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ORIGINAL RESEARCH

Induced voltage at the closest pole on parallel line due to direct triggered lightning on 10 kV double circuit distribution line

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Abstract

In 2019, triggered lightning was used to directly strike phase C of a 1.5 km, 10 kV double-circuit distribution line in Guangzhou, China, with 2 flashes (13 return strokes) recorded. This paper presents the characteristics of induced voltage at the closest pole on the parallel line. The induced voltage is bipolar, which can be divided into 3 stages: negative increase stage, fast and positive transition stage and slowly returning to zero stage. The positive peak value of phase A voltage ranges from 111.4 to 228.9 kV and that of phase C voltage is from 90.1 to 200.9 kV, corresponding to lightning current from −8.9 to −29.9 kA. The positive peak value of the induced voltage is approximately 3 to 10 times the negative peak value. The negative peak, positive peak and positive 10%–10% duration time of induced voltage show a good linear relationship with the peak value of the return stroke current. There was no flashover occurred during the whole process. The result in this paper can provide data support for numerical simulation and line protection analysis.

1 | INTRODUCTION

The insulation level of distribution lines is relatively low, so lightning striking directly on distribution lines or near the lines could both bring overvoltage and arise great damage. Due to the relative difficulty of observation and uncertainty of natural lightning, researches on line overvoltage in recent years are mainly carried out through field observations and simulations.

In 2003, Yokoyama et al. studied the induced voltage generated on a 300 m distribution line when negative lightning struck a high tower [1]. It was found that the induced voltage was affected by the limited conductivity of the earth. Uman et al. [2] measured the induced voltage due to natural lightning on a 460 m line and speculated that the polarity and the magnitude of the induced voltage depended on lightning location and the observation station, which was also reported in [3, 4] and calculated in [5]. Through the observation on a 13 kV, 2.8 km distribution line in Mexico, Rosa et al. [6] found that for the same stroke, both voltage and electric field measured at two ends of the line were of reversed polarity. In 2008, Cai et al. [7] recorded 36 return strokes in 12 flashes on a 200 V distribution line due to natural lightning. The induced voltages observed were all monopolar. Artificial triggered lightning was carried out by Barker et al. near a 682 m distribution line [8]. They found that the induced voltages measured were 63% larger than calculated by the Rusck model. However, this paper did not give definitive recommendation on arrester spacing. Rubinstein et al. [9, 10] measured the induced overvoltage and electromagnetic field on a 448 m open-circuit distribution line with triggered lightning point 20 m away from one end of it. They classified the recorded induced voltages into oscillation type and pulse type [11]. Moreover, the oscillation type of overvoltage was successfully modelled while the modelling of the pulse type was unsuccessful. Wang et al. [12] measured the induced voltage at one end of a 10 kV distribution line and the induced voltages were divided into two types according to the difference in their rise time, while the reason for the difference in the wavefront time was not given.

Since requirements for direct lightning experiments are relatively strict and the experiments are destructive, experimental data in this area is quite scarce. In 1975, Eriksson et al. [13] recorded natural lightning on an 11 kV, 1.5 km distribution line, and the voltages caused by direct strikes to the line only accounted for 4% and were all of negative polarity. In 1993, overvoltage measured at distribution arrester caused by direct

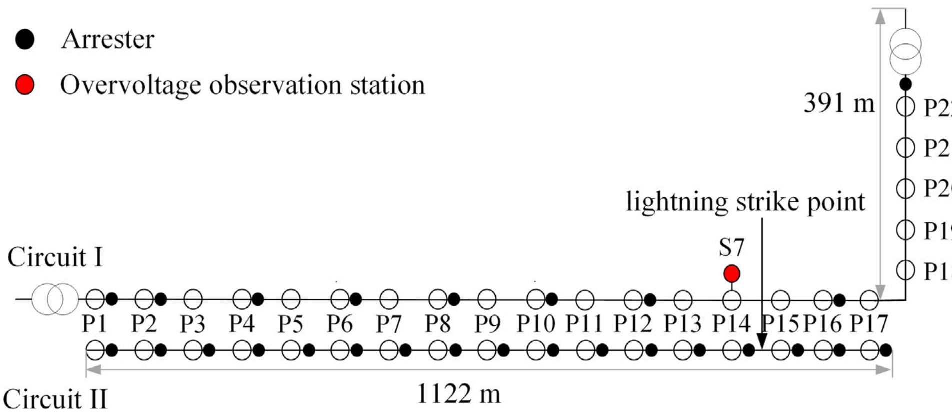

FIGURE 1 Layout of the distribution line

strikes was studied by Barker. It was found that this kind of voltage showed a steep wavefront and a high magnitude, but the bipolar precursors and oscillations were not fully studied [14]. In 1999, through artificial triggered lightning, Fernandez et al. [15] presented the arrester discharge voltage waveforms of one direct strike, which were clamped by the arrester to about −25 kV. Schoene et al. [16] did direct triggered lightning experiment in Florida, finding that despite the closer spacing between adjacent poles, phase-to-phase flashover occurrence was less frequent for horizontal line than that for vertical line. Different numerical simulation methods are also utilized to analyse the lightning transient, like FDTD and FDTD-PEEC. Recent researches can be found in [17–21].

There have been few experiments on the induced voltage caused by direct strikes on double-circuit distribution lines so far. The result of induced voltage at the closest pole on a 1.5 km, 10 kV double-circuit parallel distribution line due to direct triggered lightning was first reported here. The measuring station is highly close to the strike location, which is very scarce. The lightning waveform characteristics and its response to lightning current are valuable to line protection and double-circuit electromagnetic coupling computation.

This paper is organized as follows. Section 2 introduces the experimental arrangement and the recorded data. Section 3 describes the characteristics of lightning current, the waveform of induced voltage and the relationship between them. The fourth part discusses the effect of strike location on the waveforms of induced voltage and the differences between voltage of two phases.

2 | EXPERIMENT AND DATA

2.1 | Experiment

In 2018, a 10 kV double-circuit distribution line was built in Conghua, Guangzhou, which is a mountainous area with frequent thunderstorms. The layout of the line is shown in Figure 1. Circuit I is arranged in L-shape. Before the turning point of L, the first part of circuit I is 1122 m from pole 1 to pole 17, 2.5 m away from circuit II, which is parallel to it. After that, the second part of circuit I is 391 m from pole 18 to pole 22. Circuit I is 1513 m while circuit II is 1122 m. The distance between each pole is 70 m. The 10 kV distribution transformers are installed at both ends of circuit I. Those in circuit II are replaced by equivalent capacitance. There is no ground wire in the double-circuit system.

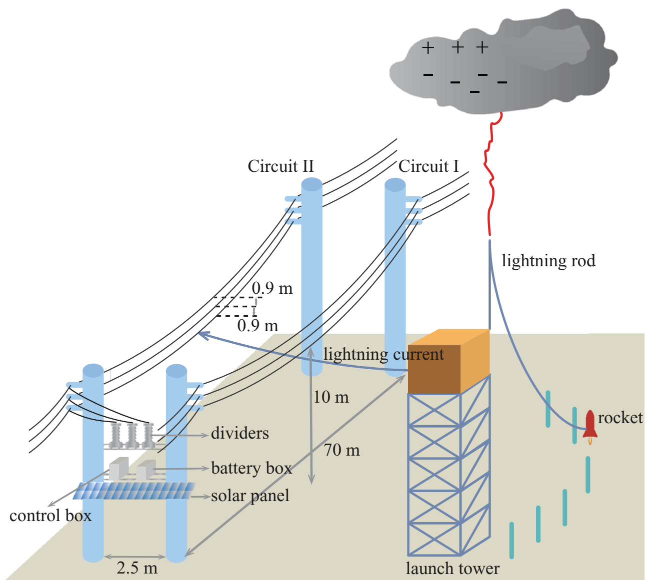

FIGURE 2 Layout of the distribution line between pole 14 and pole 15, launcher instrumentation and overvoltage sensing device

Figure 2 shows the line configuration between pole 14 and pole 15, the triggered lightning device, and the measuring instrument. Three-phase conductors are arranged vertically. From top to bottom is phase A, B, and C respectively. Adjacent conductors are separated by 0.9 m. Phase C is 10 m above the ground. The soil resistivity is around 190 Ω·m. The two ends of circuit I are equipped with 10 kV/200 kVA transformers, the same as the real 10 kV distribution line in power system. Those of circuit II are equipped with 300 Ω resistance from line conductor to ground.

The triggered lightning device consists of a small rocket with a copper wire at the bottom and a lightning rod connected. This technology is used to generate a lightning source and the lightning directly struck phase C between pole 14 and pole 15 in circuit II.

The lightning current was measured by a coaxial shunt and Rogowski coil before the lightning current injection point simultaneously. In Figure 2, the coaxial shunt and the Rogowski coil are in the yellow box. Since the measuring results of these two elements are identical, the lightning current presented here is from coaxial shunt signal, with 50 MS/s sampling rate for 2 s recording length.

The voltage observation system is mainly composed of capacitive voltage divider with ratio of 1000:1, impedance matching module, capture card, industrial personal computer, 4G module, solar panel and remote main server. The voltage divider converts the high voltage into a low voltage within the rated range of the capture card, then the capture card transmits the voltage signal to the industrial personal computer. The impedance matching module matches the impedance of the voltage divider and the capture card with an impedance ratio of 61.6:1. The industrial personal computer and 4G module are powered by solar energy and battery. Finally, the signal is transmitted to the remote main server through optical fibre. The system's sampling rate is 10 MS/s. The overvoltage observation station is on pole 14, closest to the strike location in circuit I, named station 7, abbreviated as S7 in the following part.

2.2 | Data

There were 2 flashes recorded at 3:12 PM and 3:21 PM on 2 July, 2019, named F1907021512 and F1907021521 respectively. F1907021512 consisted of 2 return strokes and F1907021521 was composed of 11 return strokes.

Figure 3 shows the lightning current and the corresponding voltage in phase A and phase C of F1907021512, which had 2 return strokes. Figure 3a is the overall time sequence of lightning current and two-phase voltage, with a time scale of 115 ms. Lightning current and voltages correspond in time. Figure 3b expands the lightning current waveform in a time scale of 2000 μs while Figure 3c,d expands the waveforms of voltage in a time scale of 120 μs. The left one corresponds to the first return stroke and the right one corresponds to the second return stroke, abbreviated as RS1 and RS2 respectively. In this flash, the lightning current is of negative polarity. The voltages of both phase A and phase C are bipolar and the negative peak value is just a fraction of the positive peak value.

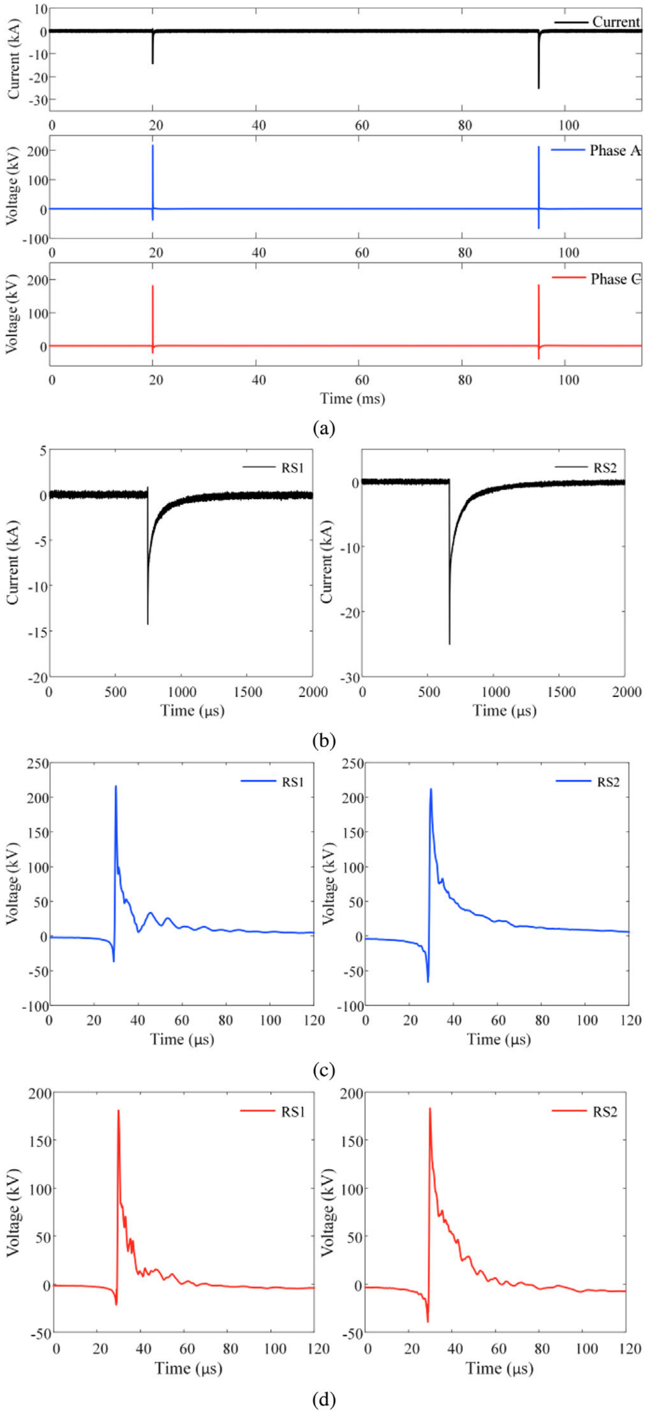

FIGURE 3 Lightning current and the two-phase voltages and their amplified waveforms. (a) Lightning current and the voltage of phase A and phase C. (b) Lightning current with 2000 μs time span. (c) Phase A voltage with 120 μs time span. (d) Phase C voltage with 120 μs time span

3 | OBSERVATION RESULTS AND ANALYSIS

This part will present the waveforms of lightning return stroke current and the induced voltage. The parameters of them will be defined and the relationship between them will be revealed. The first part will introduce the characteristics of lightning return stroke current. The second part is about the waveforms of induced voltage. The third part reveals the relationship between the parameters of lightning return stroke current and that of induced voltage.

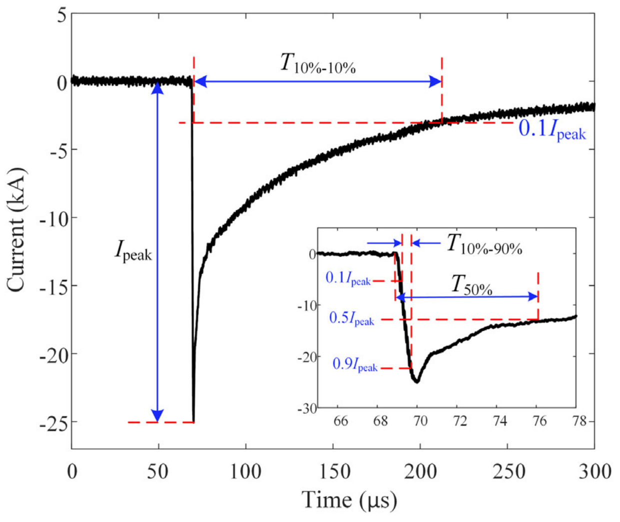

FIGURE 4 Parameter definition of lightning return stroke current

3.1 | Characteristics of lightning return stroke current

The return stroke current measured in two flashes are all negative polarity. After dropping down to the negative peak quickly, it returns to zero slowly, showing a typical double exponential waveform.

Four parameters of the current are defined, which are the negative peak I_{peak} (In the following part, the peak of the current represents the absolute value of negative peak of the current for convenience.), 10%–90% rise time of the negative peak $T_{10\%–90\%}$, 10%–10% duration time of the negative peak $T_{10\%–10\%}$, and half-peak width $T_{50\%}$, as shown in Figure 4.

The parameters of the return stroke currents are listed in Table 1. Except for the four parameters shown in Figure 4, 10%–90% gradient ($Ts_{10\%–90\%}$) and the charge in 1 ms are also listed in the table. $Ts_{10\%–90\%}$ is the quotient of the difference between 10% and 90% wavefront of the current divided by the difference between their corresponding time. The electric charge in 1 ms is calculated by the following formula [22].

$$Q_{1ms} = \int_{t_{\min}-0.4}^{t_{\min}+0.6} i(t)dt \tag{1}$$

where $t_{\min}$ represents the time of the minimum current, with its unit being ms.

For two flashes with 13 return strokes, the peak of the current ranges from 8.9 to 29.9 kA, with the geometric mean being 16.9 kA. This is quite similar to those measured in [23–25]. The charge in 1 ms is between 0.3 C and 2.3 C, with the average value being 1.2 C. In [26], the top two ranges of charge in 72 return strokes are around 0.125 C and 1 C. The rise time of the current is mainly in the range of 0.4–0.7 μs, with an average time of 0.5 μs. Zheng et al. [22] reported that 82.76% of 29 samples had a rise time of smaller than 0.75 μs and in Zhang's report [25], their rise time was mainly between 0.2 μs and 0.6 μs. 10%–90% gradient in this paper is from 14.2 to 48.0 kA/μs while Zheng et al. [22] gave a range of 3.9 to 75.0 kA/μs with a total of 29 samples. The 10%–10% duration time of the negative peak is from 93.8 to 270.1 μs, generally increasing with the peak value of the current. The duration of the half-peak width is much shorter than those reported in other places [27, 28], which is between 1.9 and 12.3 μs, with the average time being 6.3 μs. The interval time of adjacent return strokes ranges from 9.0 to 142.0 ms and its average value is 55.1 ms. There is no evidence that the peak of the first stroke current is larger than that of the subsequent stroke current mentioned in [29].

3.2 | Characteristics of induced voltage

The voltage waveforms of phase C corresponding to 13 return strokes of two flashes are arranged in the order of peak value of

TABLE 1 Parameters of lightning current

Lightning event	Return stroke number	I_{peak} (kA)	Q_{1ms} (C)	$T_{10\%–90\%}$ (μs)	$Ts_{10\%–90\%}$ (kA/μs)	$T_{10\%–10\%}$ (μs)	$T_{50\%}$ (μs)	Return stroke interval (ms)
F1907021512	#1	−14.3	0.8	0.7	16.3	148.6	11.2	\
	#2	−25.1	1.7	0.6	33.5	171.7	11	74.9
F1907021521	#1	−14.9	1.6	0.5	23.8	184.2	10.9	\
	#2	−24.1	2.3	0.5	38.6	232.5	12.1	61.3
	#3	−18.9	1.6	0.5	30.2	270.1	8.0	50.5
	#4	−8.9	0.3	0.5	14.2	94.1	5.8	9.0
	#5	−19.5	1.1	0.4	39.0	155.6	5.2	53.0
	#6	−21.8	1.3	0.5	34.9	167.9	8.7	36.0
	#7	−11.3	0.5	0.4	22.6	99.4	2.6	32.1
	#8	−12.8	0.4	0.5	20.5	104.0	3.7	18.8
	#9	−14.5	0.7	0.4	29.0	135.6	4.0	28.8
	#10	−13.1	0.4	0.5	21.0	93.8	2.2	100.0
	#11	−29.9	2.3	0.5	48.0	186.3	6.2	142.0

return stroke current from small to large, with a time scale of 80 μs.

The voltage waveforms of 13 return strokes present similar characteristics: After the initial slow negative increase, there follows a rapid rise to the positive peak, then the voltage returns to zero gently. During the whole process, there is almost no oscillation.

We divide the induced voltage into three stages: negative increase stage, fast and positive transition stage, and gently return-to-zero stage. The negative increase stage corresponds to the leader development, while the fast and positive transition stage is due to the return stroke. The bipolar waveform can be attributed to many factors, like the distance along the line from the strike location, perpendicular distance of strike location from the line, the waveform of the return stroke current etc. [30]. The perpendicular distance of strike location from the line is 2.5 m and the distance along the line from the strike location is 35 m, quite close to the line. This can explain the bipolar waveforms here. Besides, according to [31], when the strike location is perpendicular to the line, the leader effect is not as much as appreciable compared with the strike location along the line. This may explain why the negative peak value is smaller than the positive value.

The current on circuit II can generate electric field, thus circuit I will induce voltage due to capacitive coupling and electromagnetic coupling, where the latter is dominant. The electromagnetic coupling between double circuit will generate electromagnetic induced voltage along the line conductor of circuit I. These factors make the induced voltage higher on circuit I.

For the same return stoke, the induced voltages in phase A and phase C are quite similar in their waveforms. The induced voltage here is similar with that calculated by Rachidi et al. [31], who took the leader development stage into consideration. The impulse voltage recorded by Rubinstein et al. [11] started from a positive rising, then a main negative pulse follows, ending with a subsidiary negative pulse. Barker et al. [8] conducted triggered lightning on a 682 m single circuit distribution line 145 m away from the centre of the line with no lightning arrester equipped. The induced voltage waveform is similar with that in this paper, except that their waveform had only one pulse component, and the negative component we measured did not appear before the positive pulse in their waveform. Eriksson et al. [13] measured two kinds of induced voltage caused by natural lightning and one kind of voltage due to direct strike observed on a 10 km, 11 kV distribution line. The second kind of induced voltage waveform (nearby induced voltage) has a slowly decaying negative component before the positive pulse. This kind of waveform accounted for 2%–3% in their observation. Also, the absolute value of its negative peak is smaller than its positive peak value.

For the induced voltage, five parameters are defined. They are the negative peak value V_1, positive peak value V_2, peak-to-peak value V_{12}, 10%–90% rise time of the negative peak T_1, negative to positive peak time interval T_2 as well as 10%–10% duration time of positive peak T_3, as shown in Figure 6.

Table 2 presents the statistical results of five parameters of the induced voltages of phase A and phase C. The peak value of the lightning current ranges from 8.9 to 29.9 kA. The corresponding negative peak value of phase A ranges from 12.1 to 66.0 kV, while that of phase C is from 8.9 to 39.2 kV. The positive peak range of phases A and C are from 111.4 to 228.9 kV and from 90.1 to 200.9 kV, respectively. The positive peak value of phase A is about 6 times the absolute value of negative peak. That of phase C is about 7.7 times.

In F1907021512, although the peak value of lightning current for the first stroke is not necessarily large, the corresponding positive peak value of the induced voltage is very large. The positive peak value and negative peak value of phase A are always higher than that of phase C, because phase A is higher than phase C compared with the ground. The average ratio of the negative peak value of phase A to the negative peak value of phase C is 1.6, while that of the positive peak value of phase A to the positive peak value of phase C is 1.2. For peak-to-peak value of phase A, the maximum is 277.9 kV while the minimum is 123.6 kV. For phase C, these two numbers are 229.5 and 98.9 kV, respectively.

Wang et al.[12] conducted triggered lightning near a 10 kV line. The induced voltage they measured was similar with that observed in this paper. However, the values of the positive and negative peak of the measured waveforms were similar in their observation, moreover, there was oscillation at the tail of their waveforms. Because the data record station in this paper was adjacent to the lightning strike location and far away from the end of the line, besides, the oscillation phenomenon does not appear in Figure 5.

The negative peak rise time of two phases is mainly between 5 and 30 μs. It should be noted that the negative peak rise time of F1907021521's last return stroke of phases A and C were 43.1 and 50.1 μs, respectively. This can be explained by the largest peak value of the lightning current of this return stroke. In most cases, the rise time of the induced voltage of phase C is several microseconds longer than that of phase A. The average values of the negative to positive peak time interval of voltage of two phases are both 1 μs, proving that the positive peak rises extremely fast. Rubinstein et al. [11] observed oscillatory voltages and impulsive voltages on a 448 m line, and the rise time of them were 20 and 10 μs, respectively, which were in the range of what we observed. The transition time between positive peak and negative peak observed by them was about 20 μs, larger than what we recorded. Perhaps it is because their lightning strike location is farther from the line, which is about eight times that of this paper. The positive 10%–10% duration time of phase A is between 4.4 and 16.0 μs, with an average value of 8.8 ¯s and that of phase C ranges from 5.0 to 20.0 μs, with an average value of 9.0 μs.

3.3 | Relationship between voltage and lightning current

This part studies the relationship between induced voltage parameters and lightning current parameters, as shown in Figure 7.

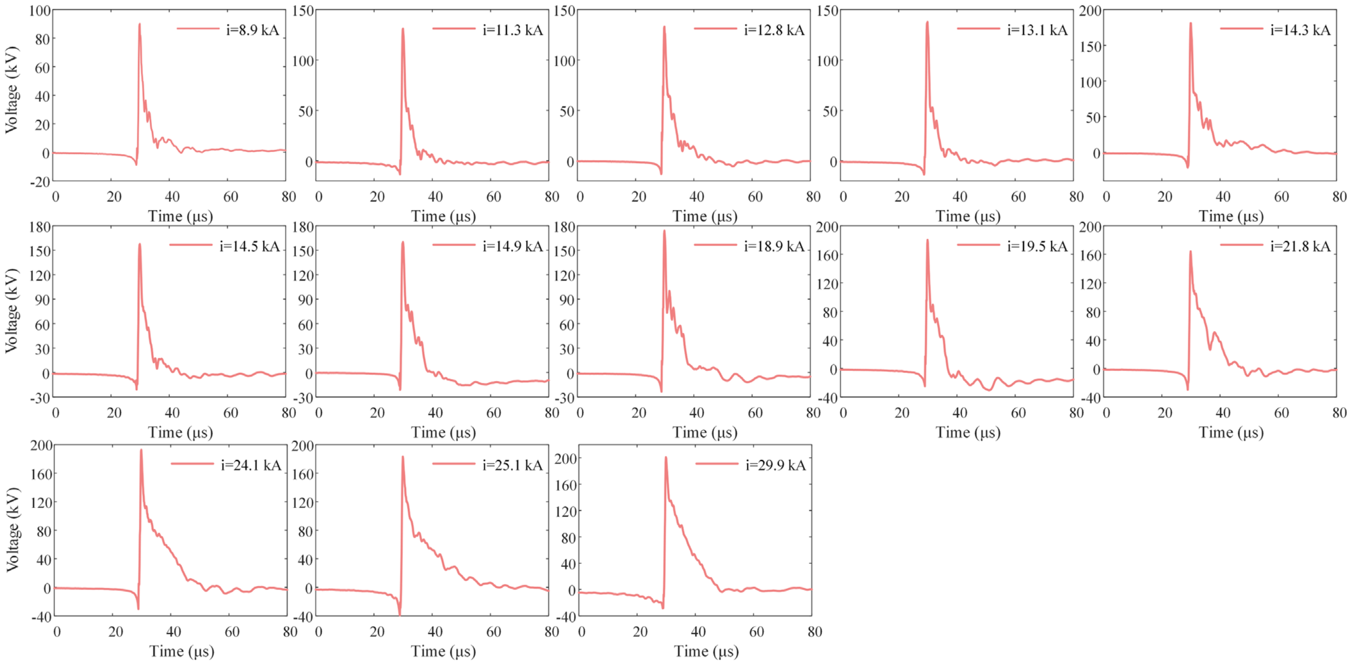

FIGURE 5 Waveforms of phase C with return stroke current from small to large

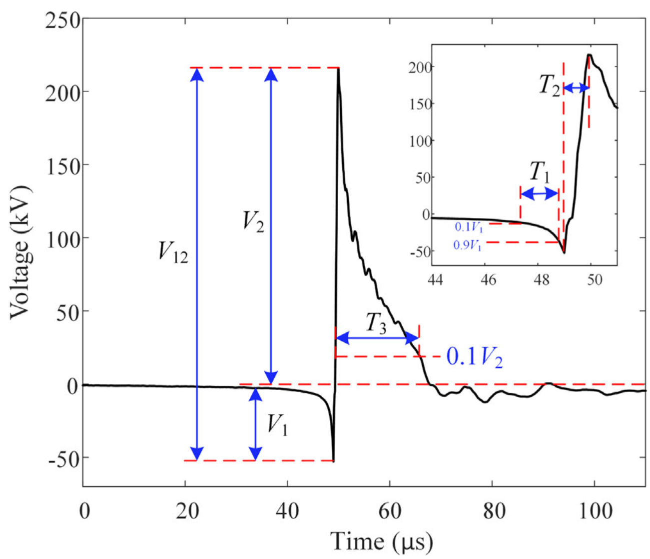

FIGURE 6 Parameter definition of induced voltage

Figure 7a shows the linear fitting result of negative peak value of the induced voltage and the peak value of return stroke current. The definition of R-square is as follows [32].

$$R^2 = 1 - \frac{\sum_i (\hat{y}_i - y_i)^2}{\sum_i (y_i - \bar{y})^2} \tag{2}$$

where y_i represents the real value, $\hat{y}_i$ represents the fitting value and $\bar{y}$ is the arithmetic mean.

The R-square coefficients between the negative peak value of induced voltage and the peak value of the lightning current of are 0.79 and 0.76 for phase A and phase C respectively, while that calculated by Barker [8] was 0.97. Figure 7b,c reflects that there is also a linear relationship between the positive peak value, the peak-to-peak value of voltage, and the peak value of the current. The correlation coefficients between the positive peak value of voltage and the peak value of current for phases A and C are 0.64 and 0.71, respectively, which are both smaller than those in Figure 7a. The linear correlation is better for the peak-to-peak value of the voltage and the peak value of the current. R-square are both 0.76, as shown in Figure 7c.

For parameters concerning time, in Figure 8, the linear relationship between positive 10%–10% duration time of phase A and phase C voltage is revealed and the R-square coefficients of two phases are 0.78 and 0.62, respectively. The two fitting lines almost overlap, because the difference of 10%–10% duration time of voltage between two phases is very small. There is no linear relationship between either the rise time of the voltage and that of the current, or the transition time of the voltage and the rise time of the current. The linear relationship between 10%–10% duration time of the positive peak of the induced voltage and that of the lightning current is not evident (R-square are 0.49 and 0.26 for phase A and phase C, respectively).

4 | DISCUSSION

In 1997, Rachidi et al. [31] researched on the effect of nearby lightning strikes on induced voltage. A 500 m long, 10 m high, single-phase line was simulated and five strike locations were considered. The most similar situation to our experiment was the strike location No. 5, which was 30 m away from the centre of the line. The positive peak value of the voltage at the right end of the line was about 200 kV. The negative peak value of that

TABLE 2 Parameters of induced voltage of phase A and phase C

Lightning event	Return stroke number	Peak value of lightning stroke current (kA)	Negative peak value of voltage (kV)		Positive peak value of voltage (kV)		Peak-to-peak value of voltage (kV)		Negative 10%–90% rise time of voltage (μs)		Negative to positive peak time interval of voltage (μs)		Positive 10%–10% duration time of voltage (μs)	
			A	C	A	C	A	C	A	C	A	C	A	C
F1907021512	#1	−14.3	−36.8	−21.4	216.1	180.8	252.9	202.2	9.2	13.4	1.0	1.0	9.1	8.7
	#2	−25.1	−66.0	−39.2	211.9	183.2	277.9	222.4	13.5	20.4	1.4	1.0	11.7	20.0
F1907021521	#1	−14.9	−26.9	−21.4	184.4	160.0	211.2	181.4	6.1	5.4	1.0	1.0	8.2	8.0
	#2	−24.1	−52.9	−30.6	215.9	192.7	268.8	223.4	5.2	7.1	1.0	1.0	16.0	15.2
	#3	−18.9	−40.2	−23.6	190.0	174.0	230.2	197.5	7.8	10.3	0.9	1.0	9.0	8.3
	#4	−8.9	−12.1	−8.9	111.4	90.1	123.6	98.9	17.2	15.5	1.1	1.2	4.6	5.9
	#5	−19.5	−42.7	−30.7	209.9	180.1	252.6	210.7	12.7	16.5	0.9	1.0	8.1	6.8
	#6	−21.8	−49.6	−30.0	193.4	164.0	243.1	194.0	8.5	11.4	1.0	1.0	14.2	7.1
	#7	−11.3	−22.5	−13.6	166.2	131.0	188.7	144.6	21.6	30.7	0.9	1.0	4.4	5.0
	#8	−12.8	−18.7	−13.3	168.8	133.0	187.5	146.3	8.6	8.8	1.0	1.0	5.4	6.8
	#9	−14.5	−31.7	−20.8	181.7	157.5	213.3	178.4	16.0	19.0	0.9	1.0	5.0	5.3
	#10	−13.1	−21.6	−13.9	175.3	137.7	196.9	151.5	17.6	21.4	1.0	1.2	4.6	5.3
	#11	−29.9	−48.0	−28.6	228.9	200.9	276.9	229.5	43.1	50.1	1.2	1.0	14.2	14.5

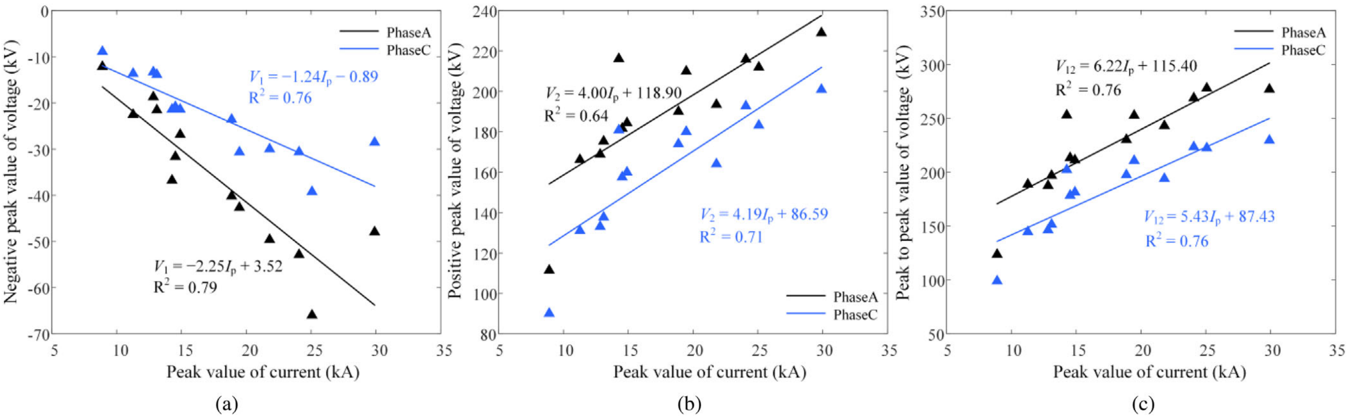

FIGURE 7 Linear fitting between induced voltage parameters and return stroke current parameters. (a) Linear fitting between negative peak value of induced voltage and peak value of return stroke current. (b) Linear fitting between positive peak value of induced voltage and peak value of return stroke current. (c) Linear fitting between peak-to-peak value of induced voltage and peak value of return stroke current

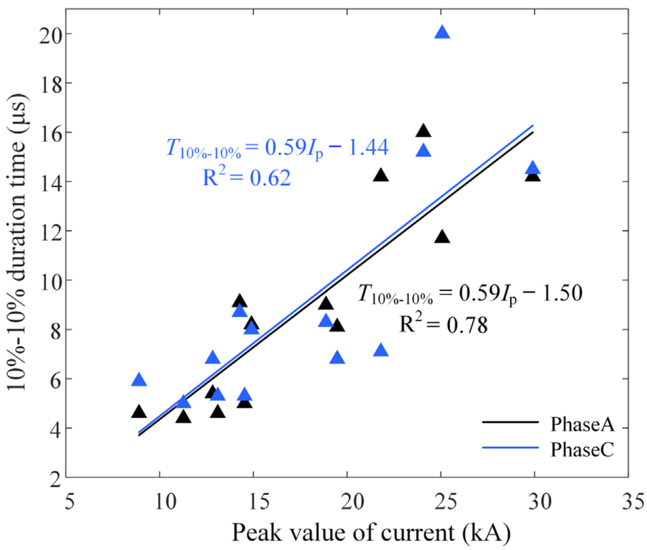

FIGURE 8 Linear fitting between 10%–10% duration time of induced voltage and the peak value of current

was −10 kV, bit smaller than what we have measured. Besides, the voltage waveform related to strike location no. 5 showed no evident negative peak. However, when strike locations were no. 2 (30 m away from the left end of the line) and no. 3 (30 m along the line prolongation at the left end), waveforms recorded at the right end were identical to ours.

The lightning strike location in the test conducted by Barker et al. [8] was 145 m away from the line. The peak value of voltage was between 8 and 100 kV corresponding to current from a few kA to 44 kA. Eriksson et al. [13] recorded that the nearby induced voltage waveform featured initial slow negative development prior to positive impulsive component, which only occurred when the distance between the strike location and the line was within 200 m. Besides, the peak value of the induced voltage corresponding to the farthest 2.5 km lightning strike location was considerable, 24 kV. According the fitting line given by them, it can be deduced that when the lightning current was

TABLE 3 Average values of parameters for the induced voltage

	Phase A	Phase C
Negative peak value (kV)	−36.1	−22.8
Positive peak value (kV)	188.8	160.4
Peak-to-peak value (kV)	225.0	183.2
Negative 10%–90% rise time (μs)	14.4	17.7
Negative to positive peak time interval (μs)	1.0	1.0
Positive 10%–10% duration time (μs)	8.8	9.0

10 kA and the strike location was 10 m away from the line, the induced voltage could reach 300 kV. When the strike location was only 20 m away from east end of the line, the oscillatory type of the induced voltage measured by Rubinstein et al. [11] at the west end of the line had an average peak value of –72 kV and that at the east end of the line was −47 kV. In [33], they observed that only in rare cases like direct strikes, the maximum voltage could exceed 300 kV. In [34], it was found that when the strike point distance is 200 m, the induced voltage on line was still monopolar, but when it shortened to 50 m, an initial negative peak appeared.

In Table 3, the average values of six parameters concerning voltage are listed. Except for parameters related to time, others show the regulation of phase A > phase C. For the average negative peak voltage, phase A is 13.3 kV larger than that of phase C, −36.1 and −22.8 kV, respectively. The average positive peak voltage and average peak-to-peak voltage of phase A are 188.8 and 225.0 kV, respectively, 28.4 and 41.8 kV larger than those of phase C. The difference between the average values for time parameters is small. The average negative peak value and the average positive peak value of phase A are 13.3 and 28.4 kV larger than those of phase C. The lightning channel will generate induction field, which is related to the height of the line. Since phase A wire is higher than phase C wire, phase A voltage on circuit I is larger than phase C voltage.

Since the 50% full-wave impulse flashover voltage has a positive polarity of 240 kV and a negative polarity of −296.4 kV, it can be inferred from the fitting result between positive peak value of voltage in phase A and the peak value of current that when the lightning current reaches 30.27 kA, a flashover may occur. In addition, considering that the transmission line is much higher, when the lightning strikes one circuit of the double-circuit transmission line on the same tower, the voltage induced on the other circuit may be high enough to cause a flashover. This problem deserves much attention and more researches in the future.

5 | SUMMARY

Triggered lightning was used to strike a 10 kV double-circuit distribution line directly. The induced voltage at the closest pole (S7) on the parallel line was revealed. The main findings are listed as follows.

1. Return stroke current shows a typical negative double exponential waveform. The peak value of the current ranges from −8.9 to −29.9 kA.
2. In all return strokes, voltages of phase A and phase C are all bipolar. The waveform of induced voltage can be divided into three stages: negative falling stage corresponding to leader development, fast and positive transition stage corresponding to return stroke, and gently return-to-zero stage. The waveform presented here can provide reference for numerical analysis.
3. The positive peak value of the induced voltage is much greater than its negative peak value, about 3 to 10 times the negative peak. For different phases, the average negative peak value, positive peak value, and the peak-to-peak value of phase A are −36.1, 188.8 and 225.0 kV, respectively, all larger than those of phase C. The differences of these three parameters for two phases are 13.3, 28.4, and 41.8 kV.
4. The negative peak value, positive peak value and 10%–10% duration time of the positive peak of the induced voltage all present a linear relationship with the peak value of the return stroke current. According to the fitting result, flashover may occur on the observation pole when the lightning current reaches 30.27 kA.

Simulations could be applied to clearly reveal the three-phase overvoltage in the future. Further study could also focus on the induced voltage of higher-level double-circuit line when lightning directly strikes one circuit of the line. Finally, the shielding effectiveness of ground wire on double-circuit line can be researched to determine the best configuration.

AUTHOR CONTRIBUTIONS

Y.Z.: Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. J.W.: Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Writing – review & editing. L.C.: Data curation Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Writing – original draft. Q.L.: Data curation, Resources, Supervision. Y.F.: Formal analysis, Resources, Software, Supervision. R.S.: Resources, Supervision. S.W.: Data curation. M.Z.: Data curation, Resources.

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CONFLICT OF INTEREST

The author declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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