Lightning Surge Response Improvement by Combinations of Varistors and Gas Discharge Tubes

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Abstract: This paper proposes a new methodology for protecting power apparatuses against overvoltage or overcurrent caused by lightning surge. Surge Protective Devices (SPDs) are used for protecting apparatuses against overvoltage or overcurrent caused by lightning surge. SPDs are mainly divided into two categories. One is clamping type and the other is switching type. Typical clamping type SPD is a variable resitor (varistor). Typical switching type SPD is a Gas-filled Discharge Tube (GDT). Both varistors and GDTs have problems when using them alone. Therefore both a GDT and a varistor are normally connected in series or parallel. However these simple connections of them have still problems. This paper proposes a lightning surge response improvement by combinations of both varistors and GDTs in order to solve the problems of them. It is that three or more GDTs are connected in series and two or more varistors are connected in parallel. This new methodology has already beeing filed as patents in many countries. The proposed methodology could solve the problems of conventional combinations of a GDT and a varistor.

Key-Words: Surge protective device, Varistor, Gas discharge tube, Lightning surge, Overvoltage, Overcurrent

1 Introduction

Both the characteristics of lightning surge and overvoltage protection technologies have been introduced in the articles [1]-[10]. Surge Protective Devices (SPDs) are used for protecting power apparatuses against overvoltage or overcurrent caused by lightning surge. Typical clamping type SPD is a varistor. Typical switching type SPD is a GDT. Both of them have problems when using them alone.

Varistors can restrict to almost constant voltage across terminals, and response time is fast, but current capability is small. On the other hand, GDT can reduce the voltage across terminals dozens of volt, and current capability is large, but response time is slow. Moreover when GDT is used for power supply circuit, there is a problem that arcing discharge still continues by power supply current after lightning current extinction (follow current). Therefore both a GDT and a varistor are normally connected in series or parallel [11] - [19]. However these simple connections of them have still problems.

Therefore we examined the method to make the response time faster and the operating voltage lower without follow current by combinations of varistors and GDTs to overcome these problems.

This paper proposes a new methodology consisting of both varistors and GDTs. It is that three or more GDTs are connected in series and two or more varistors are connected in parallel. This new methodology has already beeing filed as patents in many countries [20]-[26].

2   Problems in the case of using a varistor and a GDT

2.1 Problems in the case of using varistor alone

Fig.1 shows a waveform (temporal change) of the lightning surge voltage.

Front time: $T_1 = 1{,}67 \times T = 1{,}2 \ \mu s \pm 30 \ \%$
Time to half-value: $T_2 = 50 \ \mu s \pm 20 \ \%$.
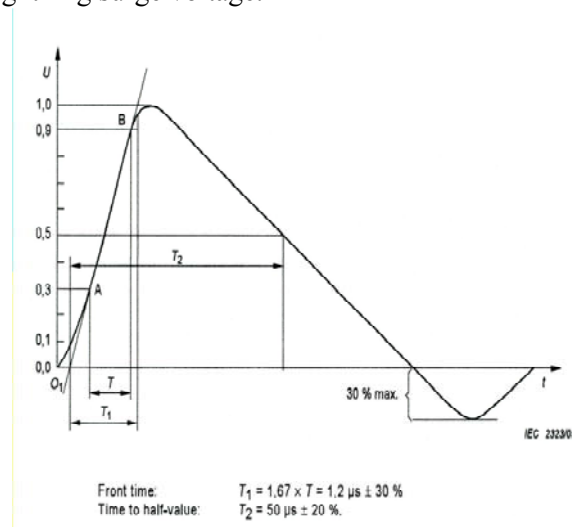
Fig. 1 The profile of voltage caused by lightning surge

Generally, a direct lightning strike causes a current having a peak value of several tens of kA, and an induced lightning surge causes a voltage having a peak value of several 10 kV. And also for example, a front time is several µsec and a time to half value is sevlal 100 µsec.

Fig.2 shows varistors. Varistor is a ceramic made of Zinc Oxide (ZnO) powder with a little additive. The V-I characteristic of a varistor is non-linear.
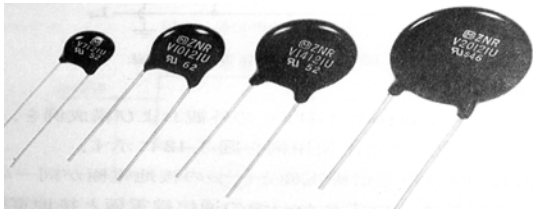

Fig. 2   Outlook of varistors

Fig.3 shows an ideal change of voltage across terminals when a varitor is used. A doted line indicates an overvoltage S(t). The solid line indicates an operating voltage V (500V, for example). T_v indicates a response time. As a varistor is composed of a semiconductor, time T_V as dealt with in Fig. 3 taken to reach its operating voltage is as small as 0.01 µsec. The curent flows during the operating period as shown in Fig.3. If the disk size of varitor is increased, the current capability is also increased. However in this case, the leakage current is also increased due to the increase of its capacitance value. This high capacitance value also affects Power Line Communication (PLC). In this case, a GDT should be connected in series in order to reduce total capacitance value [27].
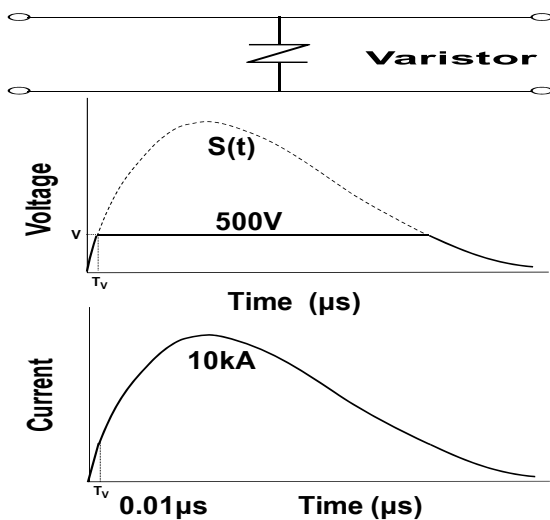

Fig. 3 Voltage and current profile of a varistor

In the case of using varistor, instantaneous power (V×I) is consumed, and there is generated a heat equivalent to energy (V×I×time) obtained by integrating the instantaneous power in the time domain. The operating voltage V is relatively high for example 500V, so when an extremely large current for example 10kA flows, its life may be affected by these instantaneous power and energy.

2.2 Problems in the case of using GDT alone

Fig.4 shows a Gas-filled Discharge Tube (GDT). GDT is made of ceramic with two metallic electrodes.
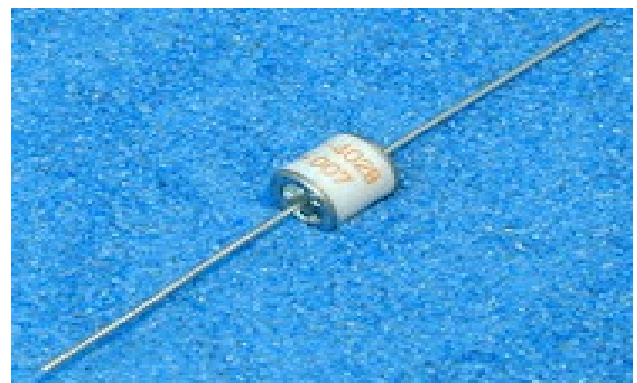

Fig. 4   Outlook of a GDT

Fig.5 shows an ideal change of voltage across terminals. A doted line indicates an overvoltage S(t). E is a spark-over voltage (1000V, for example), A is an arcing voltage (50V, for example). T_E indicates a response time.
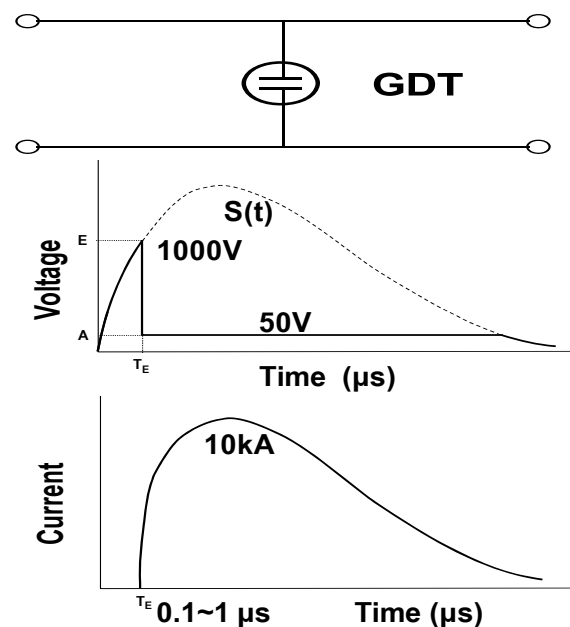

Fig. 5 Voltage and current profile of a GDT

As a GDT is based on a discharge phenomenon, time T_E as dealt with in Fig.5 taken to reach its spark-over voltage is 0.1~1 μsec, which is relatively long.

In the case of using a GDT, when an overvoltage applied from the input side exceeds spark-over voltage E, the voltage across the GDT terminals becomes sharply low by discharge. After the discharge starts, the voltage across the GDT terminals is lowered to arcing voltage A for example 50 V. However, when a commercial power supply of, for example, 110 V is used, if arcing voltage A is lower than 110 V, even after the overvoltage caused by a lightning surge disappears, discharge still continues due to the current supply from power line. Accordingly countermeasures are taken such as connecting several GDTs in series to raise total arcing voltage to more than 110 V. Such extinguishing of discharge once generated by the lightning surge and continued by the commercial power supply is referred to as "follow current". If to increase the number of GDTs in series, the response time becomes slow because the number of GDTs divides total voltage. And also, operating voltage becomes high.

The current flows during the arcing period as shown in Fig.5. In the case of a GDT, when voltage across the GDT is high (until discharge occurs), current does not flow through the GDT; when current start to flow, the voltage lowers for example 50 V due to low impedance value caused by arcing. Consequently, instantaneous power (V×I) as well as energy (time integration of instantaneous power) is relatively small. Accordingly, in the case of a GDT, even when an extremely large current for example 10 kA flows, its life is not affected.

2.3 Problems in the case of connecting a GDT and a Varistor in series

Fig.6 shows an configuration which connects a GDT and a varistor in series. Fig.6 also shows the voltage and current, when voltage S (t) is applied. Until the GDT is activated, current does not flow through the varistor, so the voltage across both ends of the varistor remains 0 V. Accordingly, in this configuration, the discharge occurs when spark-over voltage E of the GDT is reached. After discharge is started, current flows through the varistor, so the sum of arcing voltage A of the GDT and operating voltage V of the varistor is applied across the terminals. In this configuration, after the operations occur, voltage can be adjusted to V+A, thus enabling follow current

interrupt, if V+A (V=500V, A=50V, for example）exceeds the commercial power supply voltage .

However the overall current flows through the varistor, thus affecting the life of varistor caused by instantaneous power and energy.
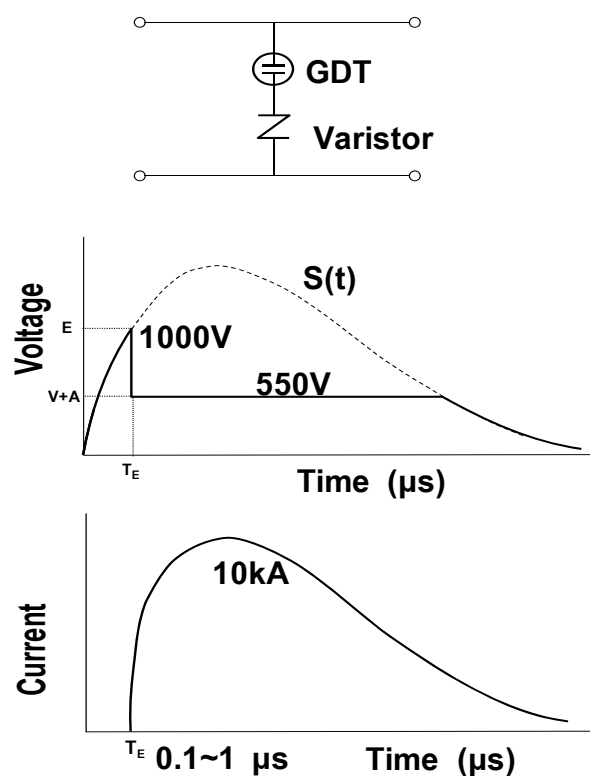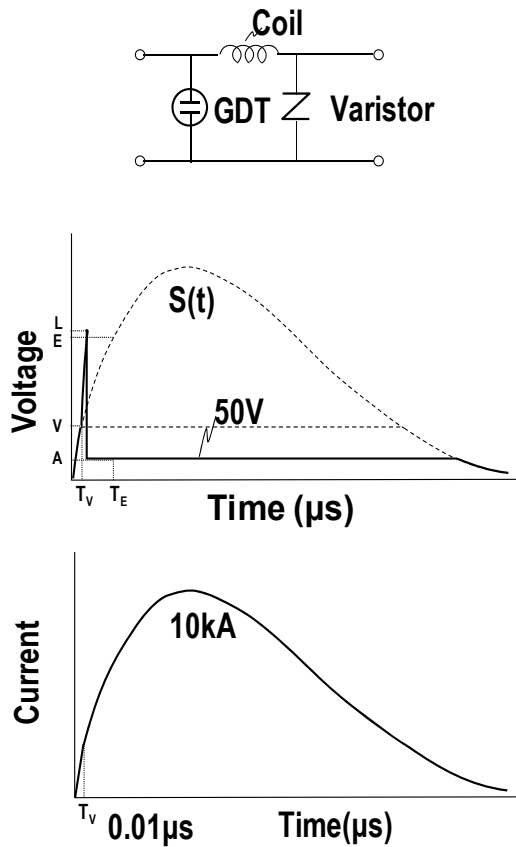

Fig. 6 Voltage and current profile of a GDT and a varistor connected in series

2.4 Problems in the case of connecting a GDT and a Varistor in parallel

Fig.7 shows a basic configuration which connects a GDT and a varistor in parallel and inserts a coil therebetween. Fig.7 also shows the change of voltage across terminals and sum of currents flowing through the GDT and the varistor, when voltage S (t) is applied.

In the varistor, it takes shorter time to reach the operating voltage compared to that of the GDT. Consequently, when voltage S (t) is applied, current first flows through the varistor. At this time, a voltage L is generated across both ends of the coil by the change of current. Thereafter the voltage across both ends of the GDT becomes higher than spark-over voltage E, whereby the GDT is activated. By operating in this manner, in a short response time substantially equal to the time taken for the varistor to reach the operating voltage (it is ideal to achieve such short response time), the GDT is activated, whereby the

voltage can be lowered to arcing voltage A of GDT. Almost all current flows through the GDT, so the life of varistor is not affected.

**Fig. 7 Voltage and current profile of a GDT and a varistor connected in parallel**

However, "follow current" problem caused by low arcing voltage of the GDT still remains.

And also, as the coil, a self-inductance value of 0.1~2mH is required in order to ensure proper coordination of the GDT and the varistor [11]. Further, at the time of normal operation, AC current from commercial power line flows through the coil, so it is needed to construct the coil with a wire having a large AC current capability. Consequently, the size of the coil becomes large, thus causing a problem in reducing the size and cost.

Other conventional combinations of GDTs and varistors are not the same as following new methodology.

3 Problem Solution using Combination of three GDTs and two Varistors

Fig.8 shows a configuration of the proposed SPD.
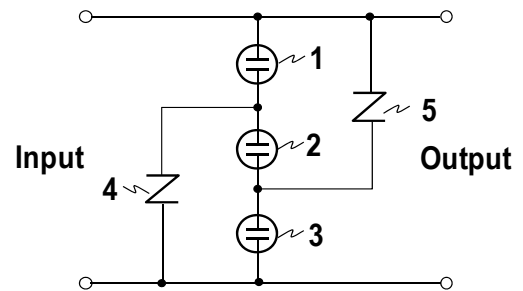
Fig. 8   A configuration consisting of three GDTs in series and two varistors in parallel

In Fig.8, three GDTs 1, 2 and 3 are connected in series and two varistors 4 and 5 are connected in parallel [20]-[26].

In this configuration, there is no leakage current and no affection on Power Line Communication, because one GDT is always connected to a varistor in series.

Here, the spark-over voltage of the GDT 2 is set lower than a voltage obtained by subtracting the arcing voltage of the GDT 3 from the operating voltage of the varistor 4, and lower than a voltage obtained by subtracting the arcing voltage of the GDT 1 from the operating voltage of the varistor 5, and at the same time higher than the spark-over voltage of the GDT 1 and the spark-over voltage of the GDT 3.

Figs.9 to 12 show operations when the overvoltage S (t) is applied across input side terminals.
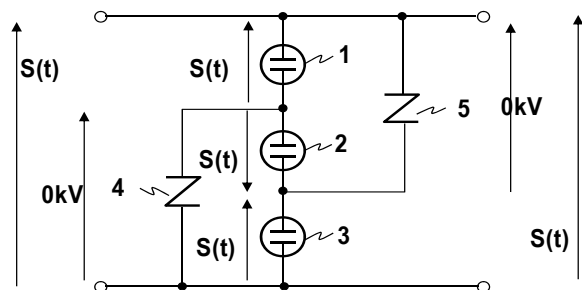
**Fig. 9   The first-state voltage of each GDT when overvoltage S (t) is applied**

When an overvoltage S (t) across input terminals is applied, none of the GDTs 1, 2 and 3 discharges in the first state. At this time, current does not flow through the varistors 4 and 5. Accordingly, no potential difference is generated between both ends of the varistors 4 and 5. Consequently, the overvoltage S (t) is applied to each GDT.

This state is shown in Fig.9. When the varistors 4 and 5 are not provided (i.e., when the GDTs alone are connected in series), approximately one-third of S (t) is applied to each GDT. More specifically, the varistors 4 and 5 serve to raise the voltage applied to each GDT, thereby enabling a high response time. Consequently, each GDT has potential difference as shown in Fig. 9.
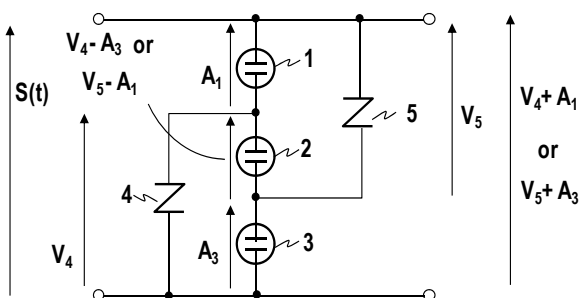
The spark-over voltage of the GDT 2 is set higher than that of the GDTs 1 and 3. Accordingly, the GDT 1 or the GDT 3 first discharges. For example, assume that the GDT 3 discharges as shown in Fig.10.
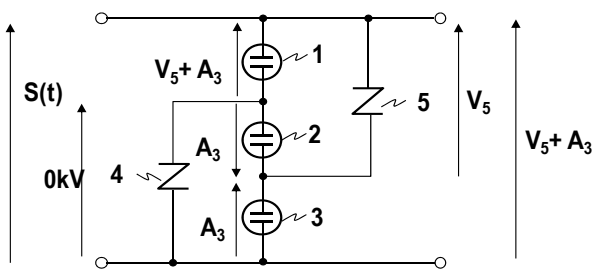
Fig. 10   The voltages of each GDT when the first GDT (GDT 3) is activated

At this time, the arcing voltage of the GDT 3 becomes A_3. Also, current flows through the varistor 5, so operating voltage V_5 of the varistor 5 is generated. Thus the voltage across output side terminals becomes V_5+A_3. Current does not flow through the varistor 4, so no potential difference is generated between the terminals of the varistor 4.

The spark-over voltage of the GDT 1 is lower than that of the varistor 5, so the GDT 1 discharges. Once GDT 1 discharges, current flows through the varistor 4, and operating voltage V_4 is generated. At this time, the voltage across output side terminals is equal to the lower one of V_4+A_1 and V_5+A_3. It may be designed so that $V_4+A_1 = V_5+A_3$. At this time, each unit has potential difference as shown in Fig.11.

**Fig. 11   The voltages of each GDT when the second GDT (GDT1) is activated**

The spark-over voltage of the GDT 2 is lower than voltage V_4-A_3 obtained by subtracting arcing voltage A_3 of the GDT 3 from operating voltage V_4 of the varistor 4, and lower than voltage V_5-A_1 obtained by subtracting arcing voltage A_1 of the GDT 1 from operating voltage V_5 of the varistor 5. Thus the GDT 2 also discharges. Potential differences of each GDT in this final state are shown in Fig.12.

In such state, almost the entire overcurrent can be made to flow through the GDTs. When the overall arcing voltage $A_1+A_2+A_3$ is set higher than the commercial power source (150 V, for example), the problems of both follow current interrupt and short circuit current capability can be solved.
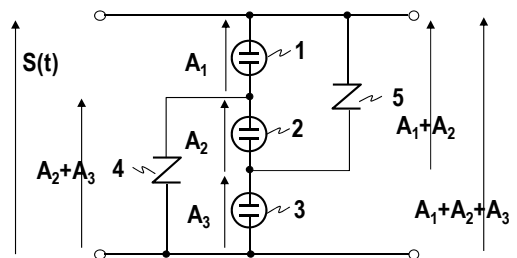
Fig. 12   The voltages of each GDT when all the GDTs are activated

Practically, the operations of Figs. 9 to 12 are performed in sevral μsec. Thus the voltage across the terminals varies as shown in Fig.13. Reference character E (3000V, for example) in Fig.13 indicates a spark-over voltage when the GDTs 1, 2 and 3 alone are connected in series (i.e., when the varistors 4 and 5 are not provided). As the varistors 4 and 5 work as a trigger for GDT's discharge mentioned above, the spark-over voltage can be lowered to E' (1000V, for example). Consequently, a high response time is possible and the maximum voltage can be lowered.
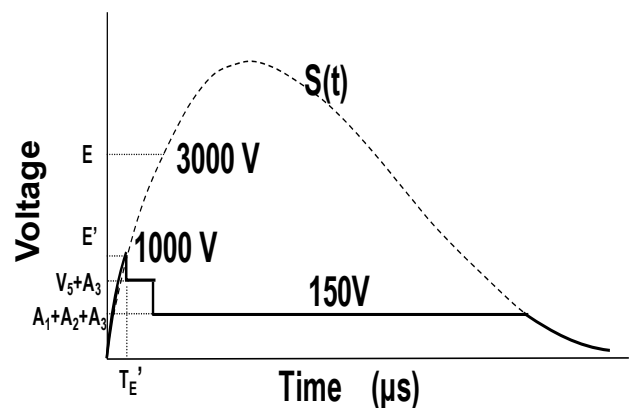
Fig. 13   The voltage in the case of connecting three GDTs in series and two varistors in parallel

Fig.14 shows the change of current flowing between the terminals. In this configuration, with voltage lowered, almost the entire current can be made to flow through the GDTs 1, 2 and 3, so a problem of life of varistor due to instantaneous power and energy does not arise. Therefore high lightning surge current capability can be achieved.
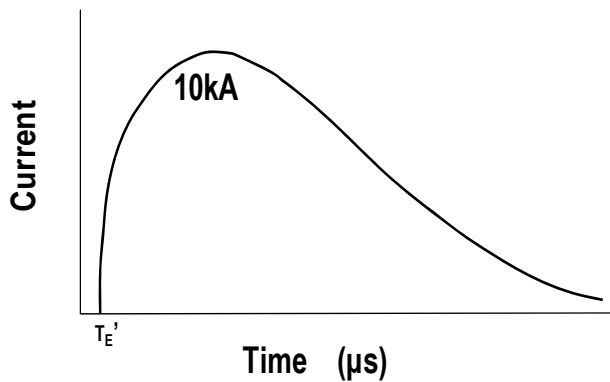
Fig. 14 The current in the case of connecting three GDTs in series and two varistors in parallel

If the GDTs 1 and 3 are designed to have the same spark-over voltage, symmetry can be improved. If the GDTs 1 and 3 are designed so that either of them has a lower spark-over voltage, a GDT which first discharges can be selected.

4 Problem Solutions using Combination of more than five GDTs and more than four Varistors

Variations according to the above idea will be described below[20]-[26].

Fig.15 shows a variation which connects five GDTs in series and four varistors in prallel. Here, assume that the spark-over voltage of the GDT n (n = 1 to 5) is E_n, the arcing voltage is A_n, and the operating voltage of the varistor m (m = 6 to 9) is V_m.

The spark-over voltage E_3 of the GDT 3 is set so as to satisfy the following conditions.

$$E_3 < V_6 - A_2 - A_4 - A_5$$
$$E_3 < V_7 - A_4 - A_5$$
$$E_3 < V_8 - A_1 - A_2 \qquad (1)$$
$$E_3 < V_9 - A_1 - A_2 - A_4$$
$$E_3 > E_1$$
$$E_3 > E_2$$
$$E_3 > E_4$$
$$E_3 > E_5$$
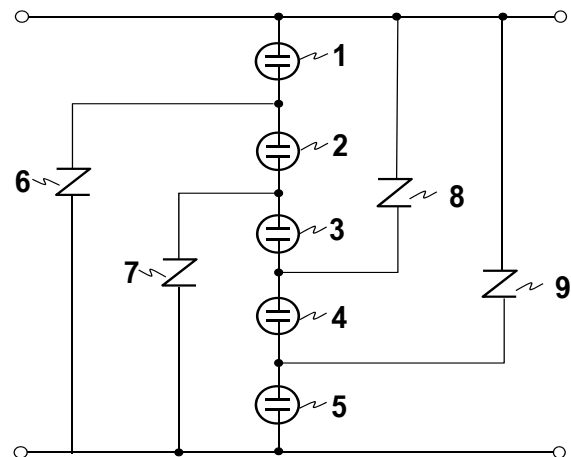
Fig. 15   A variation which connects five GDTs in series and four varistors in parallel

The above condition is described as follows; the spark-over voltage of a GDT connected in parallel to all varistors is set lower than any voltage obtained by subtracting the arcing voltages of the other GDTs connected in parallel to the varistor from the operating voltage of each varistor.

Also, the spark-over voltage of a GDT connected in parallel to all varistors is set higher than the spark-over voltage of each GDT connected in series to any one of the varistors. When the above setting is given, while overvoltage is concentrated to GDTs to be activated, discharge can be sequentially started.

In order to improve the symmetry of the entire overvoltage protective device, the following setting is required; $E_1 = E_5$, $E_2 = E_4$, $V_6 = V_9$, and $V_7 = V_8$. Further, in order to activate the GDTs unfailingly in order of being closer to the conductor, the following setting is required; $E_1 < E_4$ and $E_5 < E_2$. Herein, "activate the GDTs unfailingly in order of being closer to the conductor" means that the GDTs 1 and 5 are first activated, and thereafter the GDTs 2 and 4 are activated, and finally the GDT 3 is activated.

We can increase the number of GDT n (n $\geqq$ 7) and the number of varistor m (m $\geqq$ 6) using the same procedure mentioned above. As we can set the overall arcing voltage $A_1 + A_2 + A_3 + +A_n$ higher than that of commercial power supply, the problems of both follow current interrupt and short circuit current capability can be solved.

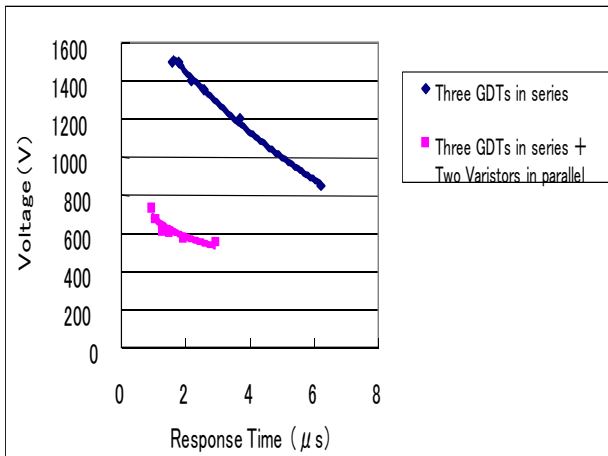# 5   Trial Test Results on Proposed Methods

Fig.16 shows a trial test results on response time and operating voltage in the case of connecting three
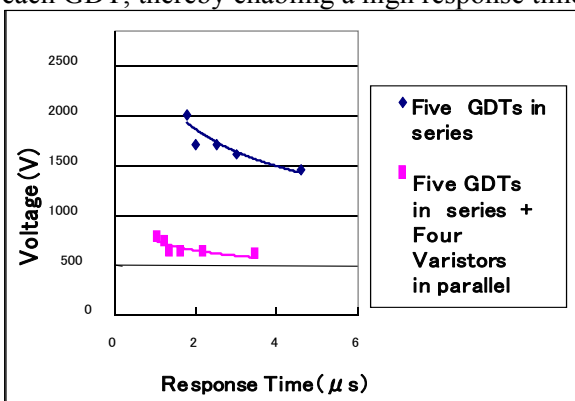
GDTs in series and two varistors in parallel. The response time is reduced by 43% in comparison with that of only three GDTs in series. And the operating voltage is reduced by 51% in comparison with that of only three GDTs in series.

Fig. 16 A trial test result on response time and operating voltage in the case of connecting three GDTs in series and two varistors in parallel

Fig.17 shows a trial test results on response time and operating voltage in the case of connecting five GDTs in series and four varistors in parallel. The response time is reduced by 45% in comparison with that of only five GDTs in series. And the operating voltage is reduced by 60% in comparison with that of only five GDTs in series.

Because varistors serve to raise the voltage applied to each GDT, thereby enabling a high response time.

Fig. 17   A trial test result on response time and operating voltage in the case of connecting five GDTs in series and four varistors in parallel

6   Product Test Results according to IEC Regulation
6.1   Product Test Samples

The commercial production evaluation tests based on IEC publication 61643-1 [19] were carried out using product samples consisting of three GDTs in series and two varistors in parallel as shown in Fig.18.

The samples were designed for 25kA Class I SPD as defined by IEC publication 61643-1. Class I SPDs are available for lightning protection against direct lightning strike current having 10/350μs（front time 10μs, mean time to half value 350μs）waveform.

Fig. 18   Product Samples

6.2   Measure the residual voltage with 8/20 current impulses according to IEC 7.5.2 clause

IEC publication 7.5.2 clause examination uses waveform as shown in Fig.19.

Front time: $T_1 = 1.25 \times T = 8$ μs ± 20 %
Time to half-value: $T_2 = 20$ μs ± 20 %
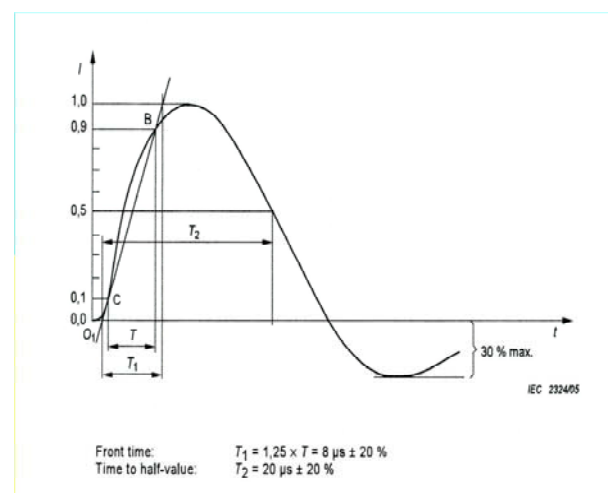
Fig. 19 I_n（25kA, 8/20μs）

The currents of 0.1, 0.2, 0.5, 1.0 times of In (In = 25kA, 8/20μs) were injected. The residual voltages of samples No.1, No.2 and No.3 were measured by injecting positive and negative polarity impulse currents.

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.
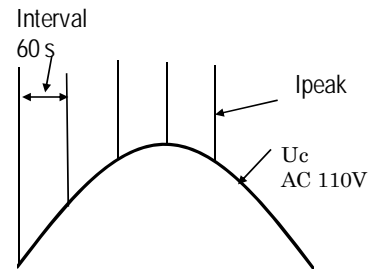
(1)Ipeak 25kA (10/350 μ s) impulses were superimposed at each 30 degree phase angle of power source Uc (AC 110V).
(2)The interval between the Ipeak impulses is 60 seconds
Fig. 20   Class I Preconditioning Tests

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.
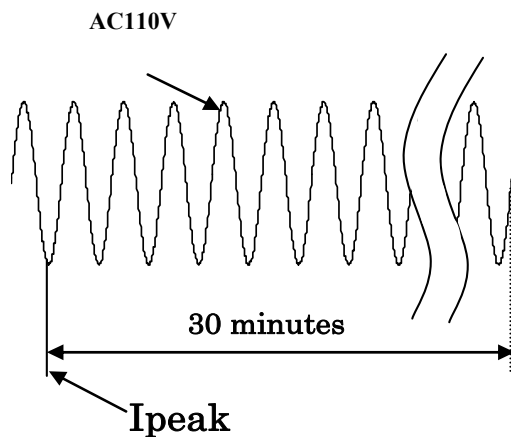
AC110V

(1)While applying AC 110V, 0.1 , 0.25, 0.5, 0.75, and 1.0 times Ipeak (25kA, 10/350μ 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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