Response Time and Surge Protective Devices: Characterization in Real Time

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Abstract -- This document examines the topic of response time and how it relates to and its relevance to surge protective devices. Further, it includes a review of the definitions, manufacturer’s component ratings, and information provided by the IEEE standards that are applicable to response time and surge protective devices. Finally, the document includes a practical example relating response time to the application of surge protective devices.

Keywords – surge protective device, transient voltage surge suppressors, power quality, response time, SPD, TVSS, component, rise time, wavefront, waveshape, let-through voltage, clamping voltage, IEEE

I. RESPONSE TIME

Typically, the characteristic of response time is associated with discrete components. However, some manufacturers market their surge protective devices (SPDs) and SPD assemblies by providing a response time rating for the assembled device. In this paper, the relevancy of using response time as a significant factor in comparing and rating SPDs and SPD assemblies will be discussed. [Note: For the remainder of the document, SPD assemblies are understood to be included in the term “SPD”.

As part of this investigation, the following issues are examined:
1. The definition of response time, according to the Institute of Electrical and Electronics Engineers (IEEE) is provided.
2. A few common surge protective device components will be explored to see how the response time of these components are rated and to see what industry standards have to say regarding the use of response time when rating components.
3. A review of the industry surge protective device standards will be included and information relevant to response time will be cited.
4. A practical example will be developed to emphasize how response time relates to SPDs.

II. DEFINITIONS

The definition of response time has been established by a few different standards. It is provided here to clarify the term for the purposes of the discussion to follow.


Response Time - The time between the point at which the wave exceeds the clamping voltage level (Vc) and the peak of the voltage overshoot.

This definition is shown graphically in Figure 1 (this figure is cited from and appears as Figure 8 in IEEE C62.33-1982 [1] and Figure 21 from IEEE C62.42-2005 [3]).

![Graphical representation of response time](image)

Simply stated, the response time is the time it takes for the device to start reacting (initial clamp voltage) to a surge until the time that the peak value of the voltage overshooot is reached. The measurement associated with the peak value of the voltage is the let-
through voltage. In short, let-through voltage may be defined as the peak residual voltage that the protected equipment will be subjected to after the operation of the SPD. By the definition above, response time is an intrinsic factor of the let-through voltage, shown as $V_1$ in Figure 1.

**III. COMPONENT MANUFACTURER’S RATINGS**

Many suppression component manufacturers discuss and include the rating of response time in their literature for surge protection components. A search of various manufacturers’ documentation via the World Wide Web provided the information that follows. The search was limited to a few common leaded components that are typically used in SPDs and have the capability of handling surge current levels that are expected in Category A, B and C locations as described in **IEEE C62.41.1-2002, IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits** [4], **IEEE C62.41.2-2002, IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits** [5], and **IEEE C62.45-2002, IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits** [6].

The components considered for this discussion include varistors, silicon avalanche diodes and gas tubes. A brief dialogue of each follows to provide the reader some background on these components.

**Varistors.** Metal oxide varistors (MOVs) are semiconductor devices that have specific breakdown voltages that allow them to change from a nearly non-conducting state to a conducting state very quickly. This action occurs as a result of a sharp change in the voltage-current characteristic of the varistor. The device begins to conduct when an applied voltage exceeds the varistor’s designed “turn-on” voltage. After this point, a small change in applied voltage causes a large change in operating or leakage current. The basic conduction mechanism of MOVs results from semiconductor junctions at the boundary of the zinc oxide grains formed during a sintering process. The varistor may be considered a multi-junction device with many grains acting in a series-parallel combination between the terminals [3].

Due to their construction, a varistor can survive higher peak surge current levels than components with single, smaller junction such as a silicon avalanche diode (SAD) of a similar voltage rating. Although varistors are able to survive higher peak surge currents than SADs, their response times are typically reported as being slower.

A search for and a review of several manufacturers’ specifications and application notes for MOVs, found that the response times of assembled MOVs were reported to be in a range from less than 15 nanoseconds (15 ns) to 50 nanoseconds (50 ns) [7][8][9] and the response time of MOV material reported to be 500 picoseconds [18].

**Silicon Avalanche Diodes.** The term “avalanche” is used to describe a distinct change in the voltage-current characteristic of semiconductors when a certain voltage level is reached. At this point, a small change in applied voltage causes a large change in operating or leakage current; this is the avalanche or breakdown region. For silicon diodes, the avalanche region refers to a specific level of reverse-bias voltage which results in a large amount of current through the diode in the reverse direction [3]. Most diodes cannot withstand sustained or repeated operation in their avalanche regions because the power dissipated in their semiconductor junction becomes very large when the reverse current increases. Since the SADs are comprised of a single junction, most cannot survive large peak surge currents like varistors. Although they cannot survive large peak surge currents, they typically have response times that are reported to be faster than varistors.

A search for and a review of a couple of manufacturers’ specifications for SADs, found that the response times of the SADs were reported to be from approximately one picosecond ($\approx 1$ ps) to less than or equal to one nanosecond (=1 ns) [10][11].

**Gas Tubes.** According to **IEEE C62.42-2005** [3], gas tube arrestors (also known as gas discharge tubes or GDTs) consist of two or more metallic electrodes that are separated by gap(s) in a hermetically sealed envelope containing an inert gas or mixture of gases, usually at less than atmospheric pressure. Electrode spacing is maintained by means of ceramic, glass, or other insulating materials, that may form a part of the sealed envelope.

Further, when the gap of a gas tube arrester is subjected to increasing field intensity due to a voltage surge, it will break down at some voltage that is determined by the design of the gas tube arrester and the rate of rise of the voltage surge; the faster the rate of rise of the surge waveform, the higher the impulse breakdown voltage [3].

A search for and a review of a couple of manufacturers’ specifications for gas tubes, found that the response times of the gas tubes were reported to be less than or equal to seventy-five nanoseconds (=75 ns) to one microsecond (1 us) [12][13], depending on the rise time of the waveform of the voltage. Note that gas tubes have the characteristic that the response time decreases as the rate of rise of the voltage waveform increases [14]. Although this is true, the resultant let-through voltage does not necessarily decrease with the response time.

As shown in the above examples of various components used in SPDs, there is a possibility for a wide range of response times ($\approx 1$ ps to 1 us) depending
on the type of component selected. Further, as shown in IEEE C62.42-2005 [3], the specification of response time is often confused by the use of a different waveform to determine the value. IEEE C62.42-2005 [3] states that:

**Due to the high frequencies involved in steep wavefronts, response time and overshoot duration measurements require special techniques, fixtures and extremely fast-responding instrumentation. Response time and overshoot duration will be a function of the wave form used for the measurement, and may not resemble the idealized illustration in Figure 21 [Figure 1 of this document]. For these reasons, reference to response time in device specification is discouraged.**

This statement emphasizes the difficulty and the diversity in how response time measurements may be performed. Further, it provides an understanding that the rating of response time may not be clear or relevant to a particular environment. That is, if the response time is determined using a method that is uncommon, the waveform used is not expected in the environment of application, or the waveform used is different from the one used for determining the response time of other components; then, the rating may not be useful in determining if a particular component is appropriate for use in a particular application or in comparing components.

**IV. IEEE STANDARDS**

A number of the standards written by the IEEE for surge protective devices (components and assemblies) address the topic of response time. A brief description of these documents and the text relevant to the topic of response time is cited here.

**IEEE C62.42-2005 - IEEE Guide for the Application of Component Surge-Protective Devices for Use in Low-Voltage [Equal to or Less than 1000 V (ac) or 1200 V (dc)] Circuits** [15] is a standard that addresses the use of various components in surge protective devices. The scope of this document is: This guide covers the application of component air gaps, gas tubes, MOVs, and avalanche junction semiconductor surge-protective devices for use within surge protectors, equipment, or systems involving low voltage power, data, communication, and/or signaling circuits.

From this document, the following excerpt is taken:

**For solid state devices with fast responding internal active elements; voltage overshoot, response time and overshoot duration are phenomena primarily caused by the effect of lead inductance. Consequently, measurements of response time should recognize the dependency of voltage overshoot behavior on lead length and loop coupling rather than treat response time as an intrinsic characteristic of solid state devices. Due to the high frequencies involved in steep wavefronts, response time and overshoot duration measurements require special techniques, fixtures and extremely fast-responding instrumentation. Response time and overshoot duration will be a function of the waveform used for the measurement, and may not resemble the idealized illustration in Figure 21 [Figure 1 of this document]. For these reasons, reference to response time in device specification is discouraged.**

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**IEEE C62.33-1982 - IEEE Standard Test Specifications for Varistor Surge-Protective Devices** [2] is a standard that addresses the use of silicon avalanche diodes (and similar) components in surge protective devices. The abbreviated scope of this document is:

**This standard applies to varistors for surge protective applications on systems with dc to 420 Hz frequency and voltages equal to or less than 1000 V rms or 1200 V dc.**

From this document, the following excerpt is taken:

**Due to the high frequencies involved in fast rise time waveforms, response measurements require special fixtures and extremely fast-responding instrumentation. Reference to response time in device specification is discouraged. It is not characteristic of its clamping effectiveness and is dependent upon defined test methods and circuit configuration.**

**IEEE C62.35-1987 - IEEE Standard Test Specifications for Avalanche Junction Semiconductor Surge Protective Devices** [2] is a standard that addresses the use of silicon avalanche diodes (and similar) components in surge protective devices. The abbreviated scope of this document is:

**This standard applies to a two terminal avalanche junction surge suppressor for surge protective application on systems with dc to 420 Hz frequency and voltages equal to or less than 1000 V rms or 1200 V dc.**

From this document, the following excerpt is taken:

**Due to the high frequencies involved in fast rise time waveforms, response measurements require special fixtures and extremely fast-responding instrumentation. Response time and overshoot duration may be a function of the waveform used for the measurement. Except for special applications, a separate test for response time and overshoot duration are not a necessary design test.**

**IEEE C62.48-2005 - IEEE Guide on Interactions between Power System Disturbances and Surge-Protective Devices** [16] is a standard that addresses the response of SPDs to disturbances within a
power system. The abbreviated scope of this document is:

This guide applies to surge-protective devices (SPDs) manufactured to be connected to 50 Hz or 60 Hz ac power circuits rated at 100–1000 V rms. This guide describes the effects on SPDs of power system disturbances occurring in these low-voltage ac power circuits.

From this document, the following excerpt is taken:

Response time is not solely a reliable means of assessing SPD operation. Response time measurements require special techniques, fixtures and instrumentation. There are no recognized SPD standards that address methods for repeatable measurements of such short times to corroborate such claims.

In reviewing the citations from the standards above, there is strong evidence that the rating of response time for SPDs should be avoided and is not supported by the IEEE.

The following is a list of key points from the citations above:

- Lead inductance (lead length) is a significant contributing factor to response time.
- Response time measurements require special techniques, fixtures and instrumentation.
- There are no recognized SPD standards that address methods for repeatable measurements of such short times to corroborate claimed response times.
- Response time is not solely a reliable means of assessing SPD operation.
- Theoretical response times ignore the effects of the connections to the circuit and the system being protected.
- Reference to response time in device specifications is discouraged.
- Response time is not solely a reliable means of assessing SPD operation.
- Evaluations should be based on let-through voltage.

V. PRACTICAL SPD RESPONSE TIME LIMITATIONS

After defining response time, examining the response time ratings of various surge suppression components utilized in manufacturing SPDs, and reviewing what current IEEE standards provide as guidance; it is prudent to look at the application of SPDs to an electrical system and how that would effect
response time. Specifically, the investigation will examine how connecting an SPD to an electrical system influences response time. To do so, a simple but practical example is developed.

From IEEE PC72.72-D3 - Draft Guide for the Application of Surge Protective Devices for Low Voltage (1000 Volts or Less) AC Power Circuits [17]:

The speed of light is approximately 0.3 millimeters per picosecond and electrical signals generally propagate through conductors at 50% to 80% of the speed of light.

Given this information, one can calculate the time it would take for a “signal” in this case a transient, to travel from the connection point of the electrical system to the suppression components contained within an SPD.

For the purpose of this example, a lead length of 300 mm (12 in) per lead will be used as the conductor length for the connection from the SPD to the electrical system. (Note: In practice, some installations may allow for less lead length and others will require longer leads.) Further, assume that the SPD is relatively small in size and that the internal length of the conductors is limited to 150 mm (6 in). Therefore, the total length of the loop (lead from the electrical system to the SPD, the internal lead length of the SPD and the lead from the SPD to the electrical system) is 750 mm (30 in).

As cited above, the speed of light is 0.3 mm per picosecond or 300 mm per nanosecond. Also, the speeds of electrical signals are limited to 50% to 80%; therefore, the speed of electrical signals would be between 150 mm per nanosecond to 240 mm per nanosecond.

Examine this situation with regard to the lead length only, the time it would take for the signal to pass through the device would be between 3 and 5 nanoseconds depending which speed of electricity is used, as shown below:

\[
t = 750 \text{mm} \times \left( \frac{240 \text{mm}}{\text{ns}} \right)^{-1} = 3.125 \text{ns},
\]

or

\[
t = 750 \text{mm} \times \left( \frac{150 \text{mm}}{\text{ns}} \right)^{-1} = 5.0 \text{ns}
\]

This calculation neglects the reported response time of the SPD component(s) used in the device.

Now, consider if an SPD is an SAD based device. To be conservative and assuming the actual response times of the SAD to be =1 nanosecond as reported, then the range of response time for the installed SPD would be from 4 to 6 nanoseconds. This calculation shows that propagation time of the signal is 3 to 5 times longer than the reported response time of the component. If the response time of ~1 ps is assumed, then the response time for the installed SPD would be 3,000 to 5,000 times longer than the reported response time of the component. Therefore, the response time rating of the component is irrelevant when compared to the possible response time of the installed SPD.

Further, this calculation ignores the affect of the conductor lengths from the SPD connection point to the source of the transient which would further increase the response time as a system. Considering that the source of the transient could be meters or kilometers away from the device and that the signal can only travel at a rate of 150 to 240 mm per nanosecond (which, using 240 mm/ns, is 0.24 m/ns or 4.167 ns/m or 4,167 ns/km), makes the response time of the surge protective component less and less relevant.

Through this simple example, it is evident that SPD lead lengths and the distance from the source of the transient certainly have a significant effect on response time. As shown, the propagation time of the “electrical signal” can make the reported or theoretical response time of the surge protection component irrelevant.

As the vast majority of transient activity expected is characterized as having voltage rise times in the range of 5 to 20 kV/us [4][5][6], it is of little or no significance to compare speeds of response. The response time of a leaded MOV, SAD or other component is significantly affected by circuit configuration and lead inductance [18].

As recommended by the IEEE, other factors such as let-through voltage should be used to evaluate the performance of SPDs [17]. The comparison of let-through voltage is well defined by such documents as IEEE Standard Test Specifications for Surge-Protective Devices for Low-Voltage AC Power Circuits - C62.62-2000 [19], and Underwriters Laboratories Standard 1449, Transient Voltage Surge Suppressors [20]. These standards define the test setups, sample preparation, waveforms used and measurement techniques for testing SPDs. Further, the tests defined in these standards are relevant to the performance of SPDs because these tests have been characterized to represent the transients expected to occur in the environment where SPDs will be utilized [4][5][6].

VI. CONCLUSIONS

The attempt to characterize the performance of an SPD by comparing the response time of various devices is a misleading approach that should not be used. As shown above, there are a number of reasons for this conclusion:
1. Although defined in general, there are too many variations in how response time can be determined including the waveform used, the measuring instrumentation limitations, and the methods used to obtain the measurement.

2. There are no recognized SPD standards that presently address methods for repeatable measurements for the reported response times.

3. Many reported response time ratings are theoretical in nature and do not consider extremely important factors such as lead length and inductance.

4. Many of the reported component response times are longer than the ratings provided by some SPD manufacturers.

5. In many installations, as shown in the example, the reported response time of the surge protective device components will be insignificant, and often irrelevant, when compared to the response time of the assembled and installed SPD.

6. The Institute of Electrical and Electronics Engineers discourages utilizing response time as a method of comparison or rating for surge protective devices.

7. Other methods of characterization and comparison, such as let-through voltage, are better defined and relevant to SPDs.

Although not considered necessary by the IEEE for a vast majority of SPD applications [1], if characterization of an SPD’s response time is altogether necessary, then special consideration must be given to all the relevant parameters involved in such an assessment including waveform, measurement methods, component selection, and lead length and inductance.

Future comparisons of surge protective devices should be conducted through the use of relevant and well defined characterization parameters such as let-through voltage.

VII. REFERENCES


3. The Institute of Electrical and Electronic Engineers, IEEE Std C62.42-2005, IEEE Guide for the Application of Component Surge-Protective Devices for Use in Low-Voltage [Equal to or Less than 1000 V (ac) or 1200 V (dc)] Circuits


5. The Institute of Electrical and Electronic Engineers, IEEE C62.41.2-2002, IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits


15. The Institute of Electrical and Electronic Engineers, IEEE C62.42-2005, IEEE Guide for the Application of Component Surge-Protective Devices for Use in Low-Voltage [Equal to or Less than 1000 V (ac) or 1200 V (dc)] Circuits


17. The Institute of Electrical and Electronic Engineers, IEEE PC72.72-D3 - Draft Guide for the Application of Surge Protective Devices for Low Voltage (1000 Volts or Less) AC Power Circuits


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