Frequency Analysis of Surge Protection Devices

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Electromagnetic Interference

EMI is the exposure and disruption of a system when subjected to different types and magnitudes of electromagnetic energy. Electromagnetic exposure can be either conducted or radiated. Conducted electromagnetic energy is coupled to the system through power or data transmission lines. Radiated electromagnetic energy is transmitted through the air. It is important to note that given the proper geometry of the power or data transmission lines, these transmission lines can actually act like antennae, thereby coupling the radiated electromagnetic energy to the equipment by the transmission lines.

To eliminate or attenuate radiated and conducted EMI, an in-depth knowledge of the system in question is required. The elimination of radiated EMI can be achieved by proper shielding, grounding, and termination of all conductors. The theory and analysis of radiated EMI suppression is beyond the scope of this paper. Electromagnetic theory is described by Paul,[1] and is presented in many governmental, industrial, and academic publications.

The attenuation of conducted EMI can be achieved by proper grounding, component layout and wiring, along with a multitude of filtering techniques and circuits. Among these filtering techniques are the strategic placement of one-port and two-port SPDs within the facility.

SPDs

This article analyzes the frequency attenuation characteristics of one-port surge protection devices (SPDs) and two-port SPDs. The low-frequency response analysis is obtained between the one-port and two-port SPDs by use of mathematical modeling techniques.

The one-port SPD is a parallel type device. These SPDs connect to the facility's power grid such that only the power of the SPD flows into the SPD. The one-port SPD has no components connected in series with the power grid of the facility. Additionally, with only minimal operating current and no series components, the one-port SPD can be applied to the power grid with little regard to the magnitude of the series current. Also, the one-port SPD can be connected to the power grid using various diameters of conductors.

A one-port SPD configured in Kelvin with the facility's power grid utilizes the building wiring to connect directly to the SPD. Although no series current flows through the one-port SPD itself, the Kelvin-connected device must have connectors and/or wiring capable of handling the full magnitude of the facility power grid to which it is connected.

A two-port SPD, like the Kelvin-connected one-port SPD, connects directly to the facility power grid. However, a two-port SPD allows full phase current to pass through not only the connection devices, but also a series component such as an inductor. A two-port SPD utilizes the high-energy surge current components found in the one-port SPDs, and it also incorporates a low-pass filter for additional transient attenuation. Therefore, the two-port SPD must be capable of handling the total current of the power grid to which it is connected.

The heightened awareness of electromagnetic interference through the requirements of the Federal Communications Commission (FCC) and the European Union's EN requirements has made the immunity or the ability to attenuate various types of electromagnetic interference (EMI) very important to manufacturers and end-users of all types of industrial devices. Additionally, many end-users are looking to the manufacturers of SPDs to help meet the requirements of the FCC and EU. In particular, an SPD is designed to attenuate the low- and high-energy caused by the indirect effects of lightning and the lower-energy transients caused by induced power line disturbances. Examples of theses transients are the combination wave transient, the ring wave transient, and the electrical fast transient.[2]

With the aforementioned types of SPDs and connection configurations available, the end-user seeking to protect sensitive industrial electronics faces the daunting task of selecting the SPD that provides the best high-energy and low-energy transient and EMI attenuation.

ONE-PORT SPD FREQUENCY ANALYSIS

When capacitors or high frequency snubber circuits are placed in one-port SPDs, their effectiveness is determined by the frequency response of that particular component plus any associated parasitic parameters. These parasitic parameters include any series inductance or resistance resulting from the connection of the SPD to the facility power grid.

The frequency analysis and testing of any EMI filter should be modeled and performed as described in MIL-STD-220A.[3] It is common to express the insertion loss IL and attenuation A_v of a device in decibels, or dB. Mathematically, the voltage attenuation in decibels A_v(dB) of a device is defined as

$$A_V(\mathrm{dB}) = 20\mathrm{Log}V(t) \qquad (1)$$

where

V(t) = Voltage ratio of the output to the input voltage of the device in question

The voltage ratio V(t) is the ratio between the voltage drop of the series components and the parallel components at a specified frequency. This ratio is defined by

$$V(t) = \frac{e_o(t)}{e_i(t)} \qquad (2)$$

where

$e_o(t)$ = Output voltage of the system

$e_i(t)$ = Input voltage of the system

The output voltage $e_o(t)$ of the circuit in Figure 1 is easily defined as

$$V(t) = \frac{Z_1}{Z_1 + Z_2} \qquad (3)$$

where

$e_i(t)$ = Input voltage

Z_1 = Impedance of the series components at the desired frequency

Z_2 = Impedance of the parallel components at the desired frequency

As shown in Figure 1, the series impedance of the one-port SPD connected to a 50-ohm spectrum analyzer is simply $Z_1 = R_1$. The parallel impedance of the one-port SPD, Z_2 is

$$Z_2 = \frac{\omega^2 L_1 C_1 + \omega R_3 C_1 + 1}{\omega C_1} \qquad (4)$$

where

L_1 = Inductance due to wiring between the surge diversion component or module and the facility power grid

R_3 = Resistance of the wiring between that same surge diversion module and the facility power grid

C_1 = Total capacitance of the one-port SPD

The angular frequency ω is in radians/second and is related to frequency in Hertz by $\omega = 2\pi f$.

A 50-ohm source is utilized for two purposes. First, many manufacturers of network analyzers, spectrum analyzers, and discrete frequency generators and receivers have a source and matching load impedance of 50 ohms. Secondly, data shows[4] that the impedance of the power grid converges to 50 ohms.

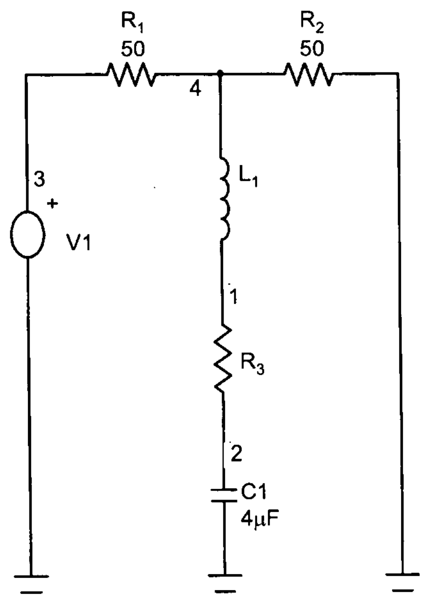

Figure 1. *Series Impedance of a One-port SPD Connected to a 50-ohm Spectrum Analyzer.*

CONVENTIONAL CONNECTED ONE-PORT SPD

An installation of a one-port SPD can be up to six feet (1.83 meters) from the main conductors of the facility power grid. Using #8 American Wire Gauge (AWG) for connection, this configuration produces an ideal series inductance of approximately 0.5 µH/meter, and a series resistance of 2.0 mohm/meter per conductor. The ideal inductance only accounts for the internal inductance. This example does not include any external inductance derived from the coupling of the electromagnetic fields in the two conductors. Utilizing the line conductor and the neutral conductor, the total series inductance, L_1, is 1.8 µH. The series resistance, R_3, is 7.32 mohm.

With a total one-port SPD capacitance of 4µF, and inserting all the values into Equation 1 through Equation 4 yields the frequency response shown in Figure 2. The frequencies calculated are from 1 Hz to 100 MHz and the input (reference) voltage is 1.0 volt.

KELVIN-CONNECTED ONE-PORT SPD

In the Kelvin-connected configuration, the conductors of the facility power grid enter and exit the enclosure of the one-port SPD. Although the facility conductors are large, usually greater than #2 AWG, there are many advantages with respect to frequency response. Because the facility conductors are connected directly to the surge protection module, a minimal inductance, L_1, of 200 nH, and a resistance, R_3, of 1.0 µohm are realized.

Inserting these values into Equations 1 through 4 yields the frequency response shown in Figure 3. As previously stated, the frequencies calculated are from 1 Hz to 100 MHz, and the input voltage is 1.0 volt.

TWO-PORT SPD FREQUENCY ANALYSIS

Determining the attenuation characteristics of a two-port SPD is more complicated than the aforementioned

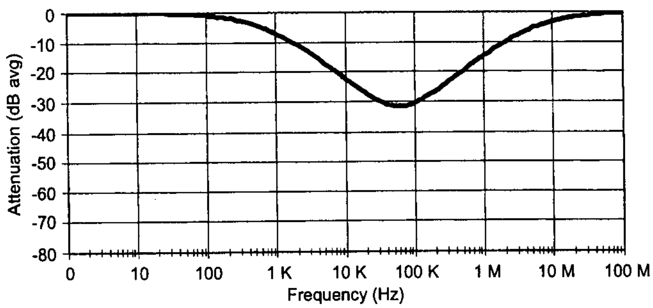

Figure 2. Conventionally-connected One-port SPD Frequency Response (Connected 1.82 m from the Facility Power Grid).

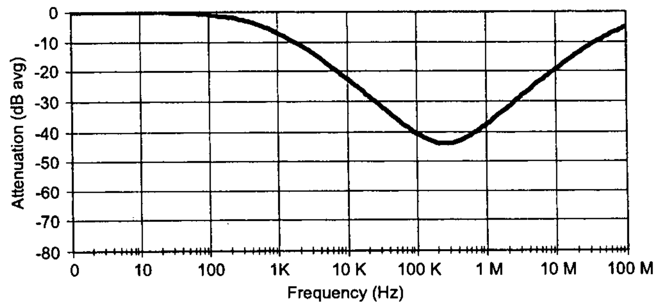

Figure 3. Kelvin-connected One-port SPD Frequency Response (Connected Directly to the Facility Power Grid).

one-port SPD. Equations 1 and 2 accurately describe the gain (attenuation) of the SPD or filter over the specified frequency range. However, the difference between determining the response of a one-port or two-port SPD is in the modeling technique and the mathematics. A simplified derivation will be shown, although a more detailed derivation is available.[5]

In determining the frequency response of the one-port SPD, one simply inserts the given values into the equations. However, because of the presence of inductors and capacitors which have imaginary components, the low-frequency response of the two-port SPD must be ascertained by examining specific points. Finally, once these points are determined, one must apply known response characteristics to obtain a graphical representation of the low-frequency response.

In examining the two-port SPD shown in Figure 4, one notes that there are no impedances in the circuit that represent the source and load impedance of the network analyzers. It can be shown through analysis and experiment that the 50 ohm of the source and load cancel.

Therefore, applying Kirchoff's voltage law to the circuit shown in Figure 2 and transforming from the time domain to the frequency domain using LaPlace transforms, the input, $E_i(s)$, and the output, $E_0(s)$, the voltage ratio of the two-port SPD is

$$\frac{E_0(s)}{E_1(s)} = \frac{R_2C_1s+1}{L_1C_1s^2+(R_1+R_2)C_1s+1} \quad (5)$$

where

L_1 = Series inductance
R_1 = Series resistance associated with the winding of the inductor
C_1 = Parallel capacitance
R_2 = Damping resistance of the filter circuit

To obtain the low-frequency response of the two-port SPD, the lead circuit is set to zero.

$$L_1C_1s^2+(R_1+R_2)C_1s+1=0 \quad (6)$$

The specific points that must be determined are the –3 dB point, and the point at maximum gain. An important characteristic of an L-C low-pass filter is that after cut-off, the gain of the filter is –40 dB per decade. This occurs until the effects of the lag circuit and the parasitic elements of modeled components become dominant.

As shown in Figure 4, the series inductance, L, is 100 μH, the series resistance of the inductor due to wiring, R_1, is 0.01 ohm, the capacitance, C, is 10 μF, and the damping resistor of the two-port SPD, R_2, is 2.5 ohm. The frequency at which the maximum gain of the filter occurs is determined by

$$f_r = \frac{\omega_n\sqrt{1-2\varsigma^2}}{2\pi} \quad (7)$$

where ω_n is the natural frequency of the two-port SPD and ζ is the damping coefficient of the two-port SPD. Utilizing the values given, the frequency at which the maximum gain occurs is 4163 Hz.

The peak gain in decibels, m_p, of the two-port SPD at the frequency, f_r, is determined by

$$m_p = 20\text{Log}\left(\frac{1}{2\varsigma\sqrt{1-\varsigma^2}}\right) \quad (8)$$

Again, utilizing the values shown in Figure 4, the maximum gain of the two-port SPD at a frequency of 4163 Hz is 2.7 dB.

The cutoff frequency, the -3 dB point, or the half-power point, is determined by

$$f = \frac{\omega_n\sqrt{(1-2\varsigma^2)+\sqrt{4\varsigma^4+4\varsigma^2+2}}}{2\pi} \quad (9)$$

Inserting the values as shown in Figure 2 yields a cutoff frequency of 7700 Hz. At this frequency, the gain of the two-port SPD is –3 dB.

Plotting the points f and f_r, and with the knowledge that the two-port SPD has a roll-off rate of –40 dB per decade

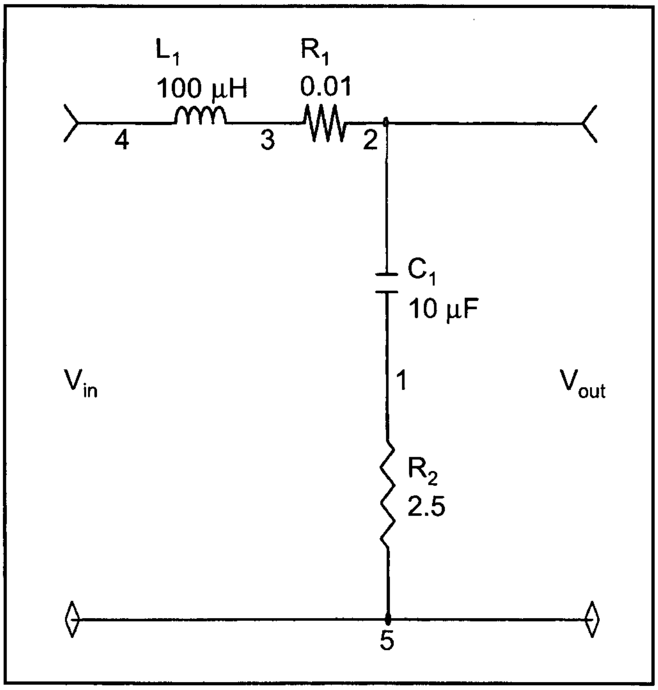

Figure 4. *Two-port SPD.*

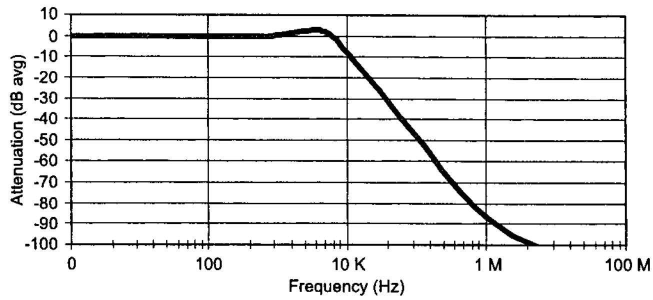

Figure 5. *Two-port Frequency Response (Directly Connected to the Facility Power Grid).*

beyond the cutoff frequency, the low-frequency graphical representation of a two-port SPD is shown in Figure 5.

Conclusion

With the increased awareness of electromagnetic interference and the requirements of the FCC and the EU, many end-users of facility-grade surge protection devices are looking for a product that not only attenuates the high-energy effects due to indirect lightning strikes to the utility power grid, but also the indirect effects of electromagnetic energy being produced or coupled to the power grid by industrial equipment.

There are currently two different connection schemes for the one-port SPD and one connection scheme for the two-port SPD which the customer can utilize. Each device and connection configuration have their own benefits and limitations.

Comparing the frequency response of the conventionally connected one-port to the Kelvin-connected one-port, it is obvious that the Kelvin-connected one-port SPD provides greater frequency attenuation over the span of 1 Hz to 100 MHz. This increase in performance is a direct result of the decrease in lead length, which involves the series inductance and resistance between the SPD and the facility power grid.

The frequency response comparison between the conventionally connected one-port SPD and the two-port SPD, shows that the two-port provides greater attenuation of electromagnetic energy as the frequency increases.

In comparing the frequency response of the Kelvin-connected one-port SPD to the two-port SPD, it is again apparent that as the frequency increases, the attenuation of the one-port SPD decreases, whereas, the attenuation of the two-port SPD continues to increase as frequency increases.

This article shows that the frequency response of a two-port SPD has the ability to surpass the frequency response performance of a one-port SPD in either wiring configuration. However, to determine the actual frequency response characteristics of any SPD, the analysis or testing should represent the actual connection to the facility power grid, taking into account all impedances such as inductance, resistance, and capacitance.

References

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