Modes of Protection within Electrical Systems for Application of Surge Suppression

by

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***Abstract*--This document details the available modes of protection within an electrical system with regard to the application of surge protective devices. Variations in the number of modes protected by various SPD designs are discussed along with the terminology used to describe these protection schemes.**

The document investigates what existing IEEE (Institute of Electrical and Electronics Engineers) and NEMA (National Electrical Manufacturers Association) standards state regarding the use of discrete individual protection elements in all modes when protecting electrical systems. Further discussed are the benefits of such a protection scheme.

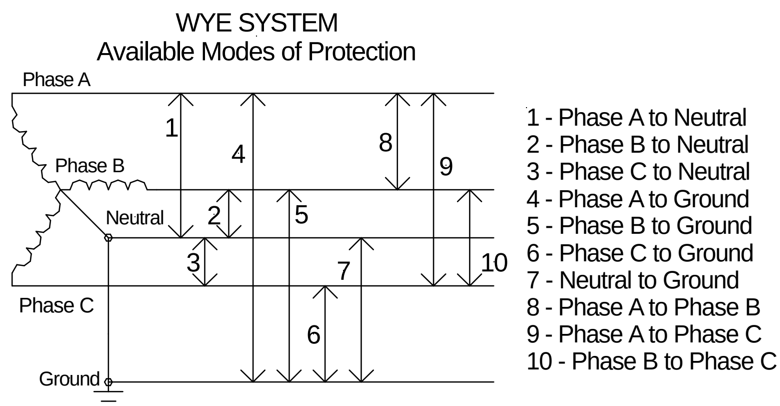
Additionally, three case studies are cited to show the effectiveness of discrete protection in the line-to-line mode through the analysis of surge protective devices that have sacrificed themselves while protecting electrical systems with a neutral connection.

Finally, a simple laboratory experiment is documented that supports the use of discrete and directly connected suppression elements within a surge protective device.

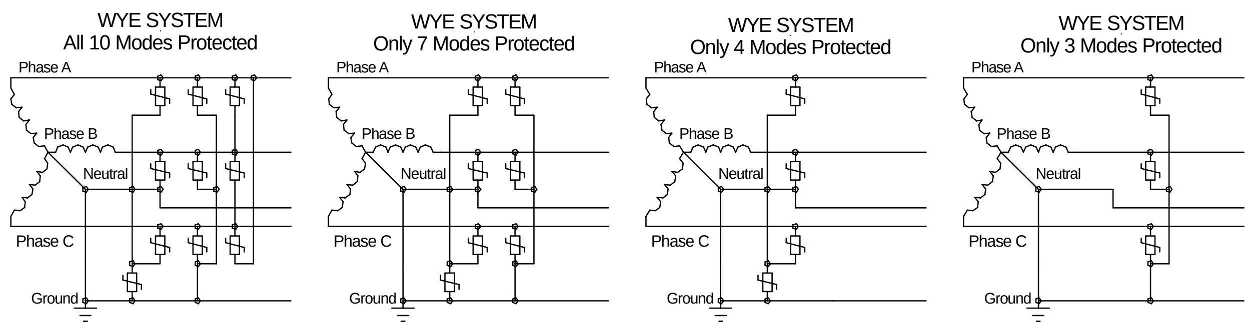
Keywords – ***protection modes, modes of protection, all mode protection, discrete all mode protection, surge protective device, transient voltage surge suppressor, power quality, metal oxide varistor***

I. Modes of Protection

The number of modes (or available protection modes) in any given electrical system depends on the system configuration. As an example, a three-phase, grounded Wye configured system, contains ten possible modes of protection. The possible protection modes include three line-to-neutral modes, three line-to-ground modes, three line-to-line modes and one neutral-to-ground mode. This figure shown illustrates the available modes of protection for a Wye-type system.



Transient voltage surge suppressors (TVSS) or surge protective devices (SPD) are available in a number of designs with regard to the number of modes protected. Most commonly, these devices offer three, four, seven or ten modes of protection. These configurations are shown in the figures below (a varistor symbol is used to represent a direct or discrete mode of protection).



II. Terminology

Various terminologies are used to describe which of the protection modes are included in a surge protective device. One such phrase is “All Mode Protection.” “All Mode Protection” could mean that all ten modes are protected by discrete protection elements; it could mean that seven modes are protected by discrete protection elements and the remaining three modes are protected by the series combination of protection elements purposed for other modes; or, it could mean that four modes are protected by discrete protection elements and the remaining six modes are protected by the series combination of protection purposed for other modes, and so on.

Another phrase that is used to describe the number of protection modes is “*Discrete All Mode Protection*.” This phrase defines that all ten available modes (of a Wye system, for example) are protected by discrete, individual protection elements purposed for protection of that mode and only that mode. With this scenario, none of the modes of protection depend on protection elements purposed for other protection modes.

The association of the phrase “all mode protection” with an SPD that does not offer individual protection elements in all modes could create confusion. “Discrete All Mode Protection” means just what is implied, that is, all modes are protected by individual suppression elements purposed only for the protection of that mode.

III. Is Discrete All Mode Protection Necessary?

Many SPD manufacturers have had continuous success in protecting electrical systems using SPDs with a discrete all mode protection topology. However, this is a method employed not based only on experience but also on the recommendations of industry standards from IEEE (Institute of Electrical and Electronics Engineers) and NEMA (National Electrical Manufacturers Association).

i. IEEE – The Emerald Book

The Emerald Book, IEEE Recommended Practice for Powering and Grounding Electronic Equipment (IEEE Standard 1100-1999) [1]. In section 8.6.1 of this standard, it is stated: *"Surge protective devices used for three-phase, four-wire [Wye] circuits are generally recommended to be connected in all combinations of line-to-line, line-to-neutral, line-to-ground, and neutral-to-ground. Surge protective devices for three-phase, three-wire circuits are recommended to be attached in both line-to-line and line-to-ground modes."*

The above excerpt clearly states that IEEE recommends protecting all possible modes within an electrical system.

ii. IEEE – The Trilogy (C62.41.1, C62.41.2 and C62.45)

The IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000V and less) AC Power Circuits (IEEE Standard C62.41.2-2002) [2]. A review of Tables 2, 3, and 5 from C62.41.2-2002 shows that all modes are afflicted by transient activity and the standard describes the voltage and current surges for the various "Location Categories". Ring Waves (100 kHz) are shown in Table 2. Combination Waves (the 8x20 µs current impulse) are shown in Table 3. Note that Table 3 specifically calls out the line-to-line, line-to-neutral, line-to-ground modes for electrical systems with more than one phase, with a reference to Table 5 for the neutral-to-ground mode discussion.

In this standard, the IEEE clearly demonstrates the need for protecting against transient activity that exists in all modes including line-to-neutral, line-to-line, line-to-ground and neutral-to-ground.

iii. NEMA – Publication LS1

NEMA LS1, Low Voltage Surge Protective Devices[3], states in Section 2.2.7 (Protection Modes): *"This parameter identifies the modes for which the SPD has directly connected protection elements, i.e. line-to-neutral (L-N), line-to-line (L-L), line-to-ground (L-G), neutral-to-ground (N-G)."*

This standard clearly states that if a mode of protection is claimed, then the SPD must contain directly connected protection elements in that mode. In turn, according to this definition, a protection mode cannot be claimed unless directly connected protection elements exist in that stated mode. That is, if a manufacturer claims "all mode protection" and does not provide directly connected protection elements in each of the ten modes (including the three line-to-neutral modes, three line-to-ground modes, three line-to-line modes and one neutral-to-ground mode for a Wye configured system, for example), then that manufacturer is not in compliance with NEMA LS1.

IV. Surges and Transients without Discrete All Mode Protection

Outside of the recommendations of IEEE and NEMA, there are other reasons why discrete all mode protection should be employed. Consider what happens when a Wye configured electrical system is subjected to a line-to-line transient. The difference in potential exists in the line-to-line mode. In the situation where discrete all mode protection is utilized, the directly connected protection elements in that mode create a (near) bond between those conductors; therefore, the only voltage that the connected equipment is exposed to is the let-through voltage that exists after the transient has been mitigated.

In contrast, if an SPD with only seven modes of protection is utilized for the same system and the line-to-line protection mode is protected by the series combination of the line-to-neutral and neutral-to-line modes or the line-to-ground and ground-to-line modes, then those modes (line-to-neutral or line-to-ground) are intentionally exposed to unnecessary and undesired transient voltages. In essence, the SPD is sharing the line-to-line transient with the line-to-neutral and line-to-ground modes and creating voltages on those modes that would not be present with the use of a discrete all mode protection SPD.

V. Surge Equalization versus Surge Diversion

Another concept that is often overlooked or misunderstood is that the function of the SPD is not to merely divert or shunt surges to ground via the path of least resistance; but, to create a condition of voltage equalization. In the example cited above with a line-to-line transient, the voltage potential difference exists from one line to the other and not from each line to ground or neutral; therefore, the function of the SPD is to equalize and stabilize the voltage and remove the difference of potential between the lines. In doing so, the lack of difference of potential in that mode prevents significant surge current from flowing to the load being protected.

Even in some of the earliest publications of surge component manufacturers, such as Littelfuse (adopted from and formerly Harris Semiconductor and General Electric), it was noted that *"The logical approach is to connect the transient suppressor between the points of potential difference created by the transient. The suppressor will then equalize or reduce the potentials to lower and harmless levels."[4]* This statement not only affirms the concept discussed above but also recommends connection of suppression elements between any points that could have a voltage potential difference created by a transient and, thus, recommends discrete all mode protection.

VI. Case Studies Supporting Discrete All Mode Protection

To show the effectiveness of discrete protection and direct protection in the line-to-line mode through the examination of surge protective devices that have sacrificed themselves in the electrical systems with a neutral connection, three case studies are discussed below. In all of these cases the devices were installed on the electrical system for several months and did not fail as a result of a defect or improper installation.

For the sake of ambiguity and non-commercial representation the manufacturer and model numbers have been removed from this discussion.

Case 1: For Case #1, a three-phase, high-leg delta (120/240 V) SPD (3 phases, neutral and ground) with all ten modes discretely protected was examined. This device was exposed to a direct lightning strike at the service entrance of a facility and the suppressor was sacrificed. No equipment within the facility was lost.

In the analysis of the failed device, the findings were consistent with the report of the customer. Further, all modes were inspected and it was found that the line-to-neutral, line-to-ground and neutral-to-ground modes were intact and functioning properly. The only sacrificed mode was from line A to line B.

In this case, it is obvious that the line-to-line mode took the majority of the surge energy rather than the energy being distributed through protection elements from line-to-neutral-to-line or from line-to-ground-to-line.

Case 2: For Case #2, a three-phase, wye (277/480 V) SPD (3 phases, neutral and ground) with all ten modes discretely protected was examined. This device was exposed to a sustained overvoltage in the line-to-line mode due to a utility fault and the suppressor was sacrificed. No equipment within the facility was lost.

In the analysis of the failed device, the findings were consistent with the report of the customer. Further, all modes were inspected and it was found that the line-to-neutral, line-to-ground and neutral-to-ground modes were intact and functioning properly. The only sacrificed mode was from line A to line C.

In this case, it is obvious that the line-to-line mode took the majority of the energy from the sustained overvoltage rather than the energy being distributed through protection elements from line-to-neutral-to-line or from line-to-ground-to-line.

Case 3: For Case #3, a three-phase, wye (120/208 V) SPD (3 phases, neutral and ground) with all 10 modes discretely protected was examined. With this device, an unobserved event caused the suppressor to be sacrificed. No equipment within the facility was lost and there was no disruption of normal service within the facility.

In the analysis of the failed device, all modes were inspected and it was found that the line-to-neutral, line-to-ground and neutral-to-ground modes were intact and functioning properly. The only sacrificed mode was from line B to line C.

In this case, the line-to-line mode took the majority of the energy from the event that caused the failure rather than the energy being distributed through protection elements from line-to-neutral-to-line or from line-to-ground-to-line.

In the examples cited above, the discrete line-to-line protection modes were the only modes damaged by any of the disturbances–in fact, the other modes were still fully functional. After having provided protection for the electrical system and connected equipment, the ten mode devices (with nine modes of protection still fully functional) still provided more discrete protection modes than what many other manufacturers sell as new products—that is, a three, four or seven mode product without discrete line-to-line protection modes.

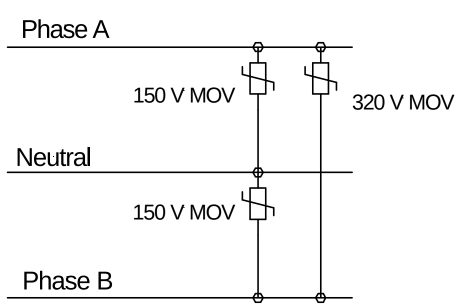
The inclusion of the discrete line-to-line protection modes, as shown in the case studies above, proved effective and protected the respective electrical systems and connected equipment from transient damage without exposing uninvolved modes to undesirable and unnecessary transient voltages.

VII. Laboratory Test Illustrating Effectiveness of Discrete Modes of Protection

Further, as stated by surge component manufacturers, such as Littelfuse (formerly Harris Semiconductor and General Electric), *"It is incorrect to believe that an MOV* [metal oxide varistor] *device merely redirects energy. In fact, the MOV dissipates heat energy within the device by actually absorbing this energy." [5]* This fact is brought to light because this characteristic is utilized in the following experiment to further illustrate the effectiveness of discrete all mode protection.

At standard temperature and lab conditions, an experiment was conducted at an unnamed SPD manufacturer's test laboratory to illustrate the effectiveness of discrete all mode protection.

To do so, a protection circuit was assembled that consisted of MOVs arranged as shown:



Note that 150 V MOVs are used in the connection from Phase A to Neutral and from Phase B to Neutral and that a 320 V MOV is used in the connection from Phase A to Phase B. This arrangement makes the voltage of the Phase A to Neutral to Phase B combination of MOVs have a maximum operating voltage of 300 V while the directly connected MOV from Phase A to Phase B has a maximum operating voltage of 320 V.

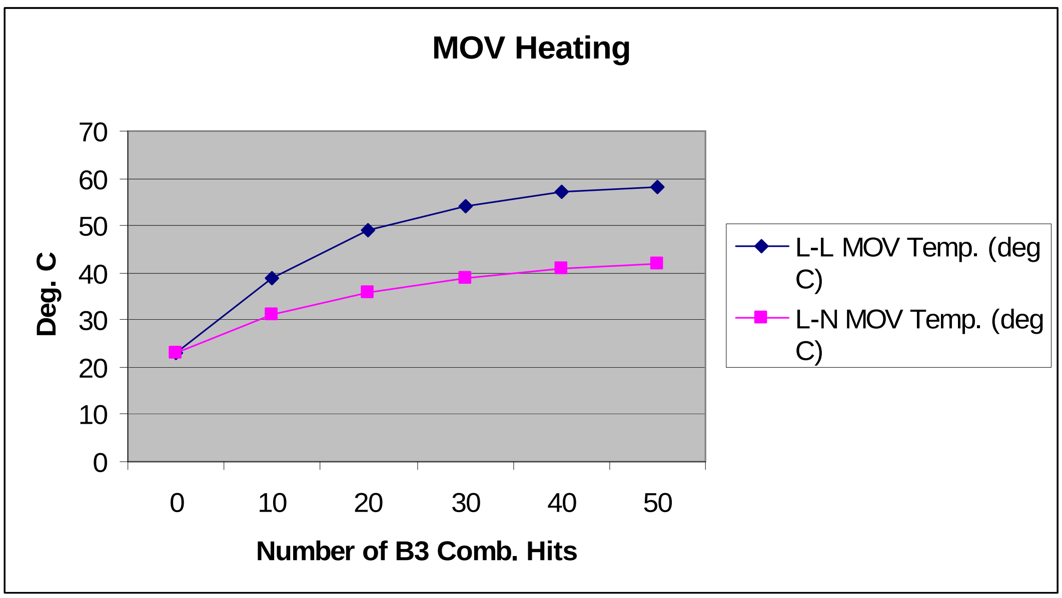
With this configuration, thermocouples were applied to each of the MOVs using polyamide tape. Temperatures were recorded using a Fluke 80TK Thermocouple Converter and a Fluke 87 DMM. Surges were applied using an EMC Partner Surge Generator.

Before the test was started, the initial temperature was recorded. The test was performed by applying Category B Combination Waves at the 6,000 V and 3,000 Amp level every 10 seconds for a total of 50 surges to the line-to-line mode (Phase A to Phase B). The temperature was measured every 10 surges. The MOVs used for the test were 25 mm diameter components and are rated for 20 kA of surge current so that the application of the 3 kA surges would not overstress the devices.

The results of the test are as follows:

# Surges	L-L MOV Temp. (deg C)	L-N MOV Temp. (deg C)
0	**23**	**23**
10	**39**	**31**
20	**49**	**36**
30	**54**	**39**
40	**57**	**41**
50	**58**	**42**

In graphical form:



Note that the temperature rise is much higher in the discrete or directly connected 320 V MOV (connected directly from Phase A to Phase B) even though it has a higher maximum operating voltage than the combination of 150 V MOVs in the Phase A to Neutral and the Phase B to Neutral MOVs (300 V total).

The temperature rise measured on the discrete Phase A to Phase B MOV is a result of the surge current flowing through this discrete protection mode and being dissipated in the form of heat as discussed prior.

Based on the much higher temperature rise in the discrete line-to-line MOV, the discrete line-to-line MOV absorbs a much larger portion of the surge current and energy than the combination of the two line-to-neutral paths.

This basic experiment further supports the concept of utilizing discrete and directly connected protection elements when providing surge protection for electrical systems.

VIII. Summary

In the discussion of modes of protection above, it is evident the use of individual suppression elements in all possible modes of protection is supported by such agencies as IEEE and NEMA. Also, this type of design has been successfully utilized by many manufacturers. Further, the phrase “Discrete All Mode Protection” has been used purely to distinguish between an SPD that provides discrete, individual suppression elements for each and every possible mode versus an SPD that provides suppression elements only for selected modes.

All designs including three, four, seven and ten modes of discrete protection provide a degree of protection from transient activity; it is simply a design choice when selecting the number of discrete modes to be protected.

Based on the recommendations by the IEEE, the case studies cited, and the experiment above, the inclusion of discrete all mode protection elements in surge protective devices is clearly an effective method in the protection of electrical systems.

Care should be taken when selecting a surge protective device to be sure it is understood how many modes are actually directly protected within the device and how this may impact the electrical system being protected.

IX. References

1. The Emerald Book, *IEEE Recommended Practice for Powering and Grounding Electronic Equipment (IEEE Standard 1100-1999).*
2. The Institute of Electrical and Electronic Engineers, *IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000V and less) AC Power Circuits (IEEE Standard C62.41.2-2002).*
3. NEMA Publication LS1-1992 (R2000), *Low Voltage Surge Protective Devices, 1992 (R2000)*
4. Littelfuse Application Note: Littelfuse Varistors - Basic Properties, Terminology and Theory - AN9767.1 – July 1999
5. Littelfuse Application Note: Littelfuse Varistors – The ABCs of MOVs- AN9311.6 – July 1999