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Further coordination tests between SPDs and between SPD and Equipment

Alain Rousseau

SEFTIM
Vincennes, France
alain.rousseau@seftim.fr

Qibin Zhou, Yang Zhao

Shanghai Lightning Protection Center
Shanghai, China
zhouqb@lightning.sh.cn

***Abstract*—There may be SPD from many manufacturers on the same line. One SPD is installed by the contractor in charge of electrical installation and then various panel boards are used in the installation made by various panel builders. All of them may use a different brand of SPDs. A solution would be to perform the coordination tests proposed by the European CLC TS 61643-12 standard. A preliminary paper was presented at ICLP 2012 and this is a further contribution taking care of comments received.**

Keywords-SPDs; tests, coordination; equipment, installation

I. INTRODUCTION

In order to protect an electrical installation the use of more than one SPD type is often necessary depending on the overvoltage category of the equipments to be protected and on the wiring of the electrical installation (cable length, routing etc). In this case effective SPD coordination should be examined so as not to overstress downstream SPDs but also to limit the overvoltage level to a value lower than the withstand voltage of the under protection equipment. When SPDs are from different brand there are two basic ways to show coordination of SPDs: either simulations or testing. This contribution only deals with tests. A preliminary paper was presented at ICLP 2012. This paper concentrates on three questions following the initial presentation. Namely, there are three main questions which need discussion, as follows,

- Q1. Influence of the cabling and typical material around the cables. This will address coordination tests when the two conductors run together in a plastic PVC tube, in a metallic pipe or inside a metal tray.
- Q2. The influence of the load characteristic. This will address coordination effect between SPDs and resistive load (such as light, heater) as well as between SPDs and inductive load (such as motor, transformer)
- Q3. The influence of the surge type. This will address coordination effect for different types of surge, such as steesurge as 0.2/0.5 μs, short surge as 8/20 μs and long surge as 10/350 μs.

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All above three aspects have been experimentally studied in Shanghai Lightning Protection Center recently. Results are presented and discussed below.

II. COORDINATION TEST DESCRIBED IN CLC TS 61643-12

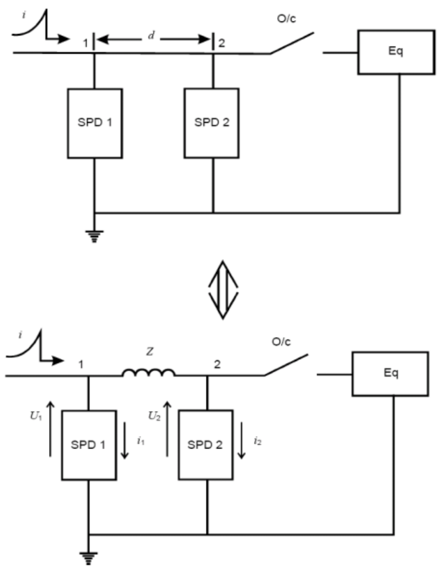
A. Coordination criteria

Co-ordination of SPDs requires the completion of two basic criteria, the energy criterion and the voltage protection level criterion.

Energy co-ordination can be achieved if, for all the values of the total incoming lightning/surge current, the portion of the energy that is dissipated through the upstream SPD is higher than the energy dissipated through the downstream SPD. Additionally any elements between the upstream and the downstream SPDs should be able to withstand the same energy as the downstream SPDs. This is the basis for coordination as per today's version of the standard.

Moreover, it is additionally proposed that the voltage protection level for the downstream SPDs should be equal or ideally, lower than the upstream SPDs, since they are situated nearer to the equipment to be protected, where more precise voltage protection is required.

B. Coordination test



Key
Eq - Equipment to be protected in normal cooperation
O/c - Open circuit (Equipment disconnected from supply)
i - Incoming surge

Figure 1. SPDs arrangement for the coordination test

Coordination between SPDs is based on current sharing. Three parameters are defined as essential in establishing coordination:

- the SPD themselves (One SPD is coordinated with another);
- the surge current at the entrance (fixed by front SPD's characteristics);
- The decoupling impedance Z between the 2 SPDs (the front and the downstream SPD).

The impedance Z between the two SPDs (in general an inductance) may be a physical one (a specific component inserted in the line to facilitate the sharing of the energy between the two SPDs) or represent the inductance of a length of cable between the two SPDs.

A SPD's coordination test can be performed by the SPDs manufacturer, by the installer or by the user.

Coordination for SPD is achieved if these two criterions are fulfilled.

- Energy co-ordination is achieved, if for all values of surge current from a minimum testing energy to a maximum testing energy (0.1, 0.25, 0.5, 0.75, 1 time I_{max} and I_n for Type 2 SPD. 0.1, 0.25, 0.5, 0.75, 1 time I_{imp} and I_n for Type 1 SPD) the portion of energy, dissipated through SPD2 is lower than or equal to its maximum energy withstand (E_{MAX2}).
- Protection coordination is achieved, if for all values of surge current from a minimum testing energy to a maximum testing energy (0.1, 0.25, 0.5, 0.75, 1 time I_{max} and I_n for Type 2 SPD. 0.1, 0.25, 0.5, 0.75, 1 time I_{imp} and I_n for Type 1 SPD) the residual voltage of SPD2 is lower than or equal to its declared protection level Up.

The testing with portion of the declared In (or Imax when it is defined) or I_{imp} current is to explore if no blind spot up from low stress to maximum stress is existing.

C. Pass criteria

The SPD has passed the test if any follow current is self-extinguished and thermal stability is achieved after each impulse of the coordinated SPD test. Both the voltage and current records, together with a visual inspection, shall show no indication of puncture or flashover of the samples. Mechanical damage shall not occur during these tests.

The measured residual voltage of the SPD2 shall never exceed its declared Up.

What is interesting is that this test is able not only to determine the energy coordination but also to show that the protective level of the second SPD is guaranteed or even that the protective level of the second SPD is much better than what is printing on the nameplate.

III. TEST PARAMETERS

A. Experimental materials

- SPD

Table 1 Parameters of selected SPDs

No.	SPD1	SPD2	SPD3
Test class	I	II	II
Type	Switching	Clamping	Clamping
U_c (V) AC	260	385	385
I_{imp} (kA)	25	/	/
I_n (kA)	25	80	20
I_{max} (kA)	/	160	40
U_p (kV)	1.5	3.2	1.6

- PVC pipe around conductors.
- Metallic pipe
- Metal trays
- 4 Cables with length of 8m and 20m.
- Load 1: pure resistor with resistance 2Ω.
- Load 2: filament lamp with resistance 55.2Ω
- Waveforms : 0.2/0.5 μs, 8/20 μs, and 10/350 μs

B. Experimental setup

1) Without load (coordination between two SPDs)

The circuit diagram and the associated pictures are shown below.

SPD_1 is selected as front SPD and SPD_3 is selected as downstream SPD. These SPDs are connected in parallel by two cables 8m long, enclosed in a PVC pipe.

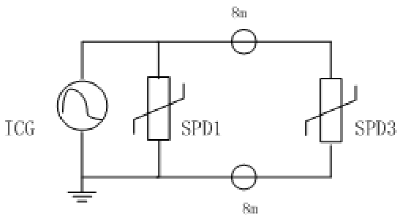


Figure 2. SPDs test circuit diagram

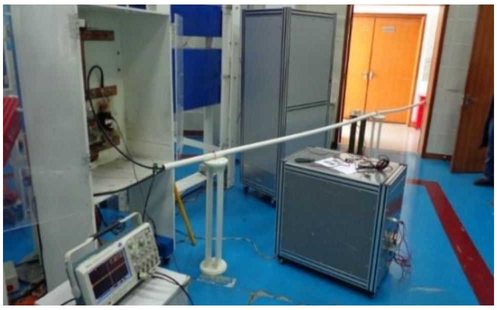


Figure 3. Cable in a pipe between two SPDs

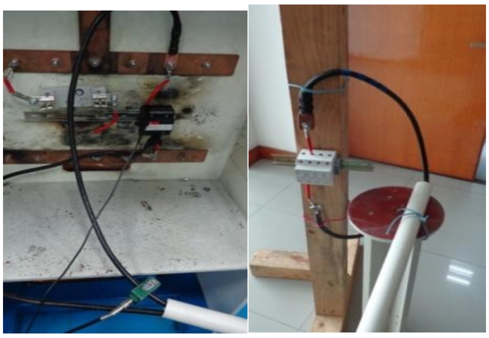


Figure 4. SPDs test pictures (left front SPD and right downstream SPD)

2) With various load (coordination between two SPDs and a load)

This takes care of two possible loads: pure resistive load and a filament lamp load.

The circuit diagram for pure resistive load is shown below. SPD_1 is selected as front SPD and SPD_3 is selected as downstream SPD. These SPDs are connected in parallel by two cables 8m long, like above. The load is connected in parallel directly with SPD_3. The two cables are enclosed in a PVC pipe. For pure resistive load, the load resistance is 2Ω.

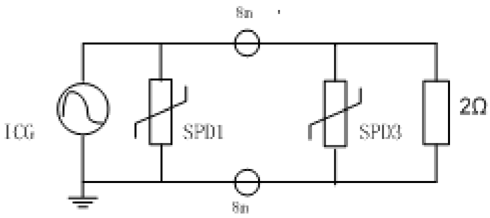


Figure 5. SPDs and resistive load test circuit diagram

Figure 6. Test arrangement for resistive load

For the lamp, the resistive load in the circuit diagram above has been replaced by a filament lamp whose resistance is 55.2 Ω. A 220V operating voltage is applied to the filament lamp.

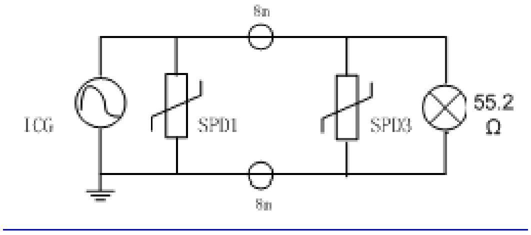


Figure 7. test circuit diagram with SPDs and lamp load

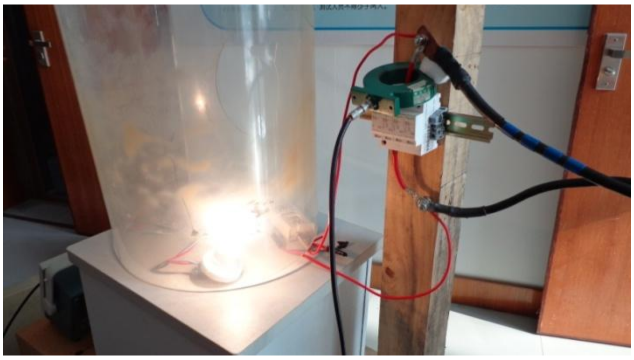


Figure 8. Test arrangement for lamp load

3) With load (coordination between two SPDs and a load) and various magnitudes and varioius cable lengths

For these tests we used different impulse current magnitudes with the lamp load and used various cable lengths with the same conditions as above. Coordination is between SPD_2 , SPD_3 and the filament lamp under protection

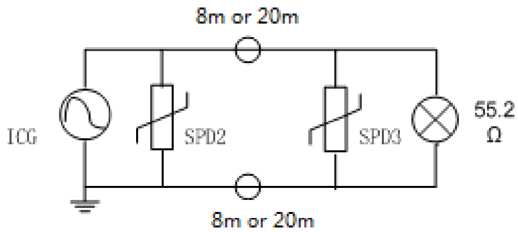


Figure 9. test circuit diagram with SPDs and lamp for various magnitudes and cable lengths

SPD_2 and SPD_3 are both of limiting type (MOV).

4) With load (coordination between two SPDs and a load) and different enclosures around the 20m cables

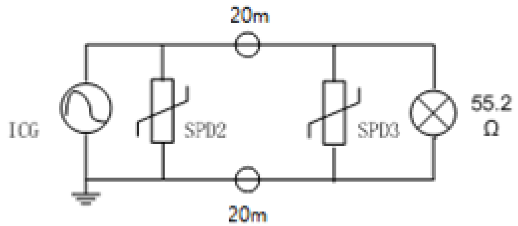


Figure 10. test circuit diagram with SPDs and lamp for difference enclosures around the cable

For these tests, we put cables in metallic pipe and metal trays. The circuit diagram of these tests is shown as Figure 10. Coordination is between SPD_2 and SPD_3 and the filament lamp protection. There is not 220V operating voltage applying on the filament lamp due to loss of power.

Figure 11. Coordination test for cables in metallic pipe and metal trays

5) Comparison between 0.2/0.5 µs, 8/20 µs and 10/350 µs surge waveforms

The length between SPD_2 and SPD_3 is fixed as 20 meters. SPD_2 and SPD_3 are both MOV-type SPDs. The waveforms are 8/20 µs, 10/350 µs and 0.2/0.5 µs. The electrical degree is 60 °.

IV. Test Results

A. Two SPDs coordination in Figure 2 setup

TABLE I. TESTS RESULTS FOR SPDS COORDINATION

Surge waveform	I_{total} (kA)	I_{SPD1} (kA)	U_{res1} (kV)	I_{SPD3} (kA)
8/20 µs	30.033	27.2	1.74	1.896

Itotal: impulse current from the generator, Ispd1: impulse current through SPD_1 Ures1: residual voltage at SPD_1, Ispd3: impulse current through SPD_3

The yellow curve is the residual voltage of SPD_1. The purple curve is the current of SPD_1. The blue curve is the current in the cable.

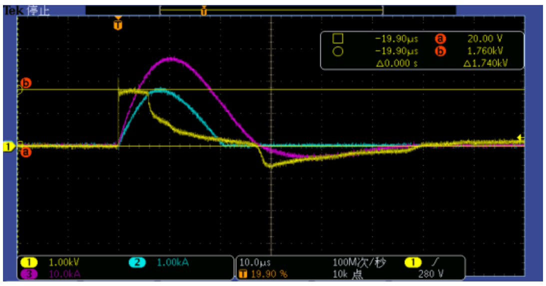


Figure 12. Oscillograms for two SPDs coordination test

B. Two SPDs and load coordination in Figure 5& Figure 7 setup

TABLE II. TESTS RESULTS FOR SPD AND RESISTIVE LOAD COORDINATION

Surge waveform	load	I_{total} (kA)	I_{SPD1} (kA)	U_{res1} (kV)	I_{SPD3} (kA)	I_R (A)
8/20 µs	Resister	30.002	27.6	1.74	1.352	480
	light	30.323	27.6	1.74	1.68	1.4

Itotal: impulse current from the generator, Ispd1: impulse current through SPD_1, Ures1: residual voltage at SPD_1, Ispd3: impulse current through SPD_3, I_R : current through the load

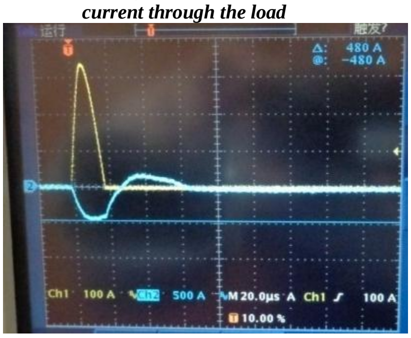


Figure 13. Oscillograms for SPD_3 and resistive load coordination test

The yellow curve is the current of SPD_3. The blue curve is the current of the resistance.

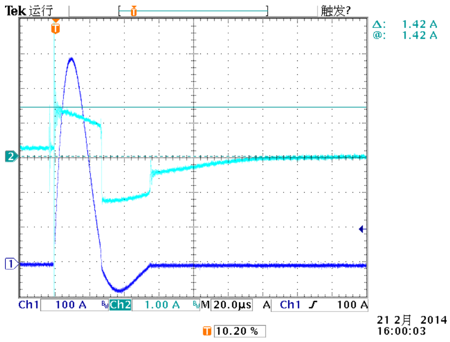


Figure 14. Oscillograms for SPD_3 and lamp load coordination test

The navy blue curve is the current of SPD_3. The sky blue curve is the current through the filament lamp.

C. Two SPDs and lamp load coordination magnitudes of injected current and with various length of cables in Figure 9 setup

TABLE III. TESTS RESULTS FOR SPD AND LAMP LOAD COORDINATION WITH VARIOUS MAGNITUDES AND 8m CÂBLE

Surge waveform	I_{total} (kA)	I_{SPD2} (kA)	U_{res2} (kV)	I_{SPD3} (kA)	U_{res3} (V)
8/20 µs	41.766	37.2	1.480	1.952	/
	50.342	44.2	1.640	2.360	79.5
	62.426	54.4	1.760	2.904	79.5
	74.278	64.6	1.940	3.600	83.9
	79.892	69.4	2.040	3.860	88.3

Itotal: the impulse current from the generator, Ispd2: the impulse current through SPD_2, Ures2: the residual voltage at SPD_2, Ispd3: the impulse current through SPD_3, Ures3: the residual voltage at SPD_3, Coupling degree: the phase degree of power source when trigging impulse current.

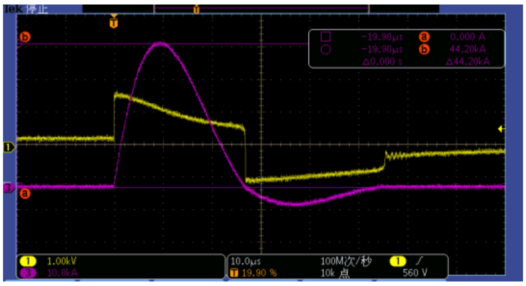


Figure 15. Oscillograms for two SPDs and lamp coordination test with 8 m cable – Ispd2(purple) and Ures2(yellow)

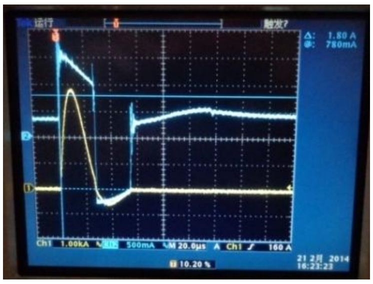


Figure 16. Oscillograms for two SPDs and lamp coordination test with 8 m - cable – Ispd3(yellow) and Ures3(blue)

TABLE IV. TESTS RESULTS FOR SPD AND LAMP LOAD COORDINATION WITH VARIOUS MAGNITUDES AND 20 m CÂBLE

Surge waveform	I_{total} (kA)	I_{SPD2} (kA)	U_{res2} (kV)	I_{SPD3} (kA)	U_{res3} (kV)
8/20µs	33.142	31.80	1.42	8.42	0.98
	42.426	40.20	1.32	10.4	1.04
	52.534	49.40	1.70	12.80	1.04
	63.845	58.60	1.84	15.36	1.04
	77.135	68.6	2.02	18.48	1.04

Itotal: the impulse current from the generator, Ispd2: the impulse current through SPD$_2$, Ures2: the residual voltage at SPD$_2$, Ispd3: the impulse current through SPD$_3$, Ures3: the residual voltage at SPD$_3$

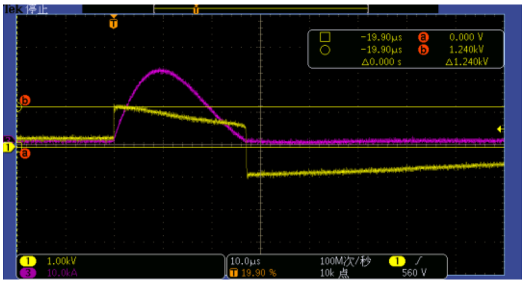


Figure 17. Oscillograms for two SPDs and lamp coordination test with 8 m cable – Ispd2(purple) and Ures2(yellow)

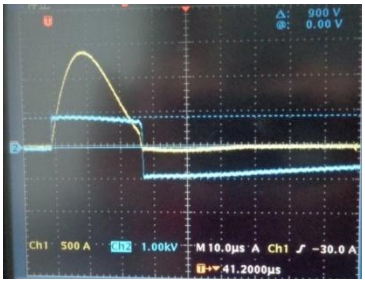


Figure 18. Oscillograms for two SPDs and lamp coordination test with 8 m - cable – Ispd3(yellow) and Ures3(blue)

D. With load (coordination between two SPDs and a load) and different enclosures around the cables in Figure 10 setup

TABLE V. TESTS RESULTS FOR SPD AND LMP LOAD COORDINATION WITH METALLIC PIPE AROUND THE CABLE BETWEEN THE SPDS

Surge waveform	I_{total} (kA)	I_{SPD2} (kA)	U_{res2} (kV)	I_{SPD3} (kA)	U_{res3} (kV)
8/20µs	10.296	10.12	1.059	0.214	0.832
	21.529	21.10	1.209	0.400	0.872
	32.761	31.90	1.362	0.608	0.860
	43.963	42.00	1.503	0.768	0.920
	52.468	48.00	1.600	0.896	0.960
	63.243	58.80	1.728	1.08	0.980
	77.400	72.80	1.885	1.32	0.980

Itotal: the impulse current from the generator, Ispd2: the impulse current through SPD2, Ures2: the residual voltage at SPD2, Ispd3: the impulse current through SPD3, Ures3: the residual voltage at SPD3

In all case the lamp was still working during and after the test.

TABLE VI. TESTS RESULTS FOR SPD AND LMP LOAD COORDINATION WITH METAL TRAYS AROUND THE CABLE BETWEEN THE SPDS AND 8/20 µs WAVEFORM

Surge waveform	I_{total} (kA)	I_{SPD2} (kA)	U_{res2} (kV)	I_{SPD3} (kA)	U_{res3} (kV)
8/20 µs	9.904	9.8	1.074	0.208	0.860
	21.494	20.4	1.270	0.412	0.880
	33.022	30.4	1.411	0.612	0.900
	43.546	40.2	1.536	0.808	0.920
	52.058	46.8	1.672	0.952	0.940
	63.135	56.2	1.807	1.15	0.960
	77.168	67.2	1.957	1.42	0.980

Itotal: the impulse current from the generator, Ispd2: the impulse current through SPD2, Ures2: the residual voltage at SPD2, Ispd3: the impulse current through SPD3, Ures3: the residual voltage at SPD3

E. *Comparison between 0.2/0.5, 8/20 and 10/350 surge waveforms in Figure 9 setup*

TABLE V. TESTS RESULTS FOR SPD AND LMP LOAD COORDINATION WITH VARIOUS MAGNITUDES AND 0,2/0,5µs WAVEFORM

Surge waveform	I_{total} (A)	U_{res2} (kV)	U_{res3} (kV)	I_{SPD2}/I_{total} (%)	I_{SPD3}/I_{total} (%)
0.2/0.5µs	400	1.22	1.05	100	6.25
	500	1.39	1.05	100	5.48
	600	1.39	1.06	100	5.23
	700	1.27	1.10	100	4.94
	800	1.28	1.14	100	4.65

TABLE VI. TESTS RESULTS FOR SPD AND LAMP LOAD COORDINATION WITH VARIOUS MAGNITUDES AND 8/20 µs WAVEFORM

Surge waveform	I_{total} (A)	U_{res2} (kV)	U_{res3} (kV)	I_{SPD2}/I_{total} (%)	I_{SPD3}/I_{total} (%)
8/20µs	33.142	1.42	0.98	95.951	24.863
	42.426	1.32	1.04	94.753	24.513
	52.534	1.70	1.04	94.034	24.365
	63.845	1.84	1.04	91.785	24.058
	77.135	2.02	1.04	88.934	23.958

TABLE VII. TESTS RESULTS FOR SPD AND LAMP LOAD COORDINATION WITH VARIOUS MAGNITUDES AND 10/350 µs WAVEFROM

Surge waveform	I_{total} (A)	U_{res2} (kV)	U_{res3} (V)	I_{SPD2}/I_{total} (%)	I_{SPD3}/I_{total} (%)
10/350µs	6.04	1.18	890	93.212	3.011
	7.91	1.26	890	94.690	3.188
	9.85	1.43	920V	96.041	3.656
	11.90	1.60	930	96.607	3.561
	13.80	1.78	1140	97.419	3.835

Itotal: the impulse current from the generator, Ispd2: the impulse current through SPD2, Ures2: the residual voltage at SPD2, Ispd3: the impulse current through SPD3, Ures3: the residual voltage at SPD3

V. CONCLUSIONS

For both the 8-meters and 20-meters long cable, the current sharing between tested SPDs is working well. Most of the surge current flows into the PE through the SPD installed at entrance and only a small part is transferred to the downstream SPD installed before the load to be protected. Only a very tiny surge current will flow through the load. So the load lamp is protected ideally.

The current flowing into the load under protection is dependent on the resistance of load. The larger is the resistance, the less is the invading surge current. This can be explained by the current-sharing between SPD3 and load.

As expected, the longer the cable, the less current (energy) will be shared in the downstream SPD (SPD_3) and more current (energy) will be shared in the upstream SPD (SPD_2), namely the best energy coordination between two SPDs.

The longer the cable, the higher is the residual voltage that appears at the downstream SPD (SPD_3), namely the worse insulation coordination between two SPDs.

Comparing the SPDs with cables which are in the enclosure of metallic pipe or metal trays for the cables, the residual voltage and impulse current are substantially equal.

For all three waveforms (0.2/0.5 µs, 8/20 µs and 10/350 µs), the majority of current was released by SPD_2 and just a little current flowed through SPD_3. The load hasn't been damaged for any of these surges. Successful energy coordination was achieved.

The steeper is the injected surge wave-front, the higher is the residual voltage at SPDs. The steeper is the injected surge wave-front, the worse is the attenuation of the residual voltage at SPD_3.

The sum of the peak values of Ispd2 and Ispd3 is not equal to I_{total} peak value because the waveform of Ispd3 is distorted from the source. Especially for steep surge like 0.2/0.5µs, the distortion is much more severe than slow surge.

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