

Universal SPD coordination towards an effective surge protection of power supply networks

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Abstract. The paper describes the principles of effective surge-protection devices (SPDs) coordination for both standard test impulses. Since the SPD coordination is strongly affected by the overvoltage protection components and SPD topology, laboratory measurements for different SPD types and topologies were conducted. The found results are given in the paper. The impact of the test surge impulse shape is recognized as important.

Keywords: surge protection, surge protection devices (SPDs), SPD coordination, metal-oxide varistors

1 INTRODUCTION

The equipment installed in households, business buildings or factories is vulnerable to surges that may originate due to atmospheric discharges or energy release present in a power supply system (e.g. switching actions or fuse clearing a fault) [1]. Due to vulnerability of electronic systems to lightning discharges, surge protection must be completed with an exceptional care. If surge protection is not completed in a proper manner, protected equipment may go out of operation. Protection of appliances from overvoltages coming from power supply installation should be completed in two or more stages since energy-withstand capability of surge protective devices (SPD) also means higher protection levels.

To allow for effective overvoltage protection, SPDs in two or more stages should be coordinated thus enabling each stage to successfully fulfill its tasks; first, to divert a large amount of the transient energy to the ground and second, to clamp the overvoltage and reduce it to the level at which the protected device can withstand it.

According to the classification defined by IEC 61643-1, SPDs installed at a service entrance to protect against direct lightning currents belong to Class I and which must be tested with the surge impulse 10/350 μ s with the peak of up to 100 kA [2]. SPDs intended for protection against indirect lightning effects and which must be tested with an impulse 8/20 μ s and an amplitude of 20 kA belong to Class II.

The ANSI/IEEE standard requires tests with an 8/20 μ s impulse with a peak of 100 kA [3]. These standards take different positions as to which simulation/test impulses should be considered for the SPD tests for a building or a house struck by a lightning stroke.

Problem to be solved is that the protection level (or residual voltage) of SPDs at a power-line entrance is

due to the need of a large energy withstand capability too high for the protected equipment. The solution is to apply a secondary surge arrester not withstanding as large transient energy as the first but reducing the residual voltage remaining at the first surge-protection stage to an appropriate level.

The SPD coordination requires some decoupling impedance that will take over the voltage drop between the first and the second stage and ensure that the second SPD doesn't take over the major stroke.

2 SPD COMPONENTS

Gas discharge tubes (GDT) and metal-oxide varistors (MOV) are the most common components of surge-protective devices. In this section we will briefly describe the major advantages and disadvantages of GDTs and MOVs important for effective surge protection.

2.1 Gas discharge tubes

GDTs usually consist of two or three electrodes in a glass or ceramic, inert gas (neon or argon) filled package. The electrodes are aligned with a small gap between themselves.

A typical V-I curve for GDT is shown in Figure 1. GDT has a symmetrical V-I characteristic [1].

When a voltage applied to the GDT electrodes is below its striking voltage (DC firing voltage of the gap), the current through the arrester is close to zero. At point A, GDT switches from an insulating to a conducting state. Once a potential reaches the striking voltage, the voltage across GDT suddenly collapses causing negative incremental resistance dV/dI .

The segment of the curve between points B and D is known as a glow region. This region can be divided into two subregions. In the first subregion (BC), the voltage across GDT is approximately independent of the current and is called a normal glow region. The second

subregion is characterized by positive incremental resistance dV/dI .

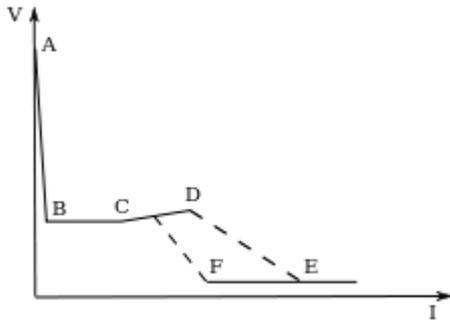


Figure 1. Typical V-I relationship for a gas discharge tube.

When the current increases (DE), the GDT voltage decreases to the level termed the arc voltage, where it stays until the surge passes away. The arrestor remains conductive until its current falls below its withstand value.

After the surge disappears, the current will be reduced to the arc extinguishing the current. At this value (point F), the arc is stopped and replaced by a glow discharge [1].

2.2 Metal-oxide varistors

MOVs are made of a ceramic material obtained by mixing ZnO with a small amount of additives. The ZnO grains are characterized by their low resistance and by being surrounded by granular layers of additives of a high resistance. This structure behaves like diodes connected in series/parallel ensuring a nonlinear performance of the varistor. The varistor nonlinear V-I characteristic can be divided into three regions [4]:

1. Low electric-field region

A low voltage is applied at the varistor terminals, the diodes don't conduct and the varistor behaves as an insulator.

2. Medium electric-field region

In this region, the current suddenly rises when the electric field reaches the value above 100 kV/mm. The current in this region varies from 1 mA to 1 kA.

3. High electric-field region

The voltage drop at MOV is linear since it is determined by the voltage drop on the ZnO grain resistance while the voltage drop at the barrier can be neglected due to the tunnel effect. Therefore, this is a linear zone of the V-I characteristic.

The published measurement results of the MOV residual voltage show the dynamic nature of the varistor since the MOV residual voltage depends on the current-surge wavefront shape [5]. In other words, the MOV residual voltage increases when the current front time decreases. The second dynamic property is that the MOV residual voltage reaches its maximum before the current maximum.

2.3 GDT vs. MOV

To meet requirements imposed by the IEC/ANSI standards, different surge protection solutions are proposed.

Some manufacturers favourise the use of GDTs in the first stage due to their ability to divert a large amount of the surge energy into the ground. Unfortunately, there are some disadvantageous of GDTs, such as requirement for arc extinguishing, presence of a follow-up current, unwanted fuse burning etc. Application of GDTs in the first stage also requires mandatory installation of a concentrated inductance for ignition, which may be also used as a decoupling inductance between the two stages. The second stage is commonly based on MOVs.

MOVs are resistors with a nonlinear V-I characteristic. Their operation causes no short short-circuits in the power supply network unlike is the case with GDTs. Application of MOVs in the first stage of internal surge protection of a certain structure is frequently avoided due to the opinion that MOVs can't withstand a direct lightning stroke.

3 SURGE TEST IMPULSES: REQUIREMENTS TO BE MET BY SPD

SPDs coordination is strongly affected by the selection of the type of the surge impulse for the reason that SPDs are decoupled by inductance. While there is no considerable difference in the front between impulses of 8/20 μ s and of 10/350 μ s, there is a notable difference in the tail and the energy carried by the impulses. The impulse shape will strongly affect current/energy sharing between SPDs in the two stages (due to the voltage drop on the decoupling inductance).

Until 1995, both IEC and ANSI/IEEE documents suggested SPD to be tested with a 8/20 μ s surge-current pulse. However, IEC in its document 61643-1 introduces SPD classes and requires that SPDs of Class 1 should be tested with an impulse of 10/350 μ s since this is the impulse which corresponds to the parameters of the direct lightning stroke [2, 6, 7]. The main aim is to define SPD satisfying requirements laid down by IEC and IEEE.

The problem to be copped with is the changeable SPD behavior during tests with impulses of 8/20 μ s and of 10/350 μ s, respectively. The impulse of 10/350 μ s is significantly longer, thus carrying a much larger amount of the transient energy. During the rise time, these pulses behave similarly. At the impulse tail of coordinated SPDs, the current gradient is low for the impulse of 10/350 μ s and the voltage drop on the decoupling inductance is small. As the second-stage SPD (with a lower protection level) takes over a significant amount of the energy, it should be designed for such scenario. When a surge-test impulse corresponds to a 8/20 μ s shape, the fall time is much

shorter and the first stage SPD takes over the main stroke. Furthermore, the lightning surge-current sharing between the neighboring structures (e.g. houses) also varies depending on the current shape due to inductances of the connecting cables.

As seen from the above, the design of the surge protection system is affected by the used surge-impulse waveform.

By the time the test-impulse shape is standardized, SPD shall have to meet both requirements to allow for a reliable operation.

Also, the above standards don't deal with the subsequent lightning strokes in the sense foreseen for SPDs. According to IEC 61312-1, a lightning stroke consists of the first stroke (90% of the negative polarity and 10% of the positive polarity), subsequent strokes of a negative polarity and a long duration stroke that might be either of a positive or negative polarity. Figure 2 shows the first three strokes and a direct lightning stroke into a tower [7].

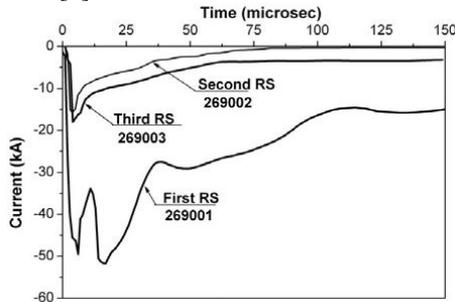


Figure 2. First three strokes of a negative five-stroke multiple lightning flash and a direct lightning discharge to an tower ([7])

The shape of the lightning strokes following the first one has a steep front and is of a short duration. According to IEC 61312-1, the subsequent strokes are modeled with an impulse of $0.25/100 \mu\text{s}$ and with a peak of 50 kA. When SPDs are coordinated in two stages, the coordination principles for the impulse of $10/350 \mu\text{s}$ do not apply to subsequent strokes (the voltage drop on the decoupling inductor is proportional to the current gradient).

4 SPD COORDINATION PRINCIPLES

As mentioned above, SPDs installed at a power-supply service entrance should withstand a direct lightning stroke. To cope with the stress, such SPD is exposed to, requires a high protection level and coordination of the two used SPDs. The role of the second SPD is besides reducing the residual voltage also to avoid flowing of the surge current through an electrical installation of a structure that would cause EMC problems [8-10]. As the energy, coordination is assumed successful if the dissipated energy through SPDs in both stages is less or equal to its maximal energy withstand capacity value.

Efficient coordination also means that the second-stage SPD is not over-dimensioned.

The two-stage SPDs are decoupled by inductor L (Figure 3). The lack of impedance would cause an overstress of the second SPD due to its lower protection level. The voltage drop on the first SPD equals the sum of the voltage drops on the inductor and on the second SPD, respectively:

$$V_{SPD1} = L \frac{di}{dt} + V_{SPD2} \quad (1)$$

Inductance L can be found in the wiring inductance. If the wiring provides satisfactory impedance, a concentrated inductance can be avoided. A concentrated inductance is preferred when the surge current should be prevented from flowing through a structure installation.

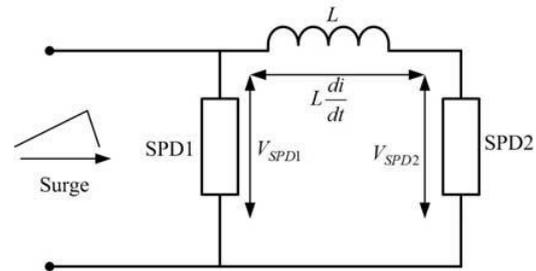


Figure 3. Two-stage SPD coordination

If the first SPD is GDT, inductance L is also required for the first SPD to reach the sparkover voltage.

Let's consider coordination with a surge impulse of $10/350 \mu\text{s}$ applied at the input of the circuit presented in Figure 3. If GDT is used as the first SPD and if an appropriate inductance guarantees ignition of a gapped SPD, GDT ensures a low-impedance connection to the ground and a low voltage drop (but also a short-circuit in the power network). The second SPD is commonly based on the MOV technology. Low impedance is important in the tail of the impulse, with the current gradient small and the inductance representing small impedance. Since the energy stored in the $10/350 \mu\text{s}$ impulse is in its tail, application of GDT ensures that the second SPD will not be overstressed. Despite the above shown GDT coordination advantage, no air-gap can be used in the power supply networks. After GDT is initiated, the electric arc can't be extinguished until the power-frequency voltage has crossed zero. The current, known as the follow-up current, continues flowing through GDT even when the surge current has disappeared. A short-circuit in the power-supply network is present until an electric arc is extinguished which causes tripping of a current-limiting fuse even at small lightning strokes. This tripping doesn't occur when using MOVs as the first SPD. Let us demonstrate the use of surge protection of a base station in a cellular telephone network. The overcurrent protection in such facilities is achieved by using a 35 A fuse withstanding up to 6 kA surge impulse of $10/350 \mu\text{s}$ without tripping [11]. If GDT is used as the first SPD and a lightning stroke of 5 kA occurs, however, GDT causes a short-

circuit, trips the fuse and the base station becomes inoperable. On the other hand, if MOV is used as the first SPD, the voltage is kept at some value (protection level) and the surge is diverted to the ground without tripping the fuse.

MOVs with a high energy withstand capability can be used in protection against direct lightning strokes. When a surge impulse of 10/350 μs is applied, MOV in the first stage will not cause a short-circuit but rather will clamp the voltage and keep it approximately constant. MOV in the second stage will take over a significant portion of the surge energy from the first SPD during the impulse tail since clamping voltage of the second SPD is lower and the voltage drop on the inductance is small.

Optionally, SPDs can be realized as MOV in series with GDT. The problem of the follow-up current is overcome by cascade connection of MOV and GDT (with appropriate protection levels). Initiated GDT will ensure low impedance and a lower voltage drop in the first branch than is the case with the single MOV.

ANSI/IEEE guidelines suggest using the test surge impulse 8/20 μs . Shorter pulse duration and a larger current gradient require a lower energy withstand capability of MOV in the second stage and an even lower value of inductance L . Further, subsequent lightning strokes presented by the pulse of 0.25/100 μs correspond to the coordination principle required for the waveform of 8/20 μs . In order to improve coordination for long-duration surge impulses, Martzloff and Lai propose coordination with MOV in the first stage having a lower clamping voltage than MOV in the second stage (10/1000 μs impulse was used) [9]. The problem is that such coordination is not successful for the 8/20 μs , as also proven by the authors in their paper. Another concept of coordination between SPD installed at a LV power-line entrance into a structure with MOVs used for protection at equipment (or installed in a device) is proposed by Mansoor et al [10]. In their case, MOV connected in series with GDT are installed at the main distribution box where the MOV clamping voltage is lower than the clamping voltage of other MOVs in the surge protection system.

This approach corresponds to the protection concept "LOW-HIGH" proposed by Martzloff. So, an approach allowing a universal coordination involves the use of a series of MOV and GDT as the first SPD.

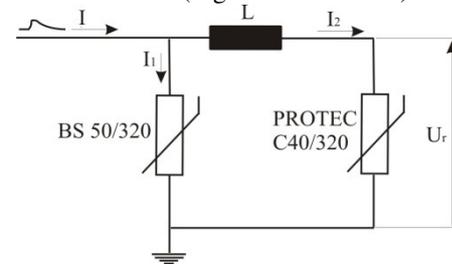
The above considerations were confirmed by laboratory measurements presented in the next section. The MOV protection capability was validated as well as the MOV ability to be successfully coordinated in two stages when applying the impulse of 10/350 μs .

5 LABORATORY MEASUREMENTS

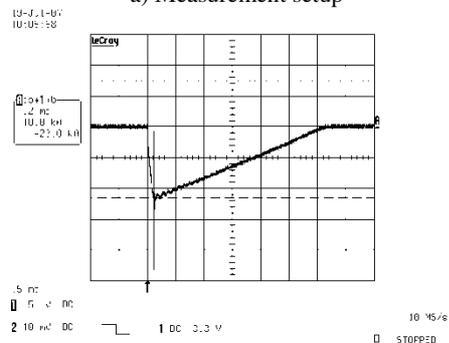
In order to confirm the above theoretical considerations, laboratory measurements of different SPD components

and topologies were conducted for the test impulses of 10/350 and 8/20 μs .

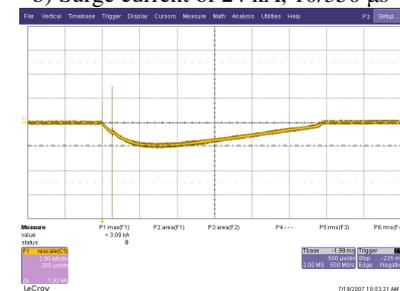
The first measurement set-up corresponded to the "classic" coordination between two MOVs including decoupling inductor $L=6 \mu\text{H}$ (Figure 4-a). The obtained measurement results for the surge impulse of 10/350 μs and the peak of 40 kA are presented in Figure 4-b. The residual voltage was 840 V and the current in the second stage was below 2 kA (Figures 4-c and 4-d).



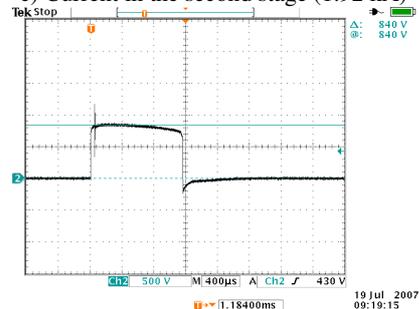
a) Measurement setup



b) Surge current of 24 kA, 10/350 μs



c) Current in the second stage (1.92 kA)



d) Measured surge current and the residual voltage after the second stage (10/350 μs impulse)

Figure 4. Coordination of MOVs in two stages

Our laboratory measurement proved that the second stage doesn't take over the major stroke. Figures 4-b and 4-c show the surge current and the current flowing through MOVs in the second stage. The measurements confirmed a successful coordination of MOVs in protection against direct lightning strokes.

Figures 5 and 6 demonstrate coordination and current sharing between a serial connection of MOVs and GDTs with MOVs in the second stage. Our measurements proved a successful universal coordination for the test impulses of 10/350 μ s and 8/20 μ s, with the advantage of the arc extinguishing due to application of MOV in the same branch with the GDT. Measurement depicted in Figure 6 shows that the MOV in the second stage are not overstressed even at a low inductance of 1 μ H for the impulse of 8/20 μ s.

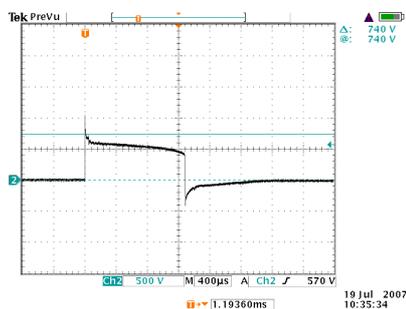
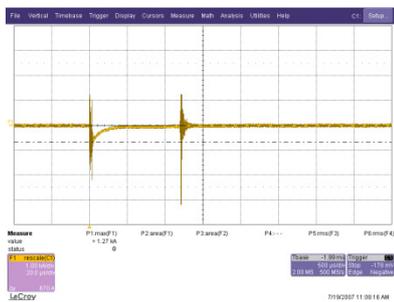
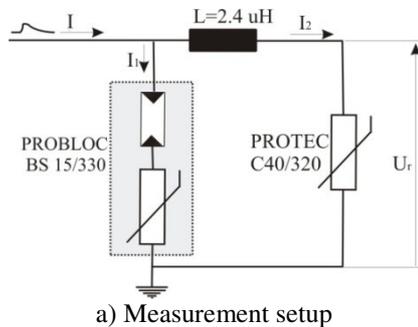


Figure 5. Current sharing in the case of coordination of MOV and GDT in the first stage with the MOV in the second stage

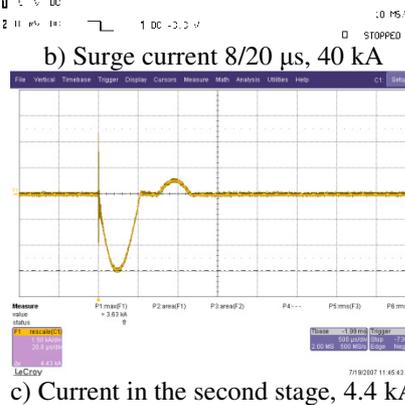
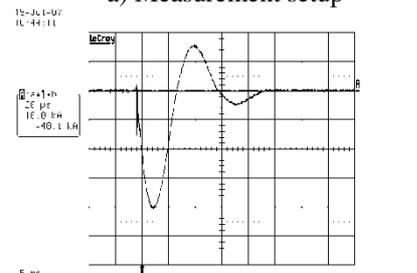
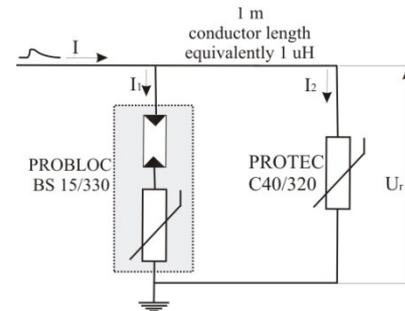
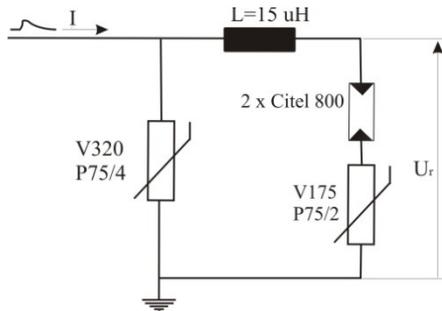


Figure 6. Current sharing in the case of coordination of MOV and GDT in the first stage with the MOV in the second stage for the test impulse of 8/20 μ s

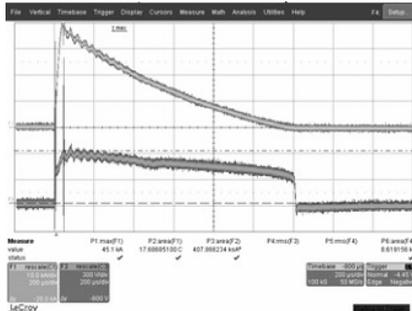
Coordination of MOVs in the first stage with a cascade connection of MOVs and GDTs in the second stage was tested in accordance with the measurement setup given in Figure 7-a. The protection levels of MOVs and GDTs were selected so as to keep the residual voltage at the second stage below 800 V at the 10/350 μ s impulse with the amplitude of 50 kA (Figure 7-b). The measurement showed that such SPD topology ensures a very low protection level, even at high surge currents.

6 CONCLUSION

The SPD coordination should be effective for both test surge impulses, i.e. 10/350 μ s and 8/20 μ s. The SPD coordination is strongly affected also by the components built-in SPDs and by the applied topology.



a) Measurement setup



b) Measured surge current (50 kA) and residual voltage after the second stage (<800 V)

Figure 7. Coordination of MOVs with a cascade connection between MOVs and GDTs in the second stage

Application of GDT causes short-circuit after ignition and trips the protected equipment even at low lightning strokes (due to the current-limiting fuse trip). Though coordination of MOVs in both stages is effective, dissipation of energy must be carried out so that the maximal energy withstand capability of each MOV is not attained and that the second-stage SPDs are not over-dimensioned.

Our measurements proved that a successful coordination may be achieved with a cascade connection between MOVs and GDTs in the first stage, for both standard test impulses. SPDs in the first stage are exposed to the major stress while a short-circuit occurrence in the LV power supply network is avoided.

ACKNOWLEDGMENT

This paper is dedicated to the memory of the late Mr sc. Vladimir Murko and represents our joint research results.

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