Demystifying surge protection

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As integrated circuits (ICs) become more fragile and industrial environments become harsher, it's no surprise that there's an increasing focus on system reliability.

Oftentimes, input IC specifications are driven by the requirement to survive surges, so any designer of front end inputs, whether power or communication, needs a strong understanding of surge protection. Avoiding equipment damage or performance degradation during electrical overstress events entails selecting ICs with noise immunity, good performance over temperature and wide common-mode ranges.

Proper selection of input ICs and transient voltage suppression (TVS) diodes is central to a robust overall protection scheme. Modern ICs for system inputs and outputs give designers the tools to simplify balancing the need for robust protection against cost and other system trade-offs, but this requires a thorough analysis of the risks and causes posed by surges.

It's often unclear what causes surges in a system or how to design a system that effectively prevents them from causing damage. In this paper, I'll attempt to demystify these transients, discussing what causes them and reviewing International Electrotechnical Commission (IEC) surge regulatory standards. Surge protection is a critical part of the design process. Understanding system protection requirements enables you to better design robust system inputs.

What causes surges?

Multiple unique mechanisms can create surges at the system input. The lack of a common source introduces uncertainty as to what sort of surges a system could experience, with large risk variances depending on the environment. Generally, systems

with the below characteristics have greater risks of exposure to surges:

- Outdoor operation (that can increase proximity to lightning).
- Power inputs operating with high currents or voltages.
- Frequent load changes.
- Equipment that expects to see hot-plug events.
- Long cabling with a higher chance for an induced surge from nearby high-powered equipment.
- Systems with cabling that will run in parallel with other systems (in a conduit, for example).
- Equipment for automotive use that connects to a car battery.

Many product standards define the surge pulses possible for a specific product. The varied causes of surges differs from the more common electrostatic discharge (ESD), which occurs when charge builds up on a foreign object and quickly discharges during contact with a system interface. ESD largely comes from a few well-characterized sources and can discharge onto any exposed interface, regardless of environment. For more information on the causes of ESD, see TI's "ESD Essentials: What is ESD?" video.

A characteristic waveform

Despite multiple causes, many surges have a similar rise time and half-length, simplifying the process of surge modeling. Surges are modeled as a current waveform with a rise time of 8μs and a half-length of 20μs, as defined by the IEC 61000-4-5 standard. A modeled surge is roughly 200 times the length of an ESD event, (modeled by IEC 61000-4-2) which has a 100ns half length. The two waveforms are compared in **Figure 1**.

Due to the longer pulse length, the energy in a surge is many times higher than the energy in an ESD pulse, regardless of the relative magnitude. The higher surge energy content in the waveform increases the importance of proper surge protection compared to ESD protection.

Although the waveform in **Figure 1** models only a current waveform, all surges consist of both a current and voltage component, so the magnitude of the surge can be described in terms of either quantity. During a surge event, either (or both) current or voltage elements can cause damage to the system. To protect against surge events, it's necessary to understand what determines the magnitude of both the voltage and current elements of the surge.

The total energy in the originating event that caused the surge and the proximity of the originating event to the system under test determine the magnitude of the fault voltage. This voltage varies significantly, from as low as 100V for events like hot plugs on smartphone cables to as high as 4kV (or even greater) for major industrial motors driving inductive loads. The proximity to the originating event matters because a distant surge will drop much of its voltage before reaching a protected system.

For example, consider surges caused by lightning strike on a cell tower: antennae in the cell tower and a nearby security camera can see damage from
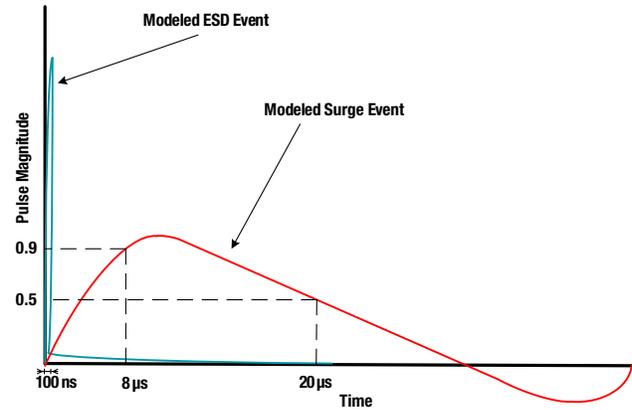

Figure 1. Modeled ESD and surge pulses.

the same lightning strike, but despite the identical originating event, the voltage exposure will vary because of the distance. The antennae will see a huge voltage transient as it's in close proximity to the lightning strike, while the security camera will be exposed to a much lower overvoltage event as the surge has largely dissipated by the time it reaches the camera.

Surge current

To calculate the surge current, divide the voltage waveform by the impedance of the connection between the originating event and the system. You can determine the impedance by looking at the electrical connection between the origination of the surge and the protected line. If the surge originates directly on the pin of an interface, the impedance will be very low; if the surge originates on the other end of a long cable, the impedance will be higher. For direct surges where the originating event is electrically connected to the system, the impedance will always be relatively low.

High impedance occurs when the surge originates near the system, such as in a neighboring cable, rather than directly on it. In this case, there is no direct electrical connection, but there is an inductive effect that causes the surge to couple onto the protected line. This inductive coupling can be modeled as a large impedance, lowering the fault

current relative to a given fault voltage. **Figure 2** shows an example of inductive coupling, where a current surge on the left wire creates a magnetic field that induces a reverse current surge on the right wire.
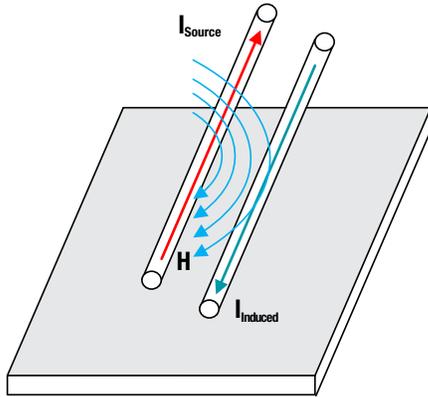

Figure 2. Inductively coupled surges.

Let's look at a motor that switches off abruptly, causing a 1kV transient. This motor cable runs in a conduit, in parallel with a cable for a nearby sensor that monitors a separate process variable, as shown in **Figure 3**. The most obvious input that requires protection is the motor drive power stage, which will see the 1kV applied directly to its output. The surge originates at the other end of a cable, but it is still electrically connected. The only impedance will be the cable resistance, which can be modeled on the order of 2Ω. The fault voltage will be 1kV and the fault current will be 500A.
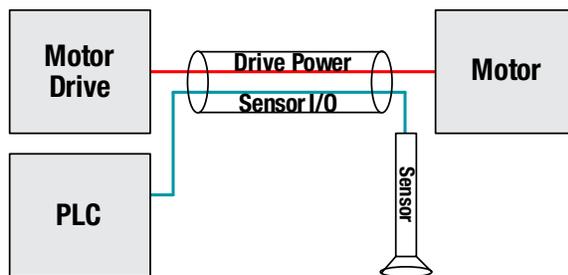
Figure 3. Surge coupling example.

However, you must also protect nearby equipment. In this example, the sensor monitoring some process variables will see the same 1kV surge event and, while there is no direct electrical connection between the motor power mains and the sensor communication lines, the cables for the two systems run in parallel in the same conduit. The surge on the mains line induces a smaller current on the sensor communication lines, with the attenuation modeled as a 42Ω impedance. Thus, the surge that the sensor sees is 1kV but only 24A. This has serious impacts on the surge harshness, so it's important to determine the magnitude of both the voltage and current in the fault to design an efficient protection stage.

The IEC 61000-4-5 standard

Now that you understand the various causes of surges, let's look at the standards that determine surge testing for product qualification. The most prominent regulation is IEC 61000-4-5, which defines a standardized surge applied through a combination wave generator (CWG).

The IEC 61000-4-5 waveform defines both a current waveform and a voltage waveform. These waveforms are measured with the voltage waveform defined as an open circuit voltage and the current waveform defined in a short-circuit condition. The two waveforms have different lengths – the open circuit voltage waveform has a 1.2μs rise time with a 50μs half-length, while the short-circuit current waveform has a 8μs rise time with a 20μs half-length. The current waveform magnitude must be half the voltage waveform magnitude for an effective output impedance of 2Ω. These two waveforms are illustrated in **Figure 4**.
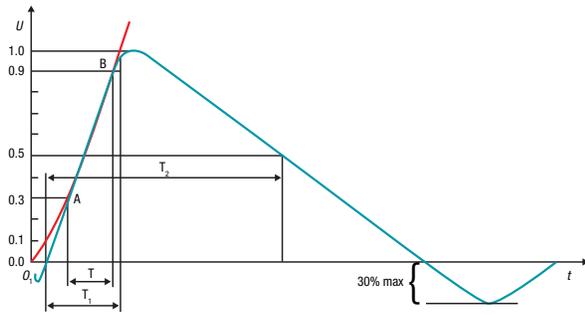
Front time: $T_1 = 1.67 \times T = 1.2\mu s \pm 30\%$
Time to half-value: $T_2 = 50\mu s \pm 20\%$
Open circuit voltage waveform
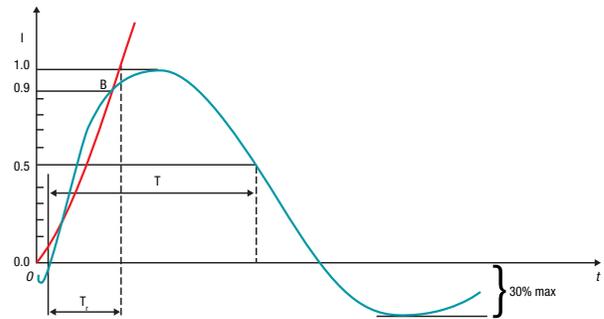
Front time: $T_r = 8\mu s \pm 20\%$
Time to half-value: $T = 20\mu s \pm 20\%$
Short circuit current waveform

Figure 4. IEC 61000-4-5 waveform.

The important characteristics for both the voltage and current waveforms can be seen in **Table 1**.

All IEC 61000-4-5 CWGs must be calibrated for both waveforms simultaneously, with the appropriate waveform present depending on whether the outputs of the CWG are shorted or open. The waveform is generally referred to as a 8/20μs waveform (as defined by its short-circuit current waveform); however, it is occasionally referred to as a 1.2/50μs waveform. Both waveforms refer to the same test.

IEC 61000-4-5 lists recommended test conditions based on environment, with the test defined as a peak voltage magnitude determining the energy in the surge. This value generally goes from 500V up to 4kV. The voltage and output impedance of the CWG determine the current waveform amplitude. Recall that the CWG is defined with a 2Ω output impedance, which simulates resistances in cabling or interconnects that are present in all systems.

Coupling networks

During coupled surges, the output impedance can be much higher than 2Ω. To model coupled surge events, the IEC 61000-4-5 standard also defines external coupling networks to attenuate the current waveform.

The IEC 61000-4-5 standard calls for the placement of a 500Ω coupling resistor for surge tests on very small sensors, a 40Ω coupling resistor for all other tests on communication lines, a 10Ω coupling resistor on tests between low-voltage power supplies and ground and no external coupling resistors for tests on power lines. The presence of an external coupling network in the test simulates whether a surge is expected to be directly or inductively coupled, and significantly impacts the test severity. These scenarios are summarized in **Table 2**.

Waveform	Rise time	Half length	Magnitude
Open circuit voltage	1.2μs	50μs	V_{PEAK}
Short-circuit current	8μs	20μs	$V_{PEAK}/2\Omega$

Table 1. Waveform characteristics.

Application	R_{SOURCE}	R_{COUPLE}	R_{TOTAL}
Low-voltage power-supply network	2Ω	0Ω	2Ω
Power-supply network to ground	2Ω	10Ω	12Ω
Communication lines	2Ω	40Ω	42Ω
Very small sensors	2Ω	500Ω	502Ω

*Table 2. IEC 61000-4-5 coupling networks.*

Surge testing examples

Going back to the 1kV voltage transient on the motor, let's look at how that test scenario is defined in IEC 61000-4-5. **Figure 5** shows the test setup on the motor drive, with the CWG setup simulating a high-energy surge event that is coupled directly to an equipment cable.

Charging the CWG to 1kV with no external coupling network means that the only impedance will be the 2Ω source impedance, creating a current waveform with a peak of 500A. This type of test is common for equipment power supplies that expect to see large, directly-coupled voltage surges.

In contrast, the test setup in **Figure 6** models the attenuated event that is inductively coupled onto the sensor I/O line. Adding a 40Ω external resistor in series limits models the coupling and attenuates the current to 23.8A during the 1kV surge. This type of test is common for equipment such as temperature sensors or other communication lines in factory settings.

Table 3 shows the relationship between voltage and current as defined in IEC 61000-4-5; it's clear that coupling networks significantly change the magnitude of the surge current, even if the voltage magnitude remains unchanged. Although Table 3 shows the current during a 1kV surge, each of these applications can see any applied test voltage which will change the short-circuit current. This current is important because it determines what an input protection TVS diode must be capable of withstanding.
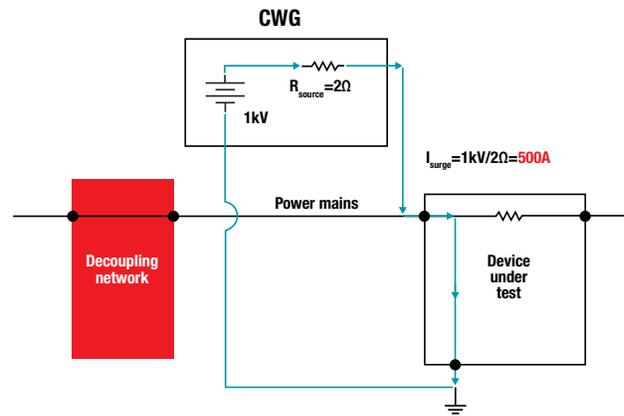
Figure 5. Surge CWG test example.
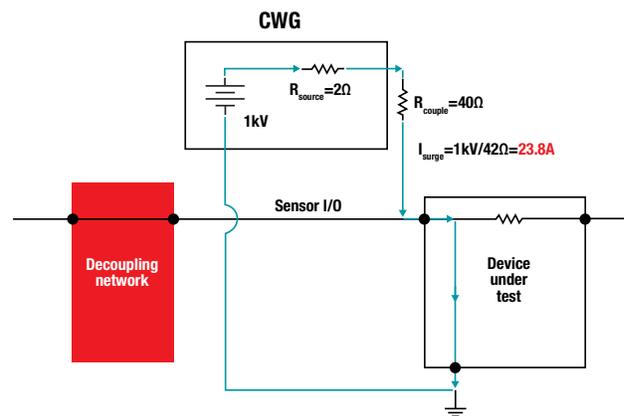
Figure 6. Surge CWG coupled test example.

IEC 61000-4-5 offers guidelines for testing levels, but does not clearly define what specific tests each type of equipment must pass. Many industrial products have separate regulations that reference IEC 61000-4-5 to define the required level of surge protection. Programmable logic controller (PLC)

R_{TOTAL}	Application	Open circuit voltage	Short-circuit current
2Ω	Low-voltage power-supply network	1kV	500A
12Ω	Power-supply network to ground	1kV	83.3A
42Ω	All other lines	1kV	23.8A
502Ω	Small sensors	1kV	1.99A

Table 3. Coupling network effect.

systems are regulated by IEC 61131, for example, while motor-drive systems are regulated by IEC 61800. If there is not a specific product standard, you will need to determine how best a product fits within the broad IEC 61000-4-5 guidelines for test levels.

For more information about how TI tests against IEC 61000-4-5, see the application report, "IEC 61000-4-x Tests for TI's Protection Devices."

IEC 61000-4-5 is the most common surge test to guarantee reliability, however, there are a few other standards used to more accurately simulate transients seen by specific products:

- 10μs/1,000μs test, defined in IEC 61643-123 to specify TVS diode capabilities.

- 10μs/700μs test, defined in IEC 61000-4-5 for telecom applications.

- 7μs/70μs test, defined in document (DO)-160 for aerospace applications.

- Medical equipment defibrillator waveform, defined in IEC 60601.

Each standard defines different waveforms, coupling methods, and test levels, but the behavior is fundamentally the same. Be careful not to confuse the IEC 61643-123 that commonly appears in TVS diode datasheets to characterize the devices with the IEC 61000-4-5 system characterization waveform.

Conclusion

Although surge protection can seem mystifying, it is possible to effectively protect systems if you understand the environmental risks and regulatory considerations. An upfront assessment of the risks of exposure to high-powered surges – taking into account the magnitude of the energy, distance and coupling method – enables you to predict what surges a system might see. To make such predictions more concrete, regulatory bodies like the IEC have defined standards that allow you to confidently test products to ensure that they can survive surges.

An understanding of these surges and their causes allows you to select ICs that enable a robust product design that will survive a lifetime of operation, regardless of environment, without requiring major design trade offs.

Additional resources

- Download the application note, "TVS Surge Protection in High-Temperature Environments."

- Read the white paper, "Flat-Clamp surge protection technology for efficient system protection."

- Review the reference designs:

  o Surge Protection Reference Design for PLC Analog Input Module.

  o 24VDC 10A eFuse and Protection Circuit for Programmable Logic Controllers (PLC).

  o Input Protection and Backup Supply Reference Design for 25W PLC Controller Unit.

- Watch the video series, "Getting Started with Interface Protection."

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