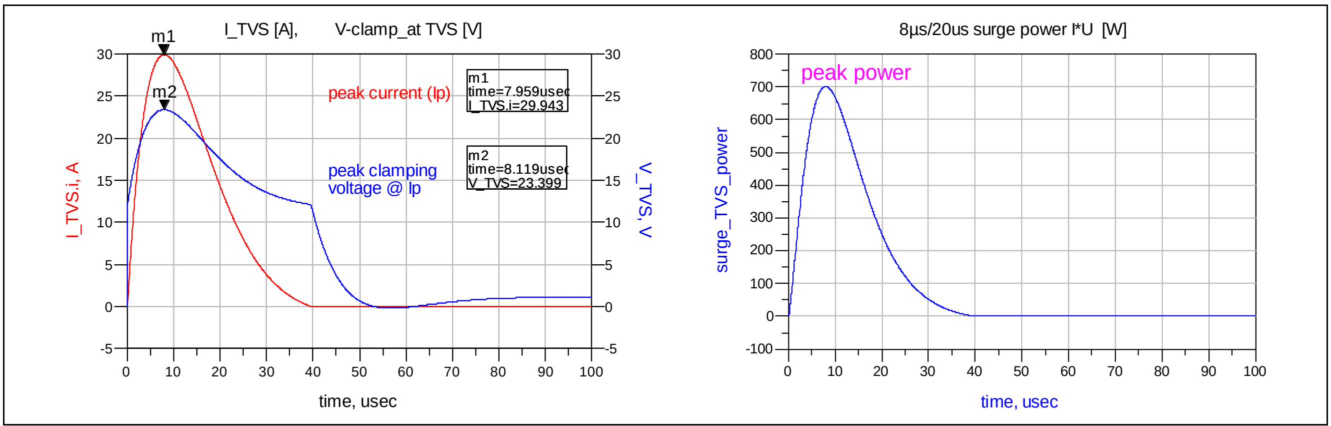


Figure 9 Correlation between I_{p_max} , $V_{p\_clamp\_max}$ and maximal peak power.

It is obvious, diode-B shows higher surge protection performance, because $V_{p\_clamp\_max}$ at given I_{p_max} is lower. The lower V_{p_clamp} is, the lower the residual surge stress is for the subsequent device e.g. I/O port is.

Diode-B shorts the surge energy better to GND.

⇨ **It is highly recommended to select diode-B for effective surge protection eventhough the maximum dissipated power is lower for diode-B**

To select a TVS diode for surge protection, the maximum peak power is not the right criteria. It is more important to check the peak clamping voltage at a given peak surge current.

According to Figure 1, it is obvious that the lower the TVS clamping voltage is, lower the clamping voltage (residual ESD stress) at the IC based TVS diode will be.

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