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Coordination between Voltage-Limiting Surge Protective Devices in Surge Currents Caused by Direct Lightning Flashes

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Abstract

This paper presents experimental results obtained from actual installation conditions of surge protective devices (SPDs), with the aim of understanding the coordination of cascaded Class I and Class II SPDs. This paper also proposes effective methods for selecting and installing coordinating cascaded SPDs. The residual voltage of each SPD and the energy sharing of an upstream Class I tested SPD and a downstream Class II tested SPD were measured using a 10/350 μs current wave. In coordinating a cascaded voltage-limiting SPD system, it was found that energy coordination can be achieved as long as the downstream SPD is a metal oxide varistor with a higher maximum continuous operating voltage than the upstream SPD; however, it is not the optimal condition for the voltage protection level. If the varistor voltage of the downstream SPD is equal to or lower than that of the upstream SPD, the precise voltage protection level is obtained. However, this may cause serious problems with regard to energy sharing. The coordination for energy sharing and voltage protection level is fairly achieved when the cascaded SPD system consists of two voltage-limiting SPDs separated by 3 m and with the same varistor voltage.

Key Words : Lightning Surge, Surge Protective Device, Coordinated SPD Systems, Energy Sharing, Voltage Protection Level

1. Introduction

The use of information and communication systems has increased widely with the development of high-speed semiconductor component technology. Electrical and electronic devices consisting of information and telecommunication systems installed in households, business and office buildings, or factories have a very low withstand impulse voltage level and can thus be easily damaged by surge voltages caused by electrical events such as lightning or switching operations. Damage can

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also be caused by surges entering through various paths such as signal lines, communication lines, AC power lines, and grounding systems [1-2]. Surge protective devices (SPDs) play an important role in protecting valuable electrical and electronic equipment against transients originating from lightning. SPDs should be properly installed to protect electrical and electronic devices against lightning surges [3-4]. To effectively protect these devices from surge currents caused by direct lightning flashes, energy sharing between coordinated SPDs should be properly achieved and the voltage protection level of the SPDs should be lower than the immunity level of the electronic devices to be protected, i.e., proper selection and installation of the coordinated SPD is required [5-6]. Coordination of cascaded SPDs requires an energy criterion and a voltage protection level criterion. Optimum coordination is achieved when the SPDs are not overloaded and the residual voltages are equal to or lower than the voltage the equipment to be protected is able to withstand [7]. Class I tested SPDs are required to divert surge currents caused by direct lightning flashes. In order to achieve effective protection of sensitive electrical and electronic systems, coordinated SPDs should be designed and installed. Appropriate energy sharing between the coordinated SPDs is closely associated with the SPD rating, location, and installation methods. To obtain information on improvement in protection by coordinated metal oxide varistor (MOV)-based SPDs, we investigated the voltage protection level and energy sharing in two-stage cascaded SPDs stressed by surge currents caused by direct lightning flashes. The coordination behavior of cascaded voltage-limiting SPDs was analyzed based on the voltage - current (V-I) characteristics of each SPD.

2. Theoretical Background

An effective approach to increase the reliability of electronic devices during and after exposure to large surge currents is to connect two SPDs in parallel [8-9]. It is important to achieve optimal coordination between them. Fig. 1 shows the cascaded configuration of voltage-limiting SPDs with V-I characteristics shown in Fig. 2. The operation sequence of SPDs is closely related to the maximum continuous operating voltage (MCOV) of the two SPDs, the front steepness of impinging surges, and the distance between the two SPDs.

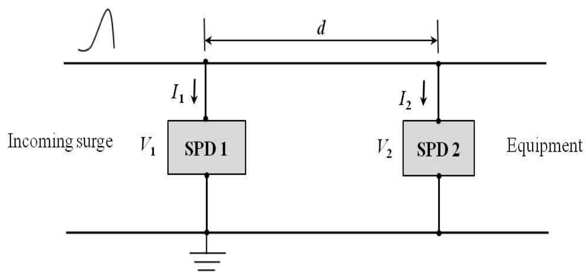


Fig. 1. Cascaded configuration of two parallel connected metal oxide varistors

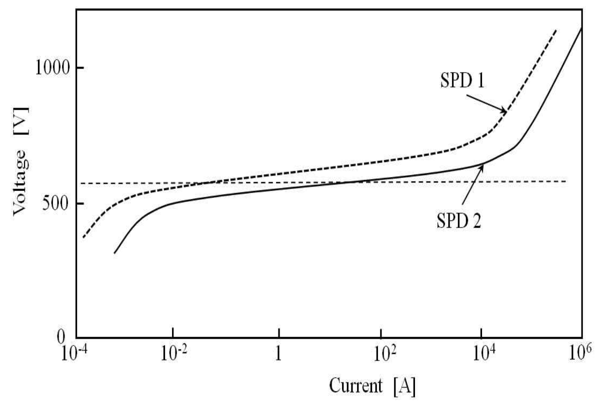


Fig. 2. V - I characteristic curves for two metal oxide varistors

The conduction sequence of the upstream and downstream SPDs is determined by the following relationship [10]:

$$V_{10} < \frac{V_{20}}{2} + \frac{\mu}{c} l \quad (1)$$

$$V_{10} > \frac{V_{20}}{2} + \frac{\mu}{c} l \quad (2)$$

where

V_{10}: the varistor voltage of the upstream SPD [kV]

V_{20}: the varistor voltage of the downstream SPD [kV]

c : the propagation velocity of surge [m/μs]

l : the distance between the two SPDs [m]

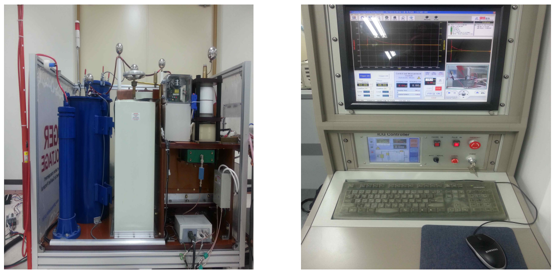
μ : the front steepness of the incoming surge [kV/μs]

If the varistor voltage of the upstream SPD is equal to or lower than the varistor voltage of the downstream SPD, eq. (1) is always satisfied and the upstream SPD starts operating first. When the varistor voltage of the upstream SPD is higher than that of the downstream SPD and if eq. (2) is satisfied, the downstream SPD can start operating first. The selection of two voltage-limiting SPDs with proper V-I characteristics allows for safe coordination. Coordination of the cascaded SPDs can be achieved using these V-I characteristics. If the portion of energy dissipated through the upstream SPD is significantly greater than that dissipated through the downstream SPD, there is no need for including any additional decoupling elements between the two SPDs.

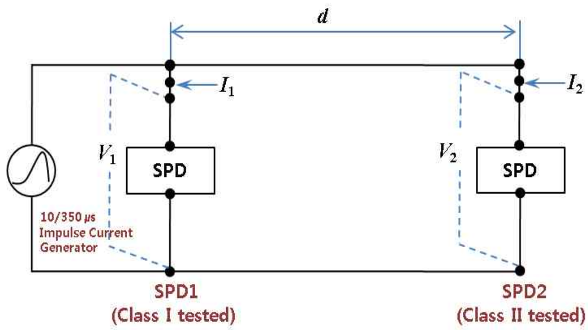
The upstream SPD should be able to dissipate a bulk of the impinging surge currents without overstressing the downstream SPD. As long as the energy dissipated in each of the two SPDs does not exceed their energy withstand capability, coordination is achieved [11]. It is important to determine the condition of optimum coordination of the cascaded SPDs, satisfying the energy criterion and the voltage protection level criterion.

3. Experiments

In this experiment, the most widely used voltage-limiting SPDs for lightning surge protection were selected. Fig. 3 shows the experimental circuit of the two-stage cascaded SPDs. The experimental conditions were illustrated in Table 1.



(a) Surge current generator



(b) Test Circuit

Fig. 3. Experimental setup

The experimental circuit was arranged using IV insulated cable with a cross-sectional area of 6 mm2 according to KS C IEC 60364-5-53 [12]. The tests were carried out according to KS C IEC 61643-11 [13]. The residual voltage of the SPDs was measured using an active differential voltage probe with a frequency bandwidth of DC to 50 MHz, and the impulse currents were measured using a penetration-type current probe. The test voltage and current waveforms were observed and recorded using a digital storage oscilloscope. The energy was calculated using the operational function of the oscilloscope. The laboratory temperature is around 24 ℃ and the relative humidity is about 42%.

Table 1. Experimental conditions

Item		Upstream SPD 1	Downstream SPD 2
Maximum Continuous Voltage(Uc)	Case 1	275 V	320 V
	Case 2	320 V	320 V
	Case 3	320 V	275 V
Energy capability	Uc 320 V	3840 J	640 J
	Uc 275 V	3300 J	550 J
SPD Rating		Class I tested SPD Iimp : 12.5 kA	Class II tested SPD In : 20 kA

4. Results and Discussion

4.1 Coordination Characteristics in Case 1

A series of experiments were carried out using the surge simulator, which can generate a 10/350 μs direct lightning current. The distance between the two-stage cascaded SPDs was 3 m. Fig. 4 shows typical waveforms of the residual voltages, power, and current flowing through the SPDs in Case 1. The upper traces show the instantaneous power dissipated in the two cascaded SPDs. The middle and lower traces display the current and residual voltages of each SPD. The instantaneous power was calculated by multiplying the voltage by current using the operational function of the oscilloscope. Additionally, the energy dissipated through the upstream and downstream SPDs was calculated by integrating the electric power, and the resultant energy was displayed as a numerical value on the screen of the oscilloscope.

When the lightning surge is impinged at the upstream terminals of the experimental circuit, the upstream SPD starts discharging first because the varistor voltage of the downstream SPD is higher than that of the upstream SPD. The residual voltage of the upstream SPD propagates along the circuit, and the voltage wave is reflected at the terminal of the downstream SPD, and the terminal voltage of the downstream SPD is given by eq. (3) [14]:

$$V_2 = V_1 + 2\frac{\mu}{c} l \qquad (3)$$

where V_1 is the terminal voltage of the upstream SPD and V_2 is the residual voltage of the downstream SPD. When this voltage exceeds the varistor voltage level of the downstream SPD, the downstream SPD starts conducting.

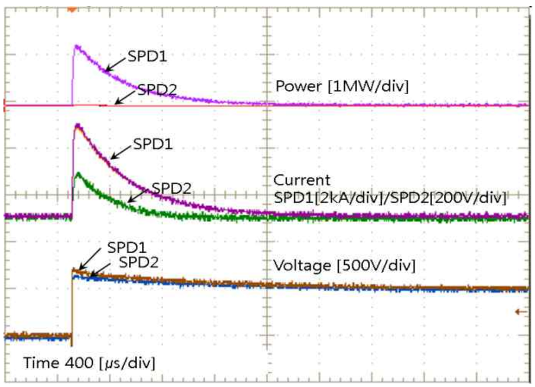
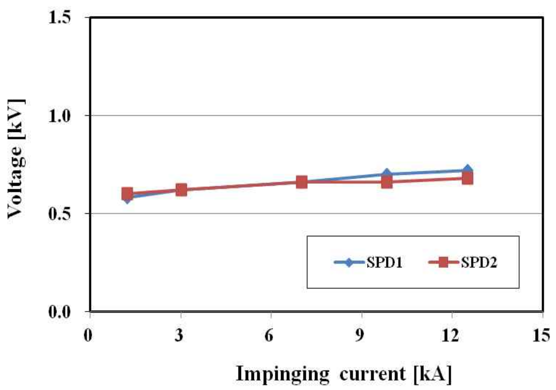


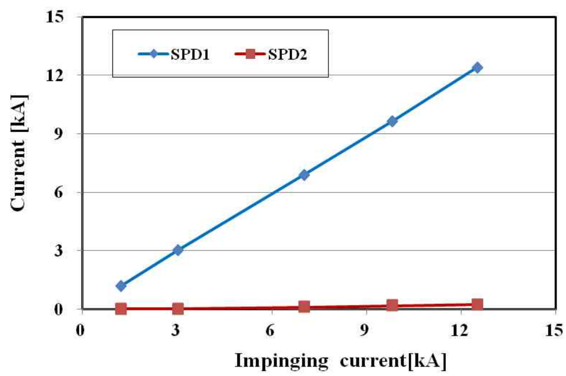
Fig. 4. Typical waveforms of the residual voltages and currents of each SPD in Case 1

Fig. 5 shows the measured results of the residual voltage, discharge current, energy, and energy sharing rates of each SPD as a function of the impinging current in Case 1. The energy and current are concentrated to the upstream SPD. The energy sharing rate is defined as the ratio of the energy dissipated through each SPD to the total incoming energy. The residual voltages of the two SPDs are similar below 7kA. The residual voltage of the downstream SPD is inferred to be slightly lower than that of the upstream SPD at higher currents because the inductance of the connection leads between the two SPDs acts as a decoupling element. The discharge current and energy sharing values of the downstream SPD are low and constant, but those of the upstream SPD increase proportionally with the amplitude of the impinging surge current. It was found that the discharge current and energy sharing between the two-stage cascaded SPDs are strongly dependent on the varistor voltage and the $V-I$ characteristics of the SPDs. In coordinating cascaded SPDs, if the MCOV of the upstream SPD is lower than that of the downstream SPD, the energy coordination of the upstream and downstream SPDs is moderate.

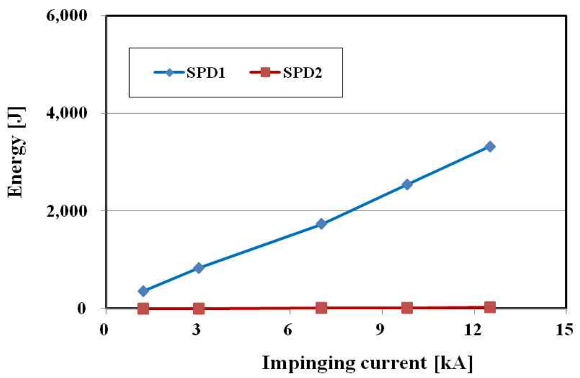
However, the voltage protection levels of the upstream and downstream SPDs are nearly the



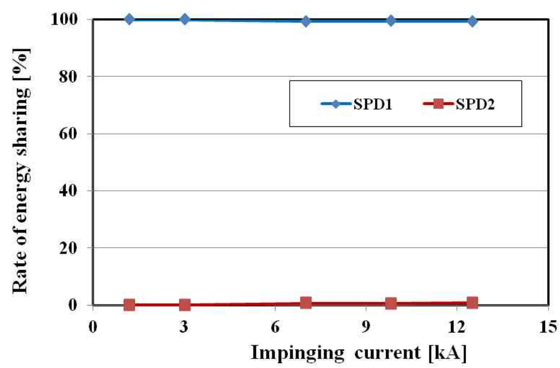
(a) Residual voltage



(b) Discharge current



(c) Energy



(d) Rates of energy sharing

Fig. 5. Measured results of the residual voltages, discharge currents, energy, and sharing rates of each SPD as a function of the impinging current in Case 1

same, it cannot limit the incoming surges to the voltage protection level below the withstand voltage of the equipment to be protected.

4.2 Coordination Characteristics in Case 2

Fig. 6 shows typical waveforms of the residual voltages and the currents flowing through the SPDs in Case 2. When the test surge current is impinged at the upstream terminals of the experimental circuit, the upstream SPD starts discharging first

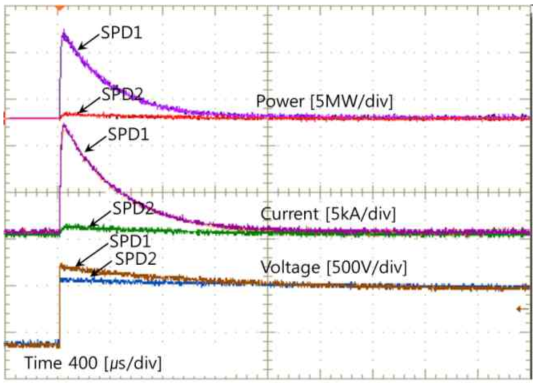
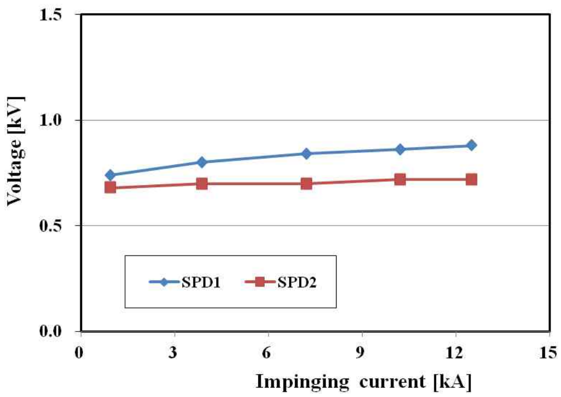
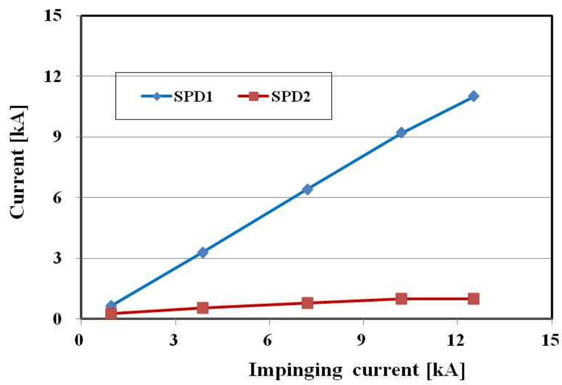


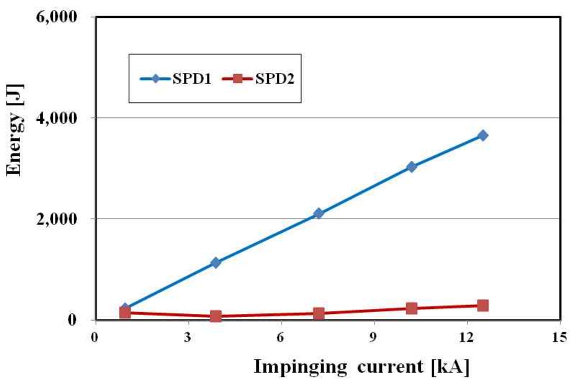
Fig. 6. Typical waveforms of the residual voltages and currents of each SPD in Case 2



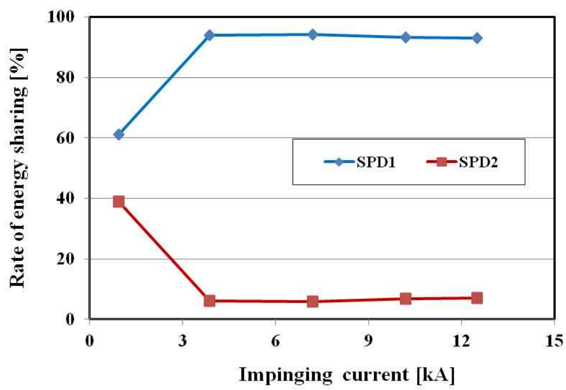
(a) Residual voltage



(b) Discharge current



(c) Energy



(d) Rates of energy sharing

Fig. 7. Measured results of the residual voltages, discharge currents, energy, and sharing rates of each SPD as a function of the impinging current amplitude in Case 2

because the varistor voltages of the upstream and downstream SPDs are same.

Fig. 7 shows the measured results of the residual voltage, discharge current, energy, and energy sharing rates of each SPD as a function of the impinging current amplitude in Case 2. The residual voltage of the upstream SPD is higher than that of the downstream SPD. The residual voltage of the upstream SPD increases with the impinging current. This is considered to occur because the inductance of the connection leads between the two SPDs acts as a decoupling element and the current flowing into the upstream SPD is higher than that flowing in the downstream SPD. However, the residual voltage of the downstream SPD is almost constant because the discharge current flowing through the downstream SPD is relatively low.

The discharge current and the energy dissipated through the two SPDs increase proportionally with the impinging current. When the impinging current is 1 kA, the energy sharing rate of the downstream SPD is 40%; however, it is approximately 7% when the impinging current exceeds 4kA. In addition, the amount of energy sharing of the downstream SPD over the entire range of injected currents is less than its energy capability. The coordination based on the energy sharing and voltage protection level criteria is implemented for the cascaded SPD system consisting of two MOVs separated by 3 m and with the same varistor voltage.

4.3 Coordination Characteristics in Case 3

Fig. 8 shows typical waveforms of the residual voltages and the current flowing through the SPDs in Case 3. In this case, when the surge current is impinged at the upstream SPD, if the distance between the two SPDs is short and the front steepness of the impinging current is slow, the downstream SPD can start discharging first, as expressed by eq. (2).

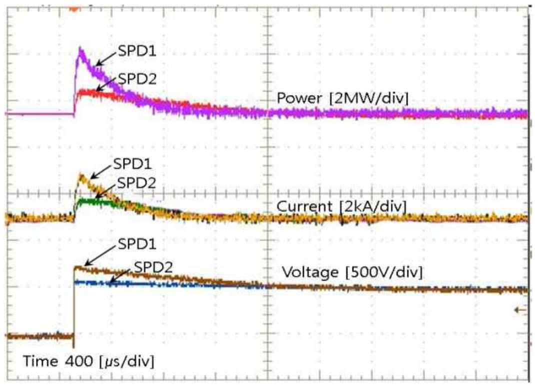
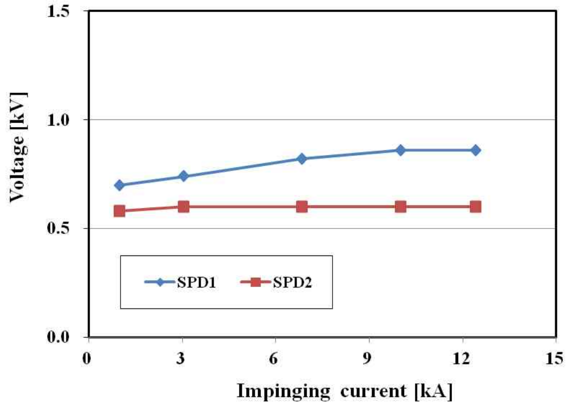


Fig. 8. Typical waveforms of the residual voltages and currents of each SPD in Case 3

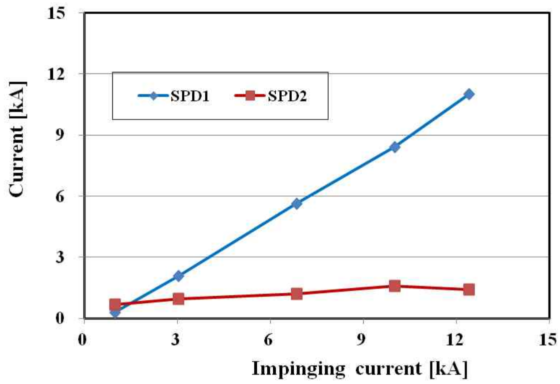
Fig. 9 shows the measured results of the residual voltage, discharge current, energy, and sharing rates of each SPD as a function of the impinging current in Case 3. The terminal voltage of the upstream SPD, V_1, is equal to the sum of the terminal voltage of the downstream SPD, V_2, and the voltage drop induced by the inductance of the connecting leads between the upstream and downstream SPDs, as given by eq. (4) [15-17]:

$$V_1 = V_2 + L\frac{di_2}{dt} \tag{4}$$

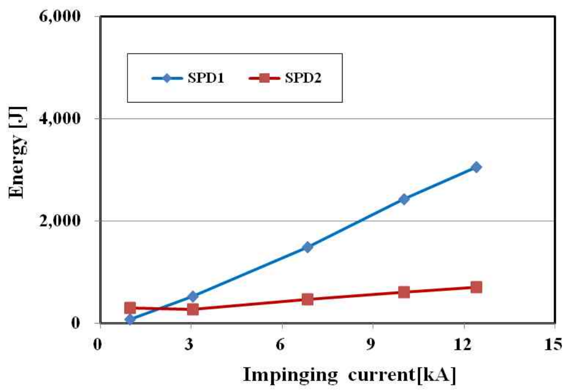
where L is the inductance of the leads connecting the upstream and downstream SPDs. The inductance per two parallel leads is 0.5 μH/m approximately at short spacing between two-leads. When V_1 exceeds the varistor voltage level of the upstream SPD, the upstream SPD starts discharging and the current flows through the upstream SPD. Thus, the residual voltage of the downstream SPD



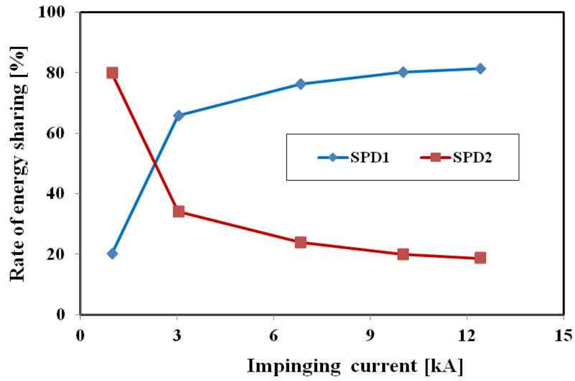
(a) Residual voltage



(b) Discharge current



(c) Energy



(d) Rates of energy sharing

Fig. 9. Measured results of the residual voltages, discharge currents, energy, and sharing rates of each SPD as a function of the impinging current in Case 3

is lower than the terminal voltage of the upstream SPD. This cascaded SPD system is thus effective in reducing the voltage protection level of the equipment to be protected.

Compared with Cases 1 and 2, the energy coordination between the upstream and downstream SPDs in this case is easy to implement because the current flowing through the downstream SPD is suppressed by the inductance of the leads connecting the upstream and downstream SPDs. Because the downstream SPD starts discharging first, the energy sharing of the downstream SPD is greater than that of the upstream SPD when a surge current below 2 kA is injected. The maximum energy sharing of the downstream SPD is 1,935 J at an impinging current of 1 kA. Because the amount exceeds the energy withstand capability of the downstream SPD, the energy coordination between the two SPDs is not satisfied. Thus, it was found that the selection of SPDs with proper V-I characteristics and the application of decoupling elements such as the inductance of leads connecting the two SPDs are key factors for achieving energy coordination in Case 3.

In coordinating cascaded-SPD systems, if the MCOV of the downstream SPD is lower than that of the upstream SPD, the downstream SPD can limit incoming surges to the voltage protection level below the withstand voltage of the equipment to be protected. However, a detailed consideration regarding the energy coordination criterion between the two SPDs has to be examined.

5. Conclusion

The energy coordination and voltage protection level criteria of two-stage voltage-limiting SPDs closely depend on the voltage–current characteristics of the SPDs. In two-stage cascaded SPDs, if the distance between the cascaded MOV–MOV SPDs is short, the coordination should be examined based on the V–I characteristics of the two SPDs. The cascaded MOV-based SPDs can achieve energy coordination as long as the downstream SPD is a MOV with a higher varistor voltage than the upstream SPD; however, it does not provide the optimum voltage protection level. If the varistor voltage of the upstream SPD is higher than that of the downstream SPD, energy coordination cannot be effectively fulfilled at a short distance between the SPDs. The coordination of a cascaded MOV-based SPD system, with a short distance between the two SPDs, is satisfactorily achieved when the varistor voltage of the upstream SPD is equal to or slightly lower than that of the downstream SPD. Further studies on various installation conditions of cascaded metal oxide varistor-based SPDs with the objectives to propose the proper selection and installation methods of the cascaded SPDs are proposed.

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