Graphical Analytical Method to estimate Energy Coordination of Two Varistors connected in parallel

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Abstract: Surge Protective Devices (SPDs) are used for protecting apparatus against overvoltage or overcurrent caused by lightning surge. Typical SPD is a varistor (variable resistor). Varistors can restrict to almost constant voltage across terminals, and response time is fast, but current capability is small. Therefore two varistors are normally connected in parallel. It is difficult to analyze the coordination of energy injected into a varistor when two varistors are installed in parallel on the same line. Because varistor has non linear V-I characteristics, energy coordination has so far been confirmed only by experimental methods. We propose a new graphic analytical method to estimate energy coordination in the case of installing two varistors in parallel on the same line.

Key-Words: Lightning, Overvoltage, Surge protective device, Energy Coordination, Varistor

1 Introduction

Both the characteristics of lightning surge and overvoltage protection technologies have been introduced in the articles [1]-[17]. Surge Protective Devices (SPDs) are used for protecting apparatus against overvoltage or overcurrent caused by lightning surge.

Typical SPD is a varistor. Varistor is a ceramic made of Zinc Oxide powder. The V-I characteristic of a varistor is non-linear. Varistors can restrict to almost constant voltage across terminals, and response time is fast, but current capability is small. Therefore two varistors are normally connected in parallel [18] - [26].

However there is no standard for the coordination behavior of a multistage protective circuit where two SPDs are installed in parallel. Therefore, each manufacturer selects its own SPDs to form protective circuits. However, some combinations of the characteristics of these SPDs may cause an incursion lightning surge current to concentrate only in one SPD with low operation voltage.

Therefore it is necessary to establish a systematic idea for the application of both SPDs. In this study, when two voltage-limiting SPD’s are connected in parallel, we propose a graphical analytical method for the energy coordination of both SPD’s. From the standpoint of EMC, it is necessary to construct systems in which multiple SPD’s are installed in parallel with coordinated energy to design and implement appropriate overvoltage protection. An important requirement for designing and implementing overvoltage protection of apparatus is energy coordination between a Class I SPD (current waveform specifying discharge capacity with wavehead/wavetail ratio equal to 10/350 μs) installed on the incursion input (initial stage) of a lightning surge and a Class II SPD (current waveform specifying discharge capacity with wavehead/wavetail ratio equal to 8/20 μs) installed near the protected apparatus. The Class I SPD (10/350 μs) mainly discharges most of the impulse current to the earth to ease the stress caused by the impulse current flowing into the Class II SPD (8/20 μs). The discharge capacity of the Class II SPD (8/20 μs) is smaller than that of the Class I SPD (10/350 μs), but the limiting voltage (protection level) is low. Therefore, its role is to limit the incursion overvoltage to an acceptable value. In this case, it is necessary to set conditions for current division between the Class I SPD (10/350 μs) and the Class II SPD (8/20 μs) so that a current exceeding the discharge capacity does not flow through the Class II SPD (8/20 μs).

2 Problems on the Energy Coordination of Two Varistors connected in parallel

2.1 Coordination between voltage limiting SPD’s
In the case of two voltage limiting SPD’s connected in parallel, when a discharge current starts to flow through the SPD’s, the amount of divided impulse current that flows through each SPD depends on its voltage and current characteristics, that is, the current is inversely proportional to the SPD resistance value (which is variable). In this case, coordination must be improved by the impedances (long wires, inductors, resistors) connected between them.

Considering low-voltage power system or telecommunication system of buildings, apparatus located near the entrance is generally characterized by a high impulse withstand voltage. Deeper into the building, the impulse withstand voltage of the apparatus tends to become lower and more sensitive to overvoltages. Therefore, an SPD installed at downstream of a low-voltage power system or telecommunication system usually has lower operation voltage than an SPD installed at upstream of a low-voltage power system or telecommunication system, and has a smaller current discharge capacity.

To coordinate both, the upstream SPD must operate as early as possible and bear most of the current, and the downstream SPD must not be overloaded. Therefore, in order to achieve coordination between the SPD’s so that the voltage applied to the protected apparatus does not exceed the tolerance and the SPD’s do not suffer overload, an SPD installed near the entrance of a building must have a large discharge capacity, whereas an SPD installed deeper inside must have a smaller discharge capacity. However, the latter must have a low operating voltage so that impulse currents are distributed according to the characteristics of each SPD. Thus, it becomes necessary to connect a decoupling impedance.

2.2 Numerical expression of energy coordination when two voltage limiting (voltage clamping type) SPD’s are used

Figure 1 shows the basic combination of two SPD’s (hereinafter referred to as “multistage SPD”) using two varistors as voltage limiting SPD’s. It is basically shown below that the energy coordination of SPDa and SPDb can be analytically determined based on their voltage-current characteristics.

In Figure 1, the discharge capacity and limitation voltage Ures of SPDa are high, and in SPDb, the discharge capacity is smaller and limitation voltage Ures is lower than SPDa. Rd is a resistor for decoupling. The following shows why a resistor is used as a decoupling element.

Normally an inductor is used as decoupling element in the case of installing SPD in power line due to the reason that the impedance of an inductor is low for the 50/60Hz current flowing through the line. On the other hand, normally a resistor is used as decoupling element in the case of installing SPD in telecommunication line due to the reason that the signaling current flowing through the line is very small so that a voltage drop is negligible.

When an inductor L is used as decoupling element for power line, lightning current waveform (10/350 $\mu$s or 8/20 $\mu$s) should be considered. In particular, in the case of waveform 10/350 $\mu$s, the decoupling effect of the inductor is limited to the range of the wave front only. In the long wave tail portion, the voltage drop $LdI/dt$ is small, that is, the decoupling cannot be realized.

![Fig. 1 Multistage SPD consisting of SPDa, SPDb and Rd](image)

Therefore, the following numerical expression is used on the assumption that resistor is used as a decoupling element.

The meanings of the symbols of the numerical expression are as follows:

- $V_1$: Voltage across SPDa terminals
- $i_1$: Current flowing through SPDa
- $R_1$: Instantaneous $V_1 / i_1$ ratio in SPDa
- $V_2$: Voltage across terminals of decoupling resistance Rd
- $i_2$: Current flowing through Rd
- $V_3$: Voltage across terminals of SPDb
- $i_3$: Current flowing through SPDb
- $R_3$: Instantaneous of $V_3 / i_3$ ratio in SPDb
\[ V_1 = R_1 \cdot i_1 \quad (1) \]
\[ V_2 = R_d \cdot i_2 \quad (2) \]
\[ V_3 = R_3 \cdot i_3 \quad (3) \]

where
\[ i_2 = i_3 \quad (4) \]
\[ V_1 = V_2 + V_3 \quad (5) \]

When all currents are \( i_0 \)
\[ i_0 = i_1 + i_2 = i_1 + i_3 \quad (6) \]

From (1) to (6)
\[ i_1 = \frac{R_3 + R_d}{R_1 + R_3 + R_d} i_0 \quad (7) \]
\[ i_2 = \frac{R_1}{R_1 + R_3 + R_d} i_0 \quad (8) \]

Therefore, it is possible to find how the lightning waveform current \( i_0 \) is split between SPDa and SPDb. In this case, however, \( R_1 \) and \( R_3 \) are constants. The voltage-current characteristics of these elements are in general non-linear. That is, since \( R_1 \) is a function of \( i_1 \) and \( R_3 \) is a function of \( i_3 \), it is difficult to carry out an analytical solution.

Therefore, in this paper, we propose a graphical analytical method and show an example of calculation as follows.

3 Evaluation by the graphical analytical method for energy coordination using voltage-limiting SPD

In Figure 1, the limiting voltage \( U_{res} \) must be large at the initial stage SPDa and small at the latter stage SPDb, and must be kept lower than the impulse withstand voltage of the protected apparatus. In addition, the surge current waveform and energy distribute between both SPD’s must be lower than the value tolerated by each SPD.

Figure 2 shows an example of the voltage-current characteristics curve A of voltage limiting SPDa at the initial stage and an example of the voltage-current characteristics curve B of voltage limiting SPDb at the latter stage.

In addition, the figure shows curve D describing the voltage-current characteristics when a decoupling resistor \( R_d \) of 0.5 \( \Omega \) - which is suitable for their coordination - is used, and also curve C, which is the sum of B and D. Since the terminal voltage of SPDa and the terminal voltage of SPDb+Rd are always equal, drawing a constant voltage line \( V_c \) parallel to the horizontal axis in Figure 2, we can obtain currents \( I_a \) and \( I_b \) flowing through the terminal voltages of SPDa and SPDb from the intersections with curve A and curve B.

By obtaining \( I_a \) and \( I_b \) for various \( V_c \)’s in Figure 2, the V-I characteristics of the multistage SPD formed by the combination of SPDa and SPDb can be found as shown in Figure 3.

From Figure 3, for example, it is possible to obtain the current waveform flowing through SPDa and SPDb when the lightning peak current of 15 kA (10/350 \( \mu \)s) shown in curve I of Figure 4 strikes directly and flows into this multistage SPD.
4 An example of graphical analysis of tolerance limit energy

Using the above procedure, we analyzed the tolerance limit energy for a lightning current with peak value of 700 to 5000 A. Table 1 shows specifications of each SPD. The tolerance limit energy of SPDa and SPDb are 50J and 27J respectively.

<table>
<thead>
<tr>
<th>Specifications of each SPD</th>
<th>Current (kA)</th>
<th>Energy (J)</th>
<th>( V_{\text{lea}} ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPDa</td>
<td>40</td>
<td>50</td>
<td>250</td>
</tr>
<tr>
<td>SPDb</td>
<td>40</td>
<td>27</td>
<td>135</td>
</tr>
</tbody>
</table>

For the decoupling resistance \( R_d \), we examined the cases \( R_d=0.1 \) \( \Omega \) and \( R_d=0.5 \) \( \Omega \) in addition to \( R_d=2 \) \( \Omega \).

For \( R_d=2 \) \( \Omega \) Figure 6 shows the result of tolerance limit energy analysis when the decoupling resistance value is set to 2 \( \Omega \).

In this case, the energy injected into SPDa exceeds the tolerance limit energy at 600 A. On the other hand, SPDb has still sufficient tolerance limit energy. Therefore, it can be found that the discharge capacity of both SPD’s is not used well from the standpoint of energy coordination. In this case, since the decoupling resistance is too large, the load on SPDa becomes too large.
For $R_d=0.1\,\Omega$

Figure 7 shows the result of analyzing tolerance limit energy when decoupling resistance value is set to $0.1\,\Omega$.

![Fig. 7 Tolerance limit energy in the case of $R_d=0.1\,\Omega$](image)

In this case, the energy injected into SPDb exceeds the tolerance limit energy at 500 A, but SPDa has sufficient tolerance limit energy.

For $R_d=0.5\,\Omega$

Figure 8 shows the result of analyzing tolerance limit energy when decoupling resistance value is set to $0.5\,\Omega$.

![Fig. 8 Tolerance limit energy in the case of $R_d=0.5\,\Omega$](image)

In this case, the energy injected into SPDa exceeds the tolerance limit energy at 950 A, while the corresponding tolerance limit energy for SPDb occurs at 800 A. Consequently, it can be said that proper energy coordination has been achieved.

5 Conclusions

In this paper, we considered energy coordination when two SPD’s are connected in parallel. Major results are shown below.

1. We proposed that instantaneous power and energy can be obtained graphically from the value of the current flowing through each voltage limiting SPD.
2. For the energy coordination of two SPD’s, it is important to specify a decoupling resistance value so as to allow surge currents up to their respective tolerance limits.

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