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文献出处：Transmission &Distribution Conference &Exposition,2008:1-8

英文4089单词，20988字符，中文7298汉字。

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Design and Application of Line Surge Arresters to Improve Lightning Protection Characteristics of Transmission Lines

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Abstract— The line surge arrester with series gap can effectively improve the lightning protection performance of the transmission line,and guarantee its safe operation.This paper discussed the design of two different series gap structures,and their influence on the line surge arresters.The so-called“transverse discharge” between the grading ring of the insulator to the upper discharging electrode of the series gap is discussed.At last,the paper introduced the application and effects of line surge arresters in China.Line surge arresters have achieved good application effect, which have become the main lightning protection measures of transmission lines.

Index Term—Metal oxide surge arrester,line surge arrester,series gap,lightning impulse,switching overvoltage,power frequency overvoltage,polymeric surge arrester

INTRODUCTION

Since 1980's,the polymeric ZnO surge arresters have been developed and put into operations on transmission lines in parallel with the insulators to improve the lightning withstand characteristics of transmission lines and increase the reliability of power supply based on their excellent performances [1]-[10].Especially,in the regions where the lightning is exceedingly active or the grounding resistances of towers are difficult to be reduced due to the high soil resistivity,the lightning withstand levels of transmission lines can be significantly improved by applying the line surge arresters.

The metal oxide surge arresters for lightning protection of transmission lines have two different kinds of structures.The first kind is the gapless surge arrester,which is directly connected with the phase conductor.It is the technology extension of the surge arrester for substation,and has the merit of no discharging time delay for reliably absorbing surge energy.Another kind of line surge arrester has a series gap which is inserted between and isolates the surge arrester and the phase conductor. Owing to the isolation effect of the series gap,such kind of line surge arrester has the following merits.

The line surge arrester with series gap only operates when a lightning strikes the transmission line or the tower,and keeps out of work,a state of "rest",under all other situations even including the AC power frequency or switching overvoltage.That is to say,there is current passing through the arrester only within very short time duration of lightning strike,which is about 1 to 2 power frequency cycles ordinarily.Thus,it makes the line surge arrester with series gap have longer life time and higher operation reliability than others.

It is always a tough problem for the gapless surge arrester that the inside ZnO varistor failure directly does harm to the normal power transmission.Whereas,the line surge arrester with series gap will not affect the normal operation of the transmission line even if the inside ZnO varistors are already in degradation state.

On account of so many merits,the line surge arresters with series gaps have been widely adopted now.However,the series gaps of the surge arresters can also be designed with different structures.How does the gap structure have influence on the performance of the line surge arrester?This paper analyzed the influence of two different gaps on the lightning impulse discharging characteristics of line surge arresters with polymer housings,and introduced the application and effects of line surge arresters in China.

STRUCTURE DESIGN OF LINE SURGE ARRESTERS

A.The Structure of Series Gap

The line surge arrester consist of the series gap and the arrester unit.At present,two different series gap structures are available.The first is the separated gap designed in Japan [1],[2],whose two discharging electrodes are isolated only by air.The second is called as fixed gap or integrated gap,with two discharging rings fixed by a composite insulator to keep their distance unchanged even if very strong wind blows on the arrester [3].

The fixed gap means that the arrester unit and the series gap are assembled into a whole body as shown in Fig.1(a).Ordinarily,a composite insulator is fixed on the bottom of the arrester unit,and two ring-shape discharging electrodes are fixed on two terminals of the composite insulator.The merit of this kind of series gap is that the distance between two discharging electrodes is never influenced by external factors. The line surge arresters developed in China have adopted this kind of series gap [3].

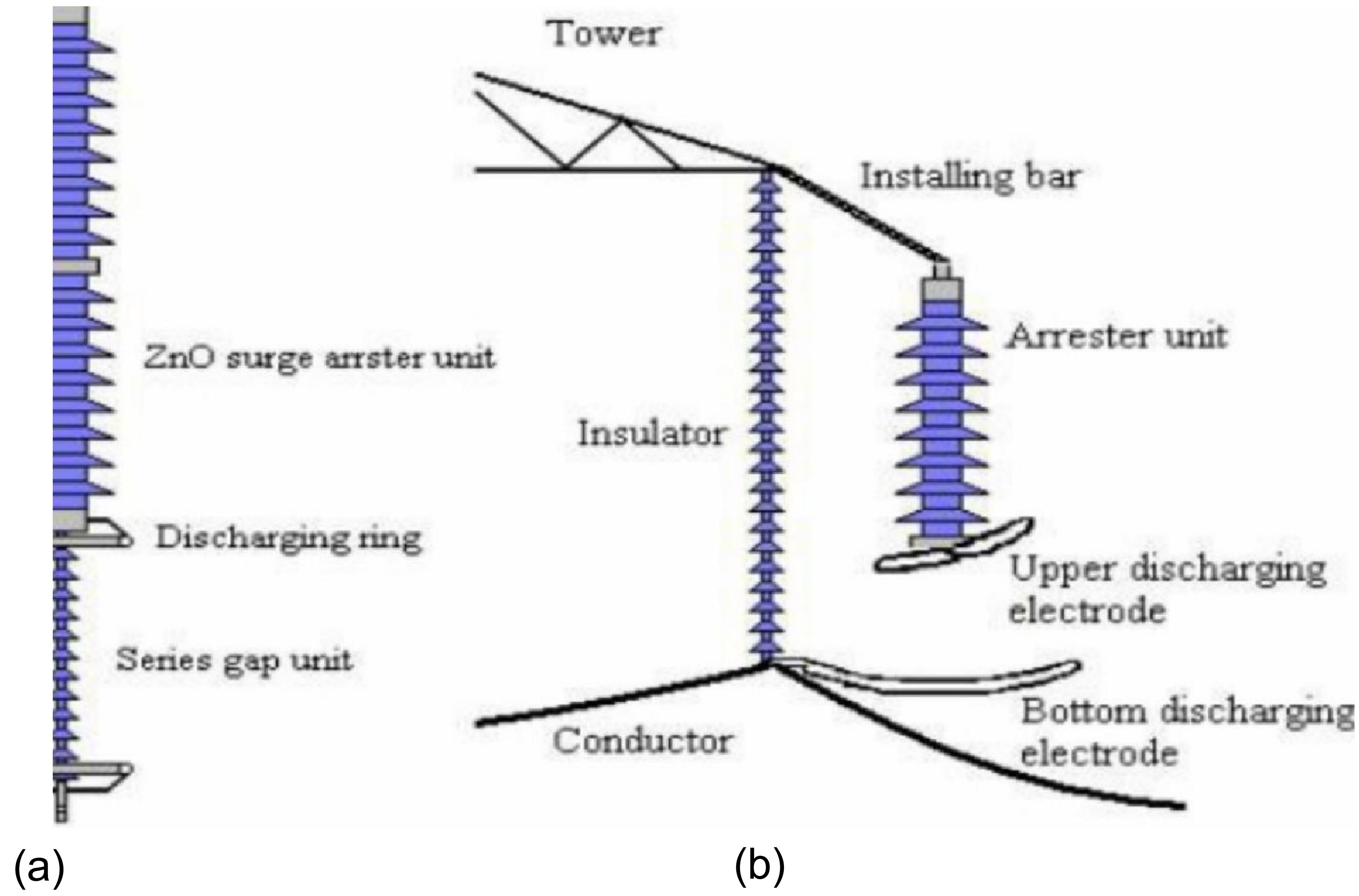

Fig.1.The polymeric surge arresters with series gaps for transmission lines. (a)The surge arrester with fixed gap;(b)the surge arrester with separated gap.

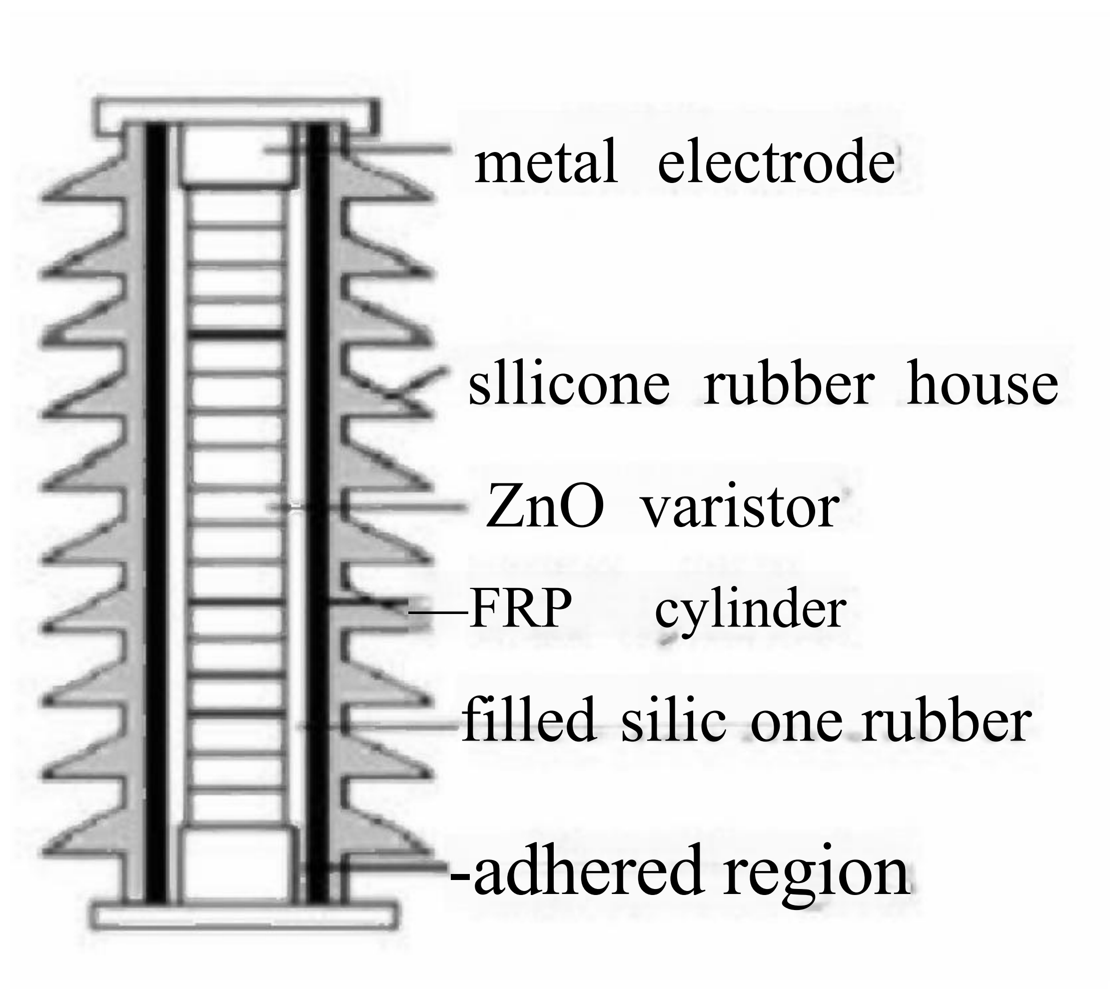

Fig.2.The structure of polymeric surge arrester unit.

For the separated gap,one of its discharging electrodes is fixed on the bottom of the arrester unit,and the other electrode is fixed on the phase conductor.This separated gap should be considered for the influence of different external factors on the distance between two discharging electrodes.In order to keep the distance unchanged,the discharging electrodes should be manufactured as complicated arc shape as shown in Fig.1(b).In Japan,77 kV,275 kV and 500 kV line surge arresters used this kind of series gap [1],[2].

As the fixed gap is supported by the composite insulator,the power frequency operating voltage applied on the arrester unit and the fixed gap in normal operation condition can be easily determined by their capacitances.The capacitance of the fixed gap of the 110 kV line surge arrester with length of 500 mm is calculated as 0.4 pF, and the capacitance per ZnO varistor disk with diameter of 70 mm is measured as 1040 pF.There are 28 pieces of disks used in the whole arrester unit,and its total capacitance is 37 pF.Then,it is obviously that the composite insulator fixing the series gap should endure almost all of the continuous operating voltage.Generally,the composite insulators for 110 kV line surge arresters are originally for 35 kV transmission lines,so there always are some potential problems existing in the composite insulators,such as performance degradation because of aging under continuous power frequency overvoltage.Thus,the composite insulator becomes the weak point of the polymeric line surge arrester with fixed gap.However,the separated gap should be a better choice to increase the operation stability of the polymeric line surge arrester.

B. The Structure ofArrester Unit

As shown in Fig.2,the developed line polymeric ZnO surge arresters has a whole-solid-insulation structure,all interior gaps are filled with middle-temperature silicon rubber material.There is not any gas gap inside the arrester,it is different from those used in Japan which still have gaps inside arrester [1].We know the main reason of arrester failure is due to moisture ingress, so the failure of the whole-solid-insulation arrester caused by moisture ingress is eliminated.The polymeric housing not only makes the surge arrester smaller and lighter but also solves the problem of pressure relief due to no air gap inside polymeric arrester,the electrical,and therefore thermal,overloading of the ZnO varistors could not cause a flashover along the side surface of the ZnO varistor column. So the whole-solid-insulation polymeric surge arresters are safety-type ones.The structure with FRP cylinder is used to endure the mechanical stress.

C.The Selection ofApplied Voltage Ratio ofArrester Unit

Generally,the applied voltage ratio is defined as the ratio of the maximum continuous operation voltage to the 1-mA DC referenced voltage of the ZnO surge arrester.The applied voltage ratio of the gapless surge arrester is recommended in the region from 0.6 to 0.8,due to the consideration of thermal stability.For example,that ratio value of 500 kV gapless ZnO surge arresters is designed as 0.712 in China.Contrastively,the applied voltage ratio of the line surge arrester with series gap can be as large as 1.0, which means lower 1-mA DC referenced voltage and impulse residual voltage.

The line surge arrester only works during lightning strike,and the voltage applied on it is suppressed by the ZnO varistors inside the arrester.So,its leakage distance of the polymer housing could be shorter than that of the gapless surge arrester.

DESIGN OF THE SERIES GAP

The design of the series gap includes selecting the gap structure and determining the length of the series gap.The gap distance between two electrodes of the arrester should keep unchanged approximately under different external forces,such as wind blowing or conductor swinging,in order to keep the discharging voltage of the series gap stable within small dispersion.

When line surge arresters are installed for lightning protection of transmission lines, the protected insulators should have no flashover during lightning strikes.So the lightning impulse voltage versus time characteristic curve of the surge arrester with series gap and that of the insulator string should be in parallel approximately,having no cross point at all.

As illustrated in Fig.3,the required lengths of the series gap for different purposes are not the same.In order to suppress the lightning overvoltage,the length of the series gap should be shorter than L1.For blowing out the power frequency following current, the length of the series gap should be longer than L2.On the other hand,the length of the series gap should be longer than both L3 and L4 to guarantee that the arrester does not operate when the switching or power frequency overvoltage occurs.

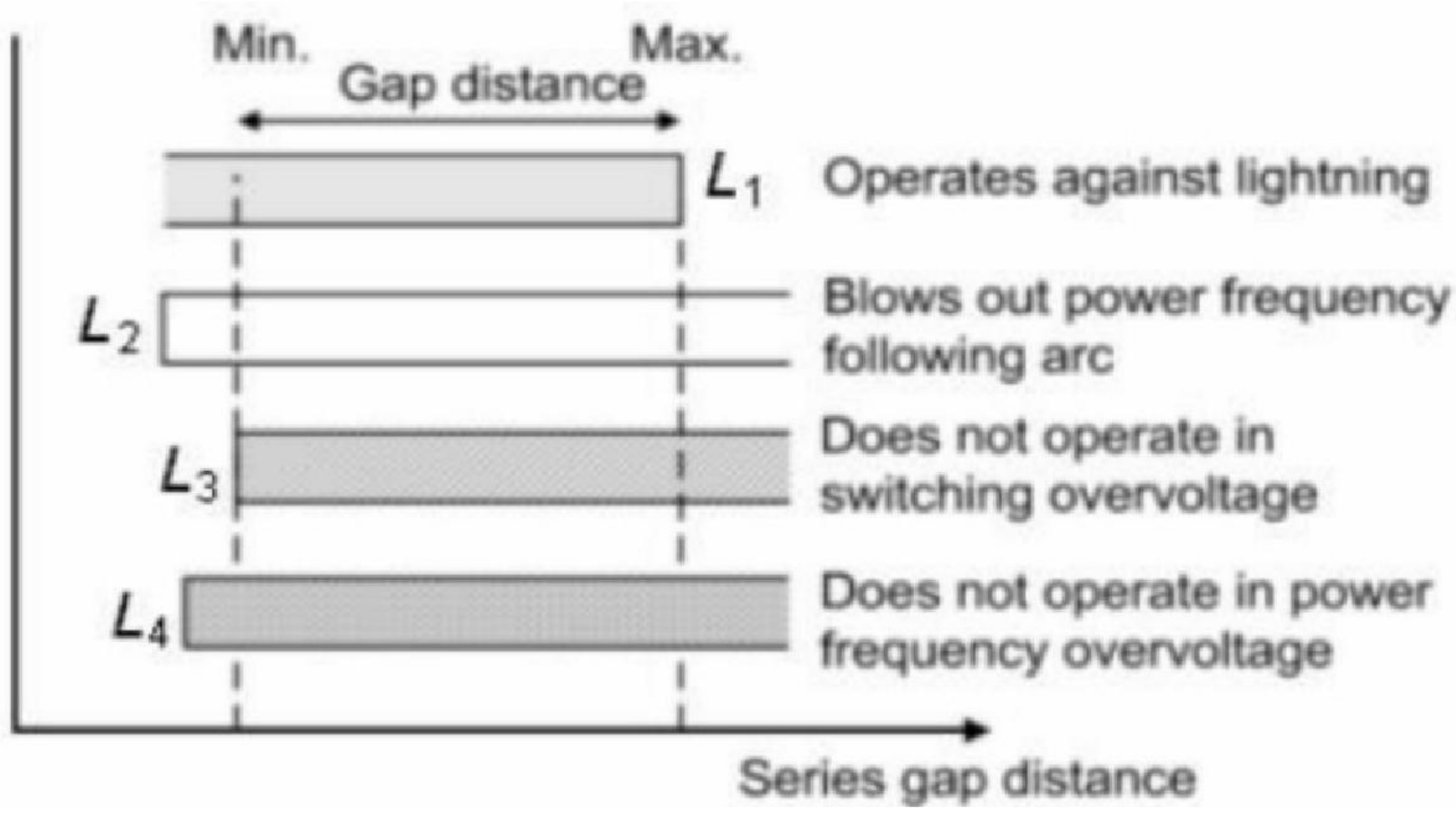

Fig.3.The region of the series gap length.

A.Coordination of the 50%Lightning Impulse Discharging Voltages

The influences of the series gap lengths on the 50%lightning discharging voltages of the line surge arresters are shown in Figs.4 and 5,while Fig.4 is for the fixed gaps, and Fig.5 is for the separated gaps.

When we determine the 50%lightning impulse discharging voltages of the line surge arresters with series gaps,the scattered discharging characteristics of air gaps should be considered for the insulation coordination of the surge arrester with the insulator string of transmission line.Ordinarily in China,the standard deviation of lightning dischargingO voltages in air is selected as 0.03 [12].In order to realize the insulation coordination between the insulator string and the line surge arrester,the series gap should put into operation reliably when a lightning strikes the transmission line,and the insulator protected by the line surge arrester should have no flashover at all.Then,if the maximum standard deviations of the series gap and the insulator are selected as 0.03 [3],the relationship between the 50%lightning impulse discharging voltage of the line surge arrester and the 50%lightning impulse flashover voltage of the insulator string can be described as

$$U_{50,I} > \frac{1+3\sigma}{1-3\sigma}U_{50,A} = \frac{1.09}{0.91}U_{50,A} = 1.20U_{50,A} \tag{1}$$

where,U50,A is the 50%lightning impulse discharging voltage of the line surge arrester,and U50,I is the 50%lightning impulse flashover voltage of the insulator string.Thus,the insulation coordination coefficient between the line surge arrester and the insulator string is 20%,which means that the 50%discharging voltage of the insulator string should be 20%higher than that of the line surge arrester.However,as the actual maximum discharging deviation is smaller than 0.03,the suggested coordination coefficient given in China Standard of Power Electric Industry DL/T 815-2002"Polymeric metal oxide surge arresters for a.c.power transmission lines" [13]is 15%when the lightning wave-front time is in the region from 1 to 10 s. From Figs.3 and 4,we can find that the lengths of separated and fixed gaps for 110 kV line surge arresters should be shorter than 650 mm and 700 mm respectively if 8 pieces of XP-7 porcelain insulators are used.If 7 pieces of XP-7 porcelain insulators are used,the corresponding lengths should be 570 mm and 650 mm.

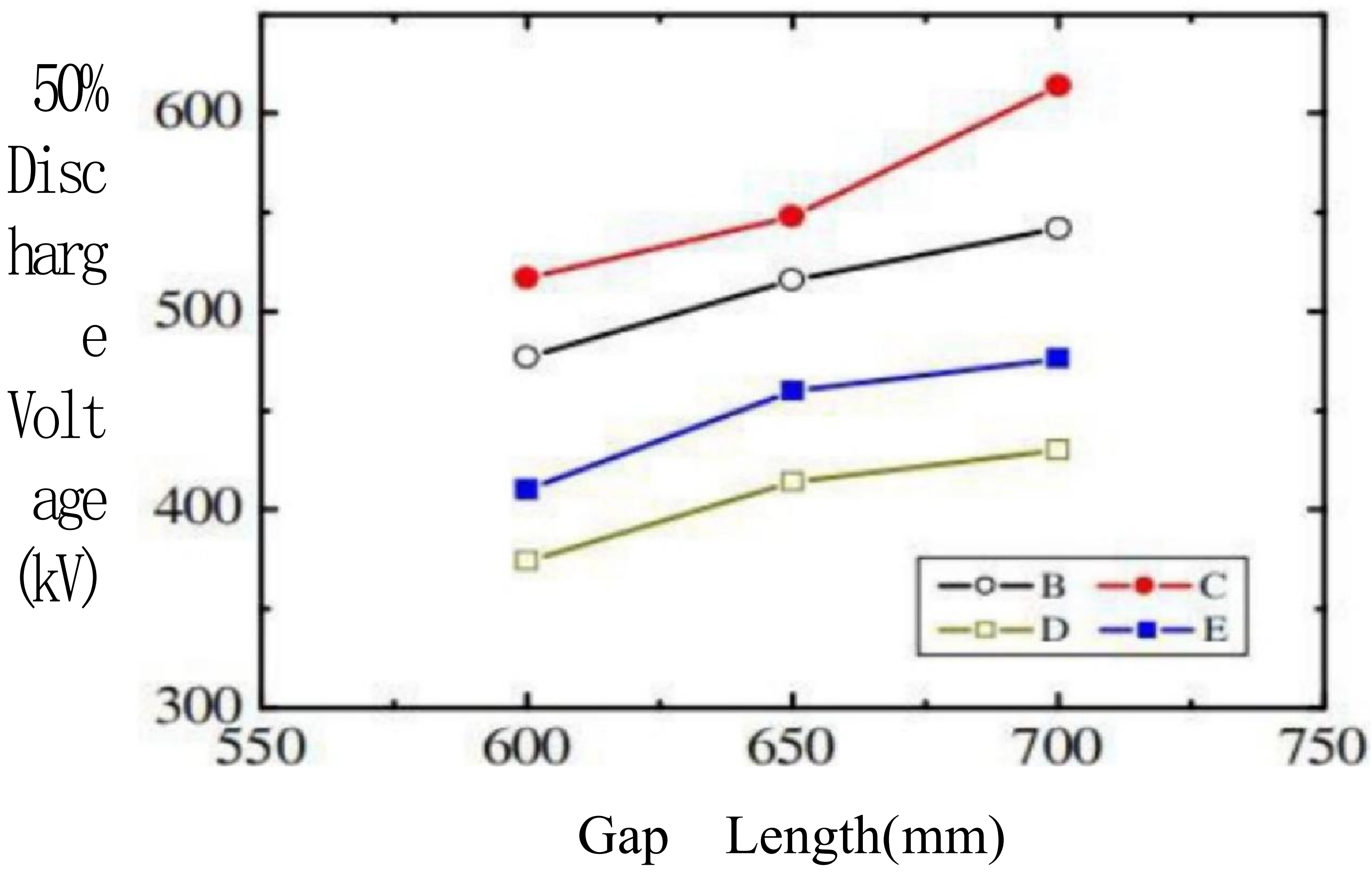

Fig.4.The 50%lightning impulse discharging voltages of the whole line surge arresters and the fixed gaps(B-the positive polarity,the whole surge arrester; C-the negative polarity,the whole surge arrester;D-the positive polarity,the series gap;E-the negative polarity,the series gap).

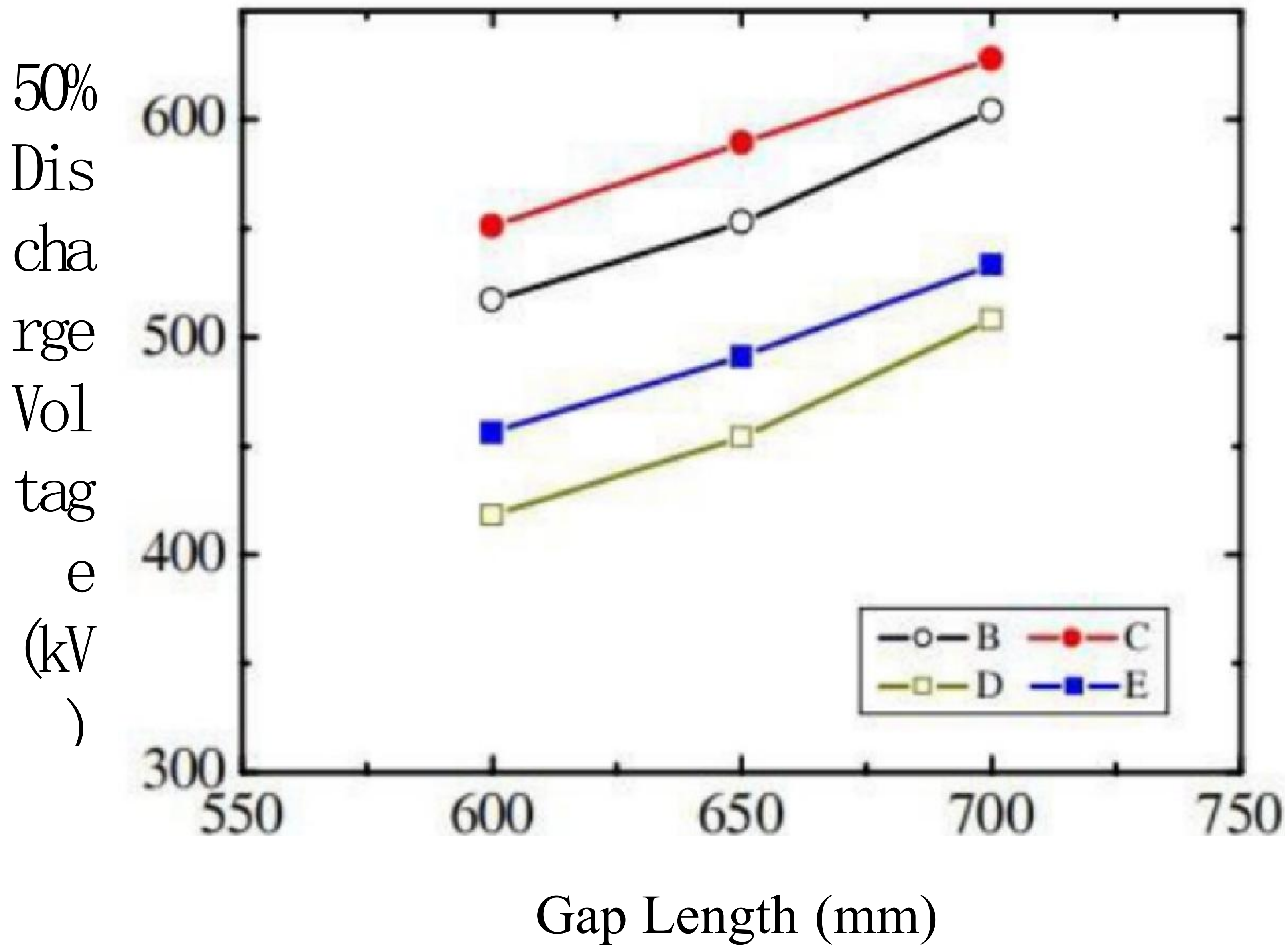

Fig.5.The 50%lightning impulse discharging voltages of the whole line surge arresters and the separated gaps (B-the positive polarity,the whole surge arrester; C-the negative polarity,the whole surge arrester;D-the positive polarity,the series gap;E-the negative polarity,the series gap)

B.Coordination of the Lightning Impulse Voltage Versus Time Characteristics

The 50%discharging voltage can not completely describe the lightning impulse discharging characteristic,and the discharging time duration is another important factor of the lightning impulse discharging characteristic.The lightning impulse voltage versus time characteristic of the line surge arrester and that of the insulator string should coordinate,too.

The tested lightning impulse voltage versus time characteristics of the line surge arresters with fixed and separated gaps and those of the insulator string are shown in Figs.6 and 7 respectively,while the length of the separated gap is 520 mm and the length of the fixed gap is 650 mm.The lightning impulse voltage versus time characteristic curve of the line surge arrester is in parallel with that of the insulator string,and they have no cross point.

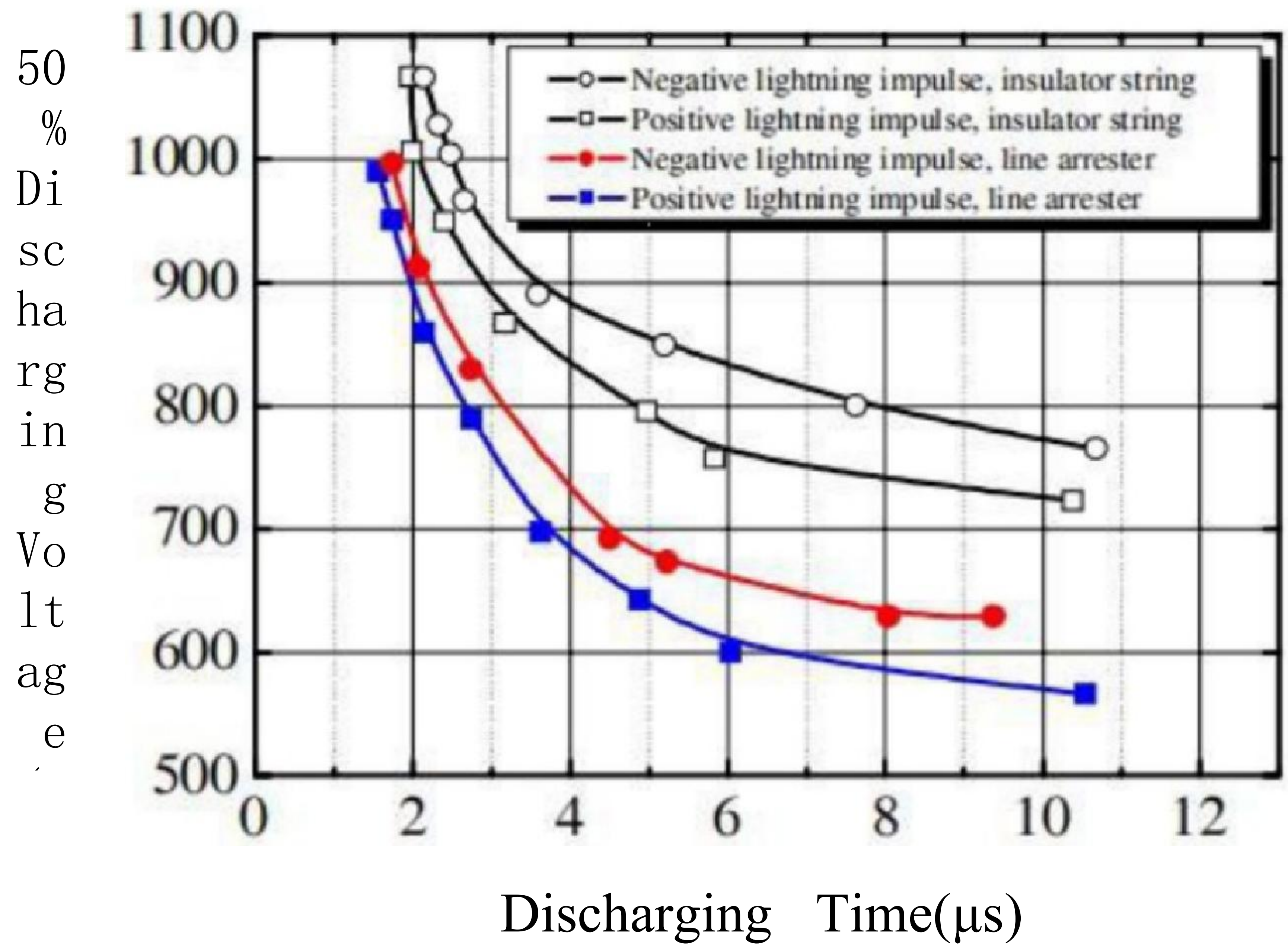

Fig.6.The lightning impulse discharging voltage versus time characteristics of the line surge arrester with fixed gap and those of the insulator string(8 pieces of XP-7 porcelain insulators).

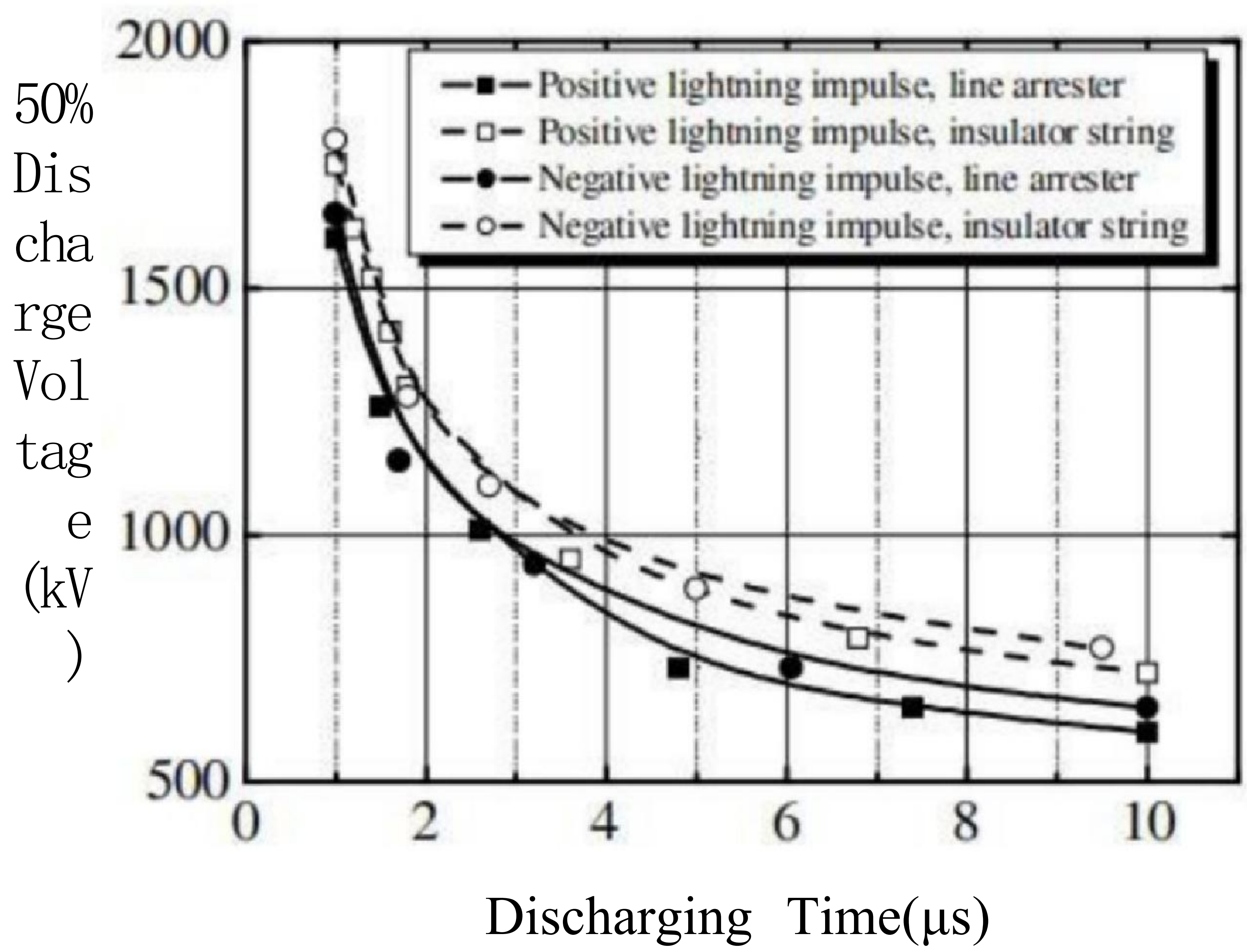

Fig.7.The lightning impulse discharging voltage versus time characteristics of the line surge arrester with separated gap and those of the insulator string(7 pieces of XP-7 porcelain insulators).

Comparing the curves in Figs.6 and 7,the lightning impulse discharging voltage versus time characteristics of the separated and fixed gaps have obviously difference, as shown in Table ⅢI.The discharging voltages of the line surge arresters with arresters with fixed gaps under the same conditions.This is caused by the effect of the composite insulator which fixes the two discharging electrodes.As a result,the length
of the separated gap can be designed shorter than that of the fixed gap.

C.The Withstand Capabilities of Power Frequency Overvoltages

The power frequency overvoltage of 110 kV power system with the neutral point grounded is suggested as 1.35 times of the maximum operating phase voltage,which is equal to 94 kV(1101.11.35/3).When the arrester unit is failed,the series gap should withstand the power frequency overvoltage and cut the power frequency following current.

The power frequency overvoltage withstand values of the series gaps are tested and shown in Table I.When the series gap is only 480 mm in length,the line arrester can withstand 174 kV power frequency overvoltage if the arrester unit is failed.According to experimental results in [1],the line surge arrester with series gap can cut off the power frequency following current in 0.5 power frequency cycle when the series gap length is longer than 313 mm.

TABLEI

THE POWER FREQUENCY OVERVOLTAGE WITHSTAND VALUES OFTHE SERIES GAPS OF 110 KV LINE ARRESTERS WHEN THE ARRESTER UNIT IS FAILED

Gap Shape	UimA (kV)	Gap length (mm)	Withstand Voltage (kVs)
Separated Gap	卡123	480 650	175* 237
Fixed Gap	本123	480 650	174 235**

Note:*withstanding one minute in dry and raining states,respectively
**withstanding 5 minutes.

D.Switching Overvoltage Withstand

There always are two different viewpoints on the line surge arrester suppressing the switching overvoltage.One opinion insists that the line surge arrester should not put into operation when a switching overvoltage emerges in the transmission line,and the other one does not consider whether the line surge arrester puts into operation in switching overvoltage condition.Similar with the lightning impulse discharging voltage,the 50%switching impulse discharging voltage of the line surge arrester can be estimated as the sum of the DC 1mA voltage of the arrester unit and the 50% switching impulse discharging voltage of the series gap.According to experimental results,when the series gap length is 500 mm,its 50%switching impulse discharging voltage reaches 318 kV.Thus,it can satisfy the requirement of not putting into operation under the conditions that the arrester unit is failed and the maximum switching overvoltage emerges in transmission line.

E.Determination of Series Gap Length

Fig.3 illustrates the demanded series gap lengths of the line surge arresters to fulfill different purposes,including cutting off the power frequency following current, withstanding the switching impulse overvoltage without discharging and discharging reliably under lightning impulse.The detailed values of those demanded series gap lengths of the line surge arrester are shown in Table II,from which we can find that the determined gap lengths of the fixed and separated gaps for 110 kV line surge arresters should be 550 mm and 500 mm(5%).

TABLE Ⅱ

THE LENGTHS OF THE SERIES GAPS OF 110 KV LINE SURGE ARRESTERS (MM)

Gap Shape	Fixed Gap		Separated Gap	
Number of insulator XP-7	7	8	7	8
Lightning impulse	+700	+650	+650	+570
Switching impulse	本500	本500	本500	本500
Cutting off power frequency following current	本313	本313	本313	本313

THE MINIMUM DISTANCE BETWEEN SURGE ARRESTER AND INSULATOR

Normally in China,the surge arrester with the fixed gap is too long to correspond with the length of the insulator string,and the special installing device is necessary to fix the arrester.The line surge arrester's installing methods would affect the protection effect of line surge arrester.From simulation experiment in laboratory,the installing sites of line surge arresters affect their protection effects whether they are installed to protect porcelain or composite insulators,when the distance between the arrester and insulator is adjusted.If this distance is adjusted to certain a critic state,so-called “transverse discharge”would take place.

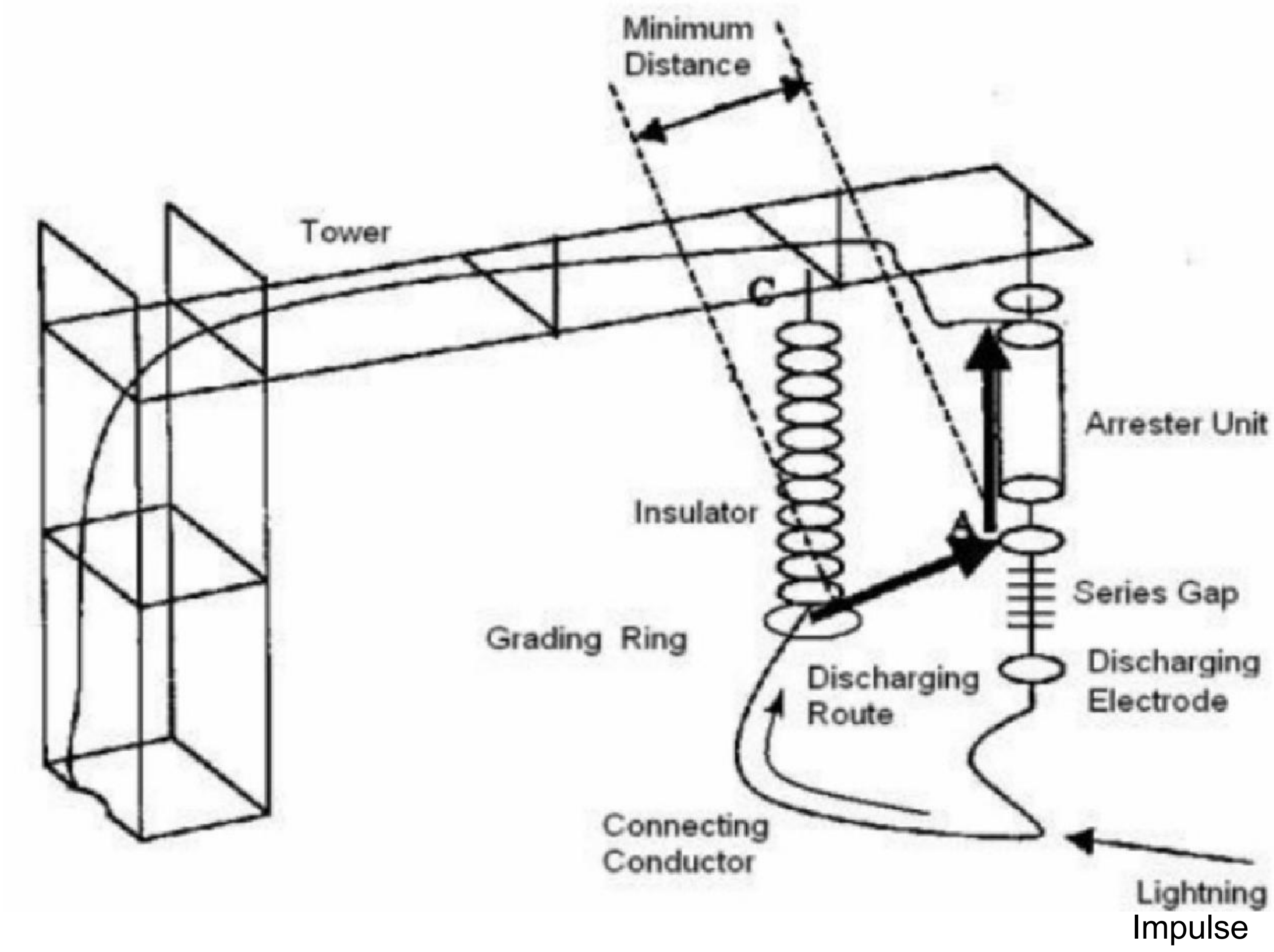

Fig.8.The so-called"transverse discharge"phenomena.

As shown in Fig.8,if the line arrester is close to the insulator,when a lightning impulse is applied on the connecting wire of surge arresters with separated and fixed gaps installed on transmission towers.

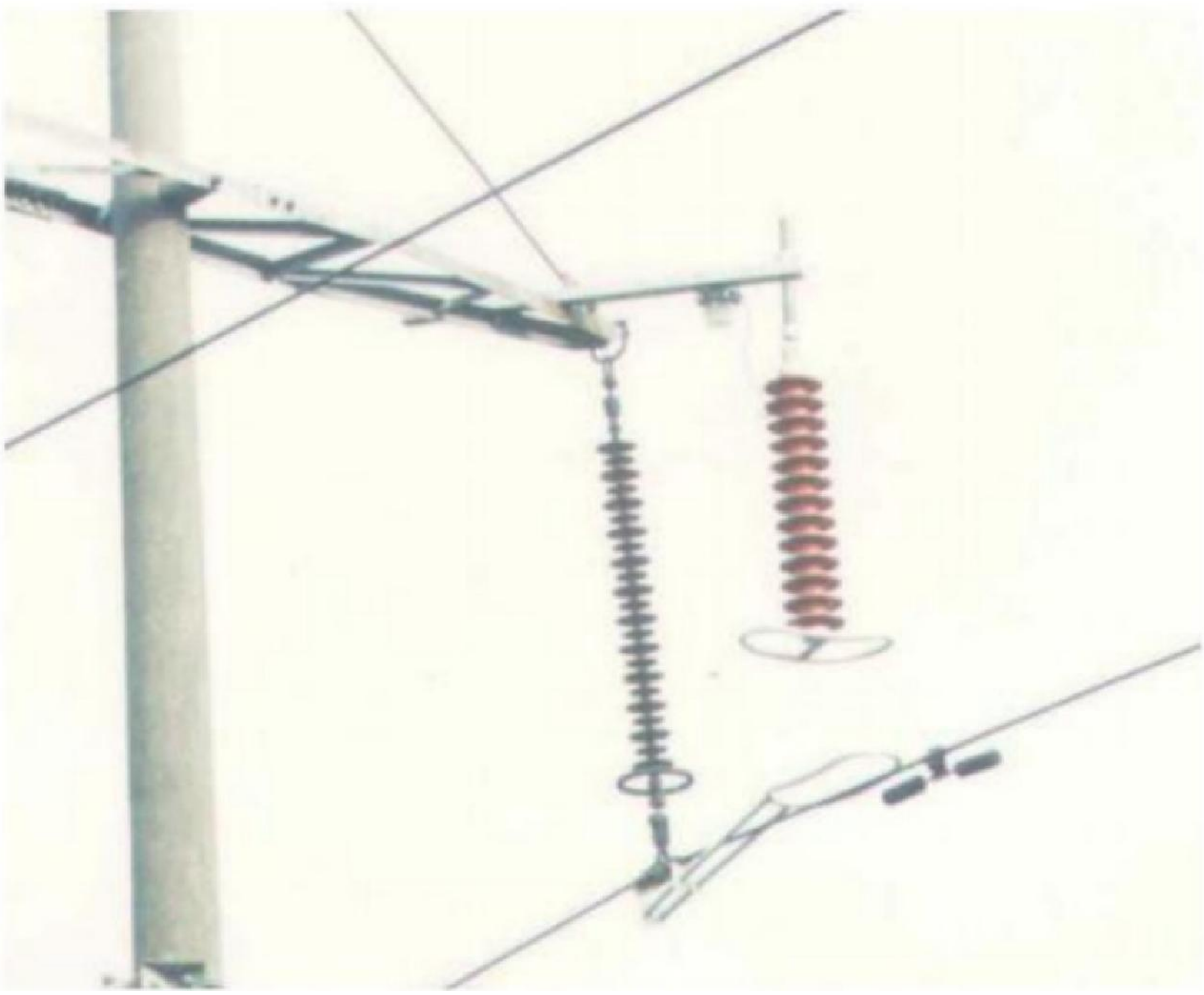

Fig.9.The 110 kV line surge arrester with separated gap.

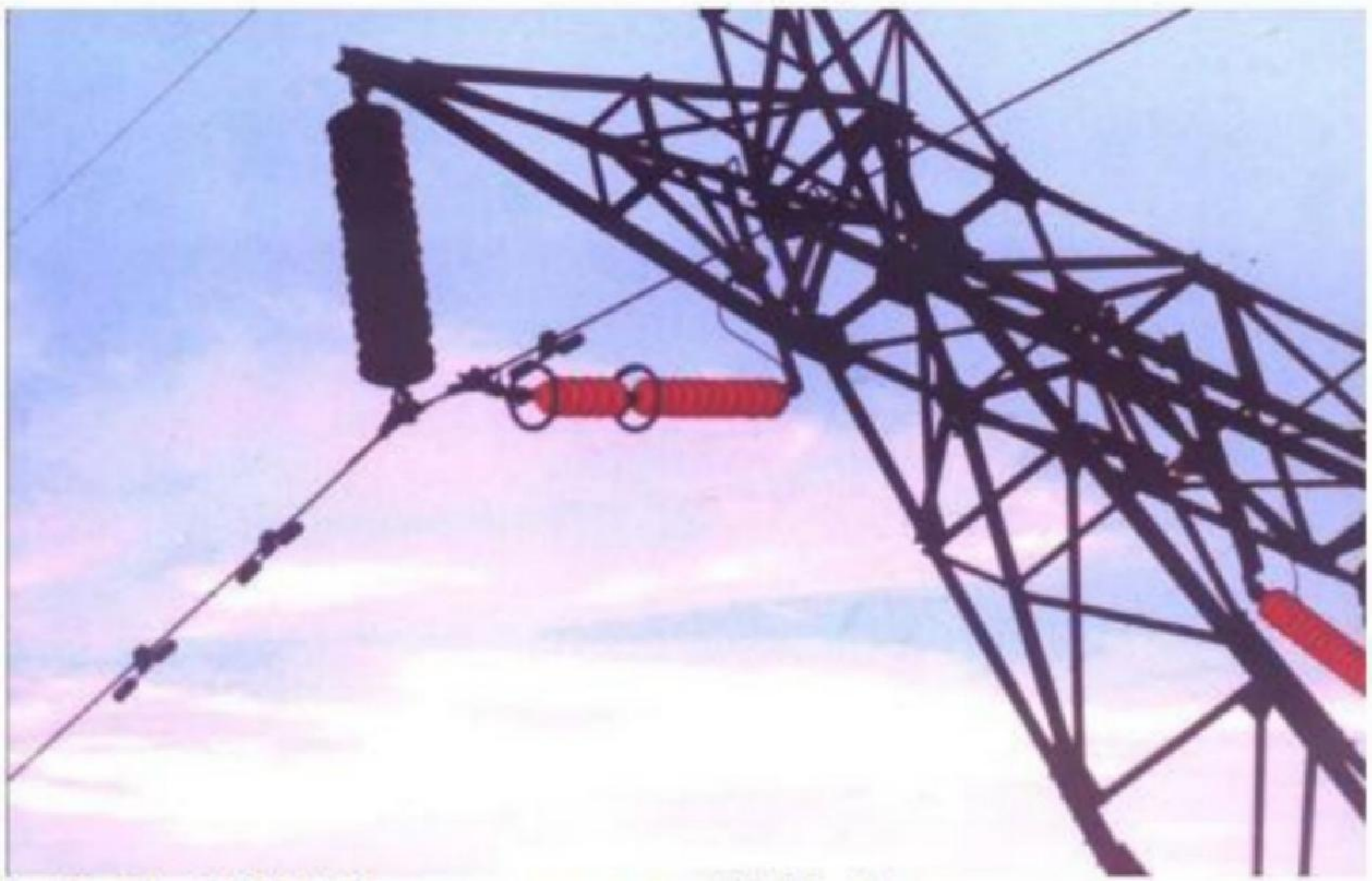

Fig.10.The 110 kV line surge arrester with fixed gap.

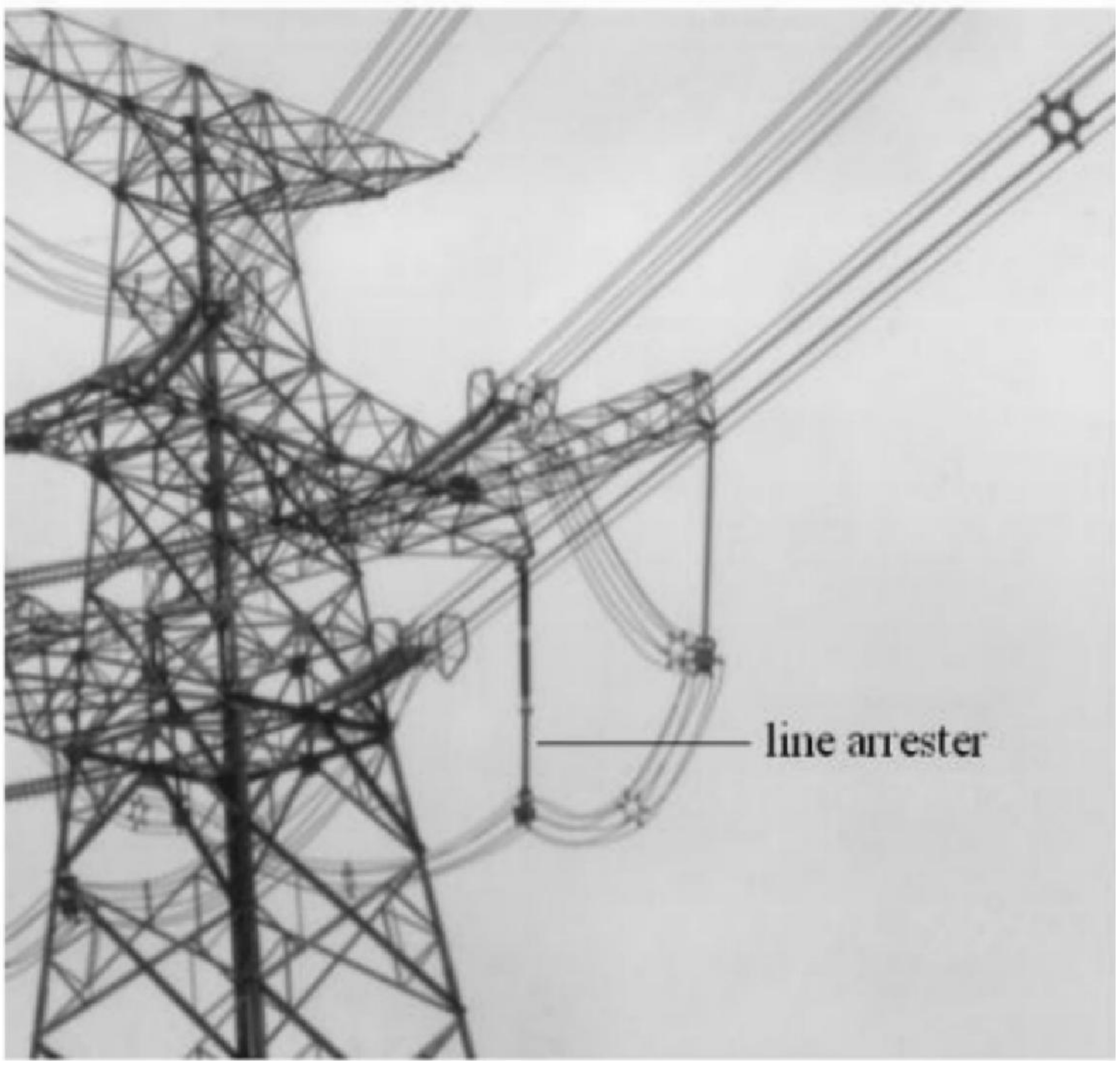

Fig.11.Field application of developed 500-kV polymeric line surge ZnO arresters.

APPLICATION EFFECT ANALYSIS OF LINE SURGE ARRESTERS

Ordinarily,the lightning withstand level(LWL)is used to measure the lightning protection performance of transmission line,which is the maximum lightning current that the transmission line can withstand without flashover.The purpose to install line arresters on transmission line towers is to increase the lightning withstand levels (LWLs).The best way to improve the LWL of a transmission line is to install line arresters in all towers,but the cost would be very high.So,ordinarily the line arresters are only installed on those towers with high impulse grounding impedances or easily being struck by lightning.When line arresters are installed on transmission lines,the following two purposes should be satisfied:

(a)When the lightning strikes the protected transmission line region by arresters, there is not any flashover in this region;

(b)When the lightning strikes the transmission line beyond the protected transmission line region,there is no flashover in this protected region,too.

The application effects of line surge arresters on the 500-kV compact transmission line were analyzed by EMTP.If three pieces of line surge arresters are installed on a tower,the influence of grounding resistance Ri of the transmission line tower stroke by lightning is shown in Table II,and the grounding resistance of all other towers is 10 Ω the applied voltage ratio q is changed in our calculation.The lightning withstand level of 500-kV Chang-Fang compact transmission line can be improved highly when line surge arresters are installed on transmission line towers.When the grounding resistance is equal to 70 Ω,and the magnitude of the lightning current is 300 kA,the discharge current through the arrester is 25.6 kA,and the absorbed lightning energy is 0.66 kJ/kVrms,it is no problem for the line surge ZnO arrester to withstand the effect of lightning.So,the 500-kV line surge arrester with the selected applied voltage ratio q=0.9 can withstand the lightning discharging current and the absorbed lightning energy when lightning strikes the transmission line tower.

TABLE III

LIGHTNING WITHSTAND LEVELOF 500-KV COMPACTTRANSMISSION LINE WITH OR WITHOUTLINE ARRESTERS(KA)

Grounding resistance R(Ω)	10	30	50	70
Without arrester	192	121	93	78
With 3 arresters q=0.712	>350	303	245	207
With 3 arresters q=0.90	>350	296	238	201
With 3 arresters q=0.95	>350	287	231	194
With 3 arresters q=1.00	>350	279	228	192