There was no discontinuous point in residual voltages, and the maximum residual voltage was less than 1.5kV as listed in Table 1. And also there was no dependence on lightning surge polarities, due to symmetric configuration.

Therefore evaluation tests were passed.

Table 1 Measured residual voltages（2.5～25kA,8/20μs）

Sample No.	+−	0.1 In	+−	0.2 In	+ −	0.5 In	+ −	In
	kA	kV	kA	kV	kA	kV	kA	kV
1	2.5	0.6	5.0	0.7	12	0.9	25	1.2
1	-2.5	-0.6	-5.0	-0.7	-12	-0.9	-25	-1.2
2	2.5	0.6	5.0	0.7	12	0.9	25	1.2
2	-2.5	-0.6	-5.0	-0.7	-12	-0.9	-25	-1.2
3	2.5	0.6	5.0	0.7	12	0.9	25	1.2
3	-2.5	-0.6	-5.0	-0.7	-12	-0.9	-25	-1.2

6.3 Measure the Sparkover Voltage according to IEC 7.5.3 clause

The impulse (6kV, 1.2/50μs) as shown in Fig.1 was used. 10 impulses were applied to samples No.1, No.2 and No.3 with five of positive and five of negative polarity. The operating voltages called sparkover voltages of SPDs were measured as listed in Table 2.

Table 2 Measured operating voltages U_p（6kV,1.2/50μs）

No	U_p(V)	U_p(V)	U_p(V)	U_p(V)	U_p(V)	
1	900	920	900	960	880	○
1	-880	-980	-940	-960	-960	○
2	760	900	820	840	840	○
2	-920	-960	-960	-960	-860	○
3	900	920	780	880	880	○
3	-780	-840	-960	-900	-920	○

The maximum measured operating voltage was less than 1.5kV. And also there was no dependence on lightning surge polarities, due to symmetric configuration.

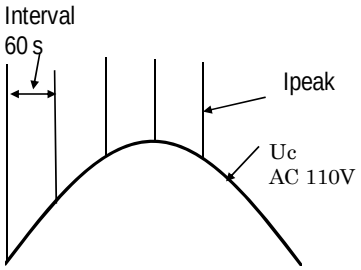
Therefore evaluation tests were passed.

6.4 Class I Preconditioning Tests according to IEC 7.6.4 clause

Ipeak 25kA (10/350μs) impulses simulating a direct lightning strike current were superimposed at each 30 degree phase angle of power source Uc (AC110V). Samples No.4, No.5 and No.6 are connected to a power source (in this case AC110V) in order to simulate the actual situation.

The phase angle is increased in steps of 30 degrees and the interval between the impulses is 60 s as shown in Fig.20.

The samples are devided into three groups. The interval between the groups is 30 minutes. It is not required that the samples be connected to a power source during the group interval.



(1)Ipeak 25kA (10/350 μ s) impulses were superimposed at each 30 degree phase angle of power source Uc (AC 110V).
(2)The interval between the Ipeak impulses is 60 seconds

Fig. 20 Class I Preconditioning Tests

The test results on groupe I are listed in Table 3.a.

Table 3.a Class I Preconditioning Test Results (Groupe I)

[AC110V＋25kA(10/350μs)]

No	Phase	0	30	60	90	120
4	(kA)	24.9	25.0	24.7	24.5	24.6
5	(kA)	26.0	25.3	25.2	25.3	25.3
6	(kA)	25.0	25.1	25.0	24.9	24.8

At 30 minutes later, Ipeak impulses were injected 5 times to group II. The test results on groupe II are listed in Table 3.b.

Table 3.b Class I Preconditioning Test results(Groupe II)

[AC110V＋25kA(10/350μs)]

No	Phase	150	180	210	240	270
4	(kA)	24.8	24.5	24.5	25.1	24.9
5	(kA)	25.9	25.3	25.3	25.4	25.4
6	(kA)	24.9	24.5	24.5	24.3	25.2

Furthermore, another 30 minutes later, Ipeak impulses were injected 5 times to group Ⅲ. The test results on groupe Ⅲ are listed in Table 3.c.

Table 3.c Class I Preconditioning Test Results(GroupeⅢ)

[AC110V＋25kA(10/350μs)]

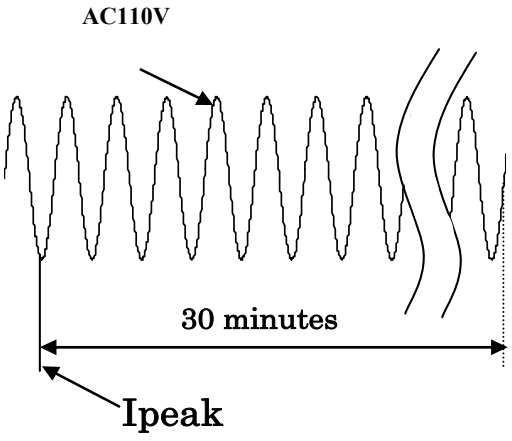
No	Phase	300	330	360	30	60
4	(kA)	24.0	24.7	24.6	25.4	25.2
5	(kA)	25.8	26.1	25.2	25.2	25.5
6	(kA)	24.9	24.9	24.8	25.0	24.8

As a result of these evaluations, there was no follow current caused by AC power supply.

Therefore evaluation tests were passed.

6.5 Class I Operating Duty Tests according to IEC 7.6.5 clause

The same samples No.4, No.5 and No.6 as dealt with in Class I preconditioning tests were used [19]. While applying AC 110V, 0.1 , 0.25, 0.5, 0.75, and 1.0 times Ipeak (Ipeak = 25kA, 10/350μs) impulses were injected as shown in Fig.21. In this case, Ipeak impulses were injected at only 90 phase angle which is the maximum value of AC110V. After each Ipeak injection, while applying AC110V, if there is no power consumption for 30 minutes and it is thermally stable, it succeeds in an examination.



(1)While applying AC 110V, 0.1 , 0.25, 0.5, 0.75, and 1.0 times Ipeak (25kA, 10/350 μ s) impulses were superimposed.
(2)Ipeak impulses were injected at only 90 phase angle
(3)If there is no power consumption for 30 minutes and it is thermally stable, it succeeds in an examination.

Fig. 21 Class I Operating Duty Tests

As a result of these evaluations as listed in Table 4, it was thermally stable. Therefore evaluation tests were passed.

Table 4 Class I Operating Duty Test Results

[AC110V＋2.5～25kA(10/350μs)]

No	$0.1I_{peak}$	$0.25I_{peak}$	$0.5I_{peak}$	$0.75I_{peak}$	$1.0I_{peak}$
	(kA)	(kA)	(kA)	(kA)	(kA)
4	2.3	6.1	13.1	18.3	23.4
5	2.3	6.5	13.2	18.7	24.5
6	2.5	6.3	12.7	18.6	25.0

6.6 Discussions on applications

SPDs requirements as dealt with in IEC [19] were formulated to be connected to 50/60 Hz AC power circuit and equipment rated up to 1000V. Even the production evaluation tests were carried out for 25kA Class I SPD applying AC 110 V, the range of AC voltage can be designed up to 1000 V by increasing the number of series GDTs and parallel varistors according to equation (1). As we can set the overall arcing voltage $A_1+A_2+A_3+ +A_n$ higher than that of commercial power supply (1000V, for example), the problem of follow current can be solved. When conditions mentioned in clause 4 are fulfilled, any combinations of series GDTs and parallel varistors are available.

Both 25kA and 50kA class I SPD products manufactured by LEUTRON for AC 220V power installations using this patented methodology have already been on the market in the world. The price is around 200 USD a one phase which is almost the same as conventional one.

7 Conclusions

This paper proposed a new methodology for protecting power apparatuses against overvoltage or overcurrent caused by lightning surge. It is that three or more GDTs are connected in series and two or more varistors are connected in parallel.

The advantages of this new methodology are as follows.

(1) No leakage current, because one GDT is always connected to a varistor in series.
(2) No affection on Power Line Communication, because one GDT is always connected to a varistor in series.

(3) No dependence on lightning surge polarities, due to symmetric configuration.
(4) Low operating voltage with high response time, because varistors serve to raise the voltage applied to each GDT.
(5) High lightning surge current capability, because almost the entire current flow through the GDTs, a problem of life of varistors due to heating does not arise.
(6) Both follow current interrupt and short circuit current capability can be solved, because we can set the overall arcing voltage higher than that of commercial power supply by increasing the number of GDTs in series.
(7) SPD products using this patented methodology have already been on the market.

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