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ORIGINAL RESEARCH

Three-phase overvoltage at lightning strike point due to direct triggered lightning to the phase wire of 10 kV power distribution line

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Abstract

This paper reports the observation results of three-phase overvoltage at the lightning strike point of a 1.5 km, 10 kV power distribution line that was struck directly by rocket triggered lightning to its phase wire C. The arrester of the direct struck phase at the lightning strike point operated in all return strokes corresponding to return stroke current from −3.3 kA to −32.9 kA. The waveform of direct struck phase includes an initial spike before negative peak, operation area of metal oxide varistor, and the final attenuation with oscillation. The overvoltage waveforms of the indirect struck phase at the lightning strike point show a small initial negative peak, rapid transition to a large positive peak, and the final negative attenuation with oscillation. The negative peak value of the indirect struck phase at lightning strike point ranged from −4.1 kV to −25.2 kV and that of the direct struck phase was between −78.1 kV and −167.8 kV. The positive peak value of indirect struck phase was between 0.2 kV and 49.8 kV. The negative peak value, zero-crossing time and the peak-to-peak value of voltage all have a good linear relation with the peak value of lightning return stroke current.

1 | INTRODUCTION

Lightning disaster is one of the main causes of distribution line faults [1] and direct lightning strikes can be great threat to power systems [2]. At present, there are various lightning protection measures for distribution lines, but the effectiveness of protection measures has not been tested sufficiently. Therefore, it is very necessary to carry out lightning experiments on power distribution lines.

Yokoyama [3] used the impulse voltage generator to hit one pole of a 250 m long distribution line. It was found that when the line is protected by arresters or overhead ground wire, the overvoltage on the line conductors tends to have shorter wave tail. Nakada et al. [4] measured the current flowing through different points when a 430 m long distribution line was struck by lightning impulse current. It shows that additional overhead ground wire can reduce the peak value and duration of discharge current and reduce the charge flowing through the arrester to less than 50%. Besides, the induced voltage caused by lightning on high stack was studied in [5–7]. The voltage caused by direct strokes of natural lightning was observed on an 800 m long distribution line in [8]. It was found that when a return stroke current had a long duration, the reduction in voltage across the arresters could absorb more energy and this may cause arrester failure. Master et al. [9] found that the stepped leader may lead to the operation of overvoltage protection devices on the line. In 2013, it was found by Cai et al. [10] that most induced voltages on a 220 V line installed with surge protective devices showed the characteristic of residual voltage and had a peak value less than 1 kV.

Since Newman et al. [11, 12] succeeded in artificial triggered lightning, people began to pay more attention to its role in the study of lightning physics. The researches on distribution lines using rocket-triggered lightning mainly focus on the division of current along the line and the measurement of overvoltage on the line. Through the experiment in Florida [13], it was found

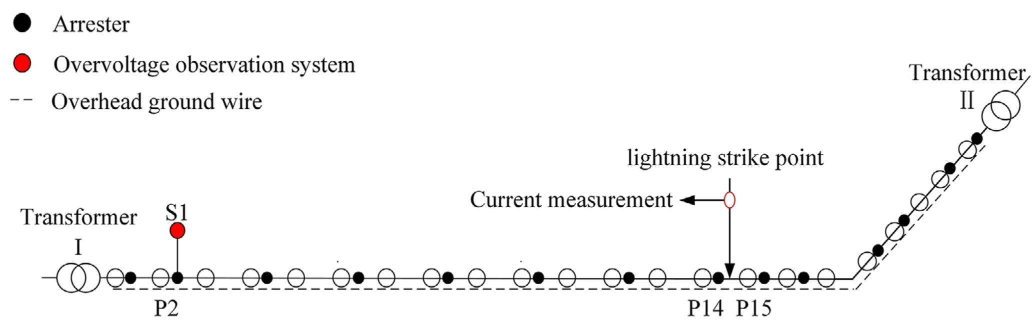

FIGURE 1 Layout of the distribution line

that for nearby triggered lightning, the lightning current injected into the earth could enter the line through the grounding system and the percentage of it depended on the waveform of the current. The voltage at the end of a 1.5 km long, 10 kV distribution line induced by triggered lightning 40 m away from the line was reported in [14], and the induced voltage was bipolar corresponding to current with negative polarity.

Since it is more difficult to conduct direct triggered lightning than nearby triggered lightning, the study of overvoltage caused by direct lightning is still on the way. In the United States, Fernandez et al. [15] measured the voltage and current response characteristics of MOV arrester at the strike point when a 730 m long distribution line was struck by triggered lightning. The authors observed that in the second flash, the arrester was subjected to about 60% of its maximum energy capacity during the first 4 ms of this event. Mata et al. [16] studied the response of two conductor distribution line subjected to direct triggered lightning on the phase conductor by experiment and simulation. It was revealed that when considering magnetic coupling to the line, the initial spike in the voltage across arresters could be reproduced. The division of the current on the distribution line when the lightning directly struck at an 829 m long distribution line was reported in [17].

Direct lighting experiments on distribution lines are scarce, and it is the great challenge now for the protection against direct flashes. Three phase overvoltage waveforms on the distribution line corresponding to lightning current when line is directly struck are still unknown. This paper presents the waveforms of the overvoltage on three phases at the lightning point when triggered lightning directly struck at the pole in the middle of a 1.5 km, 10 kV power distribution line, which was built according to typical design of Chinese southern power grid. The experiment can find and compare the range of lightning current the line insulation can withstand and the corresponding voltage waveform response to lightning current under the configuration. The voltage waveforms can also provide reference for modelling.

2 | EXPERIMENT AND DATA

A 10 kV distribution line supported by 22 poles was built in Conghua City, Guangdong Province in 2018. Figure 1 shows the detailed layout of the power distribution line. The total length of the line is 1.5 km, and the average spacing between adjacent poles is about 70 m. The distribution line shows an overall "L" shape due to geographical limitation. Three phases are arranged vertically with phase C located at the bottom. Phase C conductor is 10 m above the ground, and the spacing between adjacent phases is 0.9 m. The distance from pole 1 to pole 17 is about 1100 m, and that from pole 18 to pole 22 is about 400 m. The test line is unenergized, and two transformers are installed at pole 1 and pole 22. The schematic diagram is shown in Figure 1.

In July 2018, an overhead ground wire was installed 1 m above phase A, and the arresters were installed at every other pole, represented by the black circle in Figure 1. The poles are reinforced concrete poles with circular section. The type of three-phase conductor is JL/G1A-240/30, and the type of overhead ground wire is GJ-35. The cross arm adopts HD-75/09-230 angle steel cross arm. The shielding wire was grounded at each pole through the down conductor wire to grounding electrode in the soil. The cross arm, the shielding wire as well as the grounding end of voltage dividers are connected to the down conductor wire at the corresponding height of the pole. The surge arresters without gap were installed at the ends of the line to prevent lightning overvoltage from invading the distribution transformers, whose 1 mA DC operating voltage is 25 kV and the residual voltage is less than 50 kV at 5 kA. Other poles in Figure 1 were installed with arresters with gap to protect the line insulator, whose lightning impulse discharge voltage for the gap is 95 kV and the residual voltage is also less than 50 kV at 5 kA. The test line is mainly equipped with porcelain-arm insulator. The 50% impulse flashover voltage of the insulator measured is 240 kV for positive polarity, and −296.4 kV for negative polarity. Lightning current was injected into phase C between pole 14 and pole 15 by rocket triggered lightning, and it was measured on the connection line from rocket to the lightning injection point by coaxial shunt and Rogowski coil. Overvoltage observation station named as Station 8 (abbreviated as S8 in the following part) was installed at pole 15 to measure the three-phase overvoltage between phase conductors and the grounding. It is shown in Figure 1 as the red circle. The grounding resistance for S8 (pole 15) is 6.3 Ω, and the grounding resistivity value at this site is 26.3 Ω m.

For the measurement system of voltage, the high voltage is converted into low voltage by the voltage divider, and then the

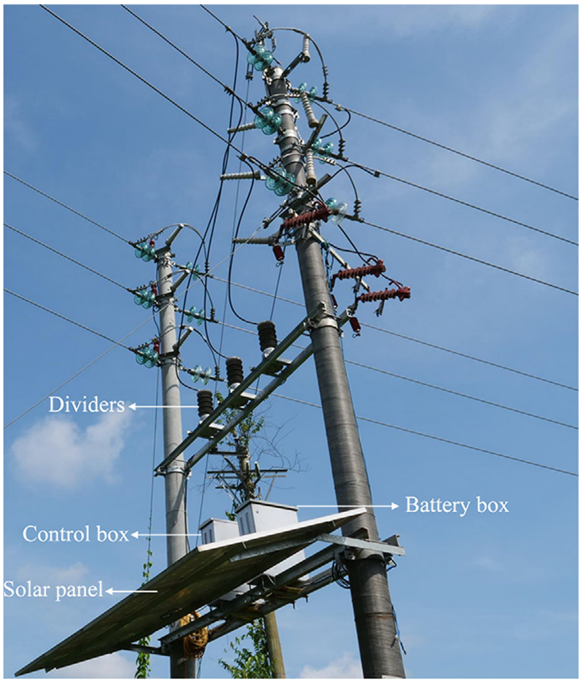

FIGURE 2 Measurement system of overvoltage

capture card transmits the voltage signal to industrial personal computer. Finally, the signal is transmitted to the remote main server through optical fibre simultaneously. Its sampling rate is 10 MS/s and the record length for each triggered voltage signal is 1 s. Figure 2 is the voltage measuring system and the details about the voltage measuring system can be found in [14].

On 26 July, 2018, a lightning event named as F1807261411 was observed at 02:11:24 PM, which was local time, Chinese Standard Time. It included 13 return strokes.

3 | RESULTS

3.1 | Return stroke current and overvoltage waveform

Figure 3 shows the lightning current and three-phase overvoltage waveforms at S8. The amplified waveform of lightning current and three-phase overvoltage corresponding to the first return stroke of this flash is shown in Figure 4. When the lightning current is injected into phase C, overvoltage appears not only in the direct struck phase but also in the other two phases. The time interval between adjacent overvoltage is the same with that of the corresponding adjacent return stroke current. The overvoltage is only related to the corresponding peak is about 55 kV. In terms of direct struck phase, the is return stroke current.

The return stroke current is negative polarity, and its waveform is double exponential as shown in Figure 4. The peak value of it is between 3.3 kA and 32.9 kA. The 10–90% rise time ranges from 0.3 to 0.7 μs, and the half peak width is between 1.0 and 24.7 μs. The time interval of adjacent return stroke has a wide range, with the minimum and maximum values being 2.4 and 213.5 ms.

The overvoltage of phase A and phase B are both bipolar and their amplitudes are similar. The negative peak value of indirect struck phase is lower than 40 kV, and the largest positive peak is about 55 kV. In terms of direct struck phase, the negative peak value of phase C ranges from −70 kV to −160 kV, which is much larger than the positive peak value.

Comparing the overvoltage of the same phase in thirteen return strokes, it is obvious that the amplitude of overvoltage is related to that of return stroke current. The greater the peak value of lightning current is, the greater the amplitude of overvoltage is.

3.2 | Overvoltage waveform of direct struck phase

Figure 4 shows the amplified waveform of lightning current and three-phase overvoltage corresponding to RS1, where phase C is the direct struck phase. The waveforms in Figure 5 are arranged according to the order of the peak of the lightning return stroke current. Due to the limitation of space, the waveforms in Figure 5 are divided into two columns. The subgraph on the left corresponds to the current from 3.3 to 14.8 kA with 90 kV spacing between adjacent waveforms, and the subgraph on the right corresponds to current from 21.4 to 32.9 kA with the waveforms staggered 160 kV.

The overvoltage waveforms of phase C are similar, containing the following stages: initial negative pulse, operation area of metal oxide varistor, and the positive tail oscillation and attenuation. The waveform of arrester discharge voltage due to nearby direct strike to the line observed by Barker et al. [18] is quite similar to that in this paper, except for the initial bipolar precursors in their waveform. They thought maybe it was due to measuring problems or a real characteristic of the waveform. We inclined to the first view because in [16] and [15], their waveform also showed no bipolar precursor, same with that in Figure 5 in this paper.

To analyse its characteristics, after the negative peak, the waveform of each return stroke is overlapped with the negative peak as the baseline, as shown in Figure 6. The overvoltage of direct struck phase corresponding to most return strokes has an initial spike before the negative peak, and the time between these two stages is about 1 μs. After that, it rises to about −20 kV in 1 μs. Then, the voltage drops again in 0.5 μs followed by the long operation area of metal oxide varistor at −40 kV.

The waveform parameters of overvoltage of direct struck phase are defined in Figure 7, including the negative peak V1, the rise time of the negative peak T1, the residual voltage V2 and zero-crossing time T2. Table 1 presents these parameters, arranged according to the peak value of the current.

For the voltage of direct struck phase, the negative peak value ranged from −78.1 to −166.9 kV, with its average value being −126.8 kV. The negative rise time is shorter than 5 μs, from 1 to 4.9 μs. However, the value reported by Fernandez [15] was only 0.4 μs corresponding to a lightning current being −12 kA.

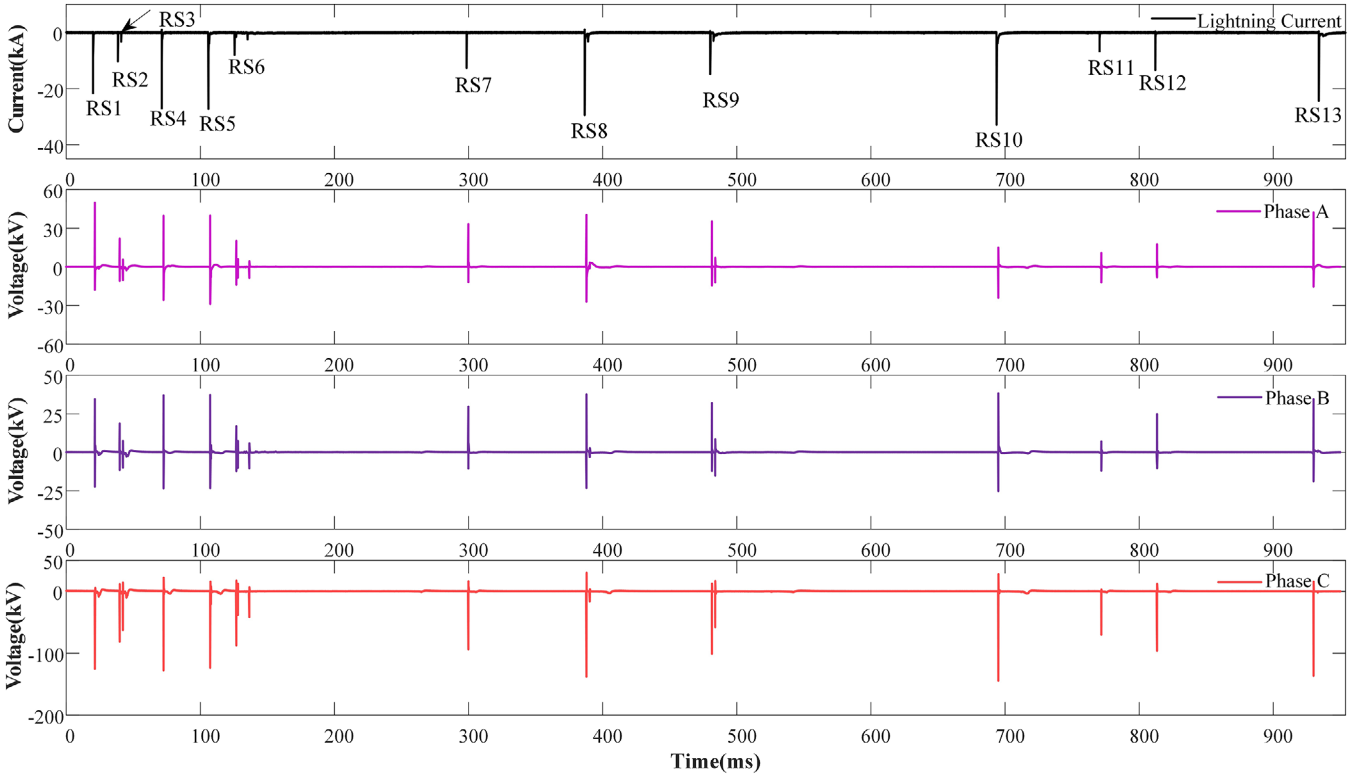

FIGURE 3 Lightning current and three-phase overvoltage waveforms at S8 of event F1807261411

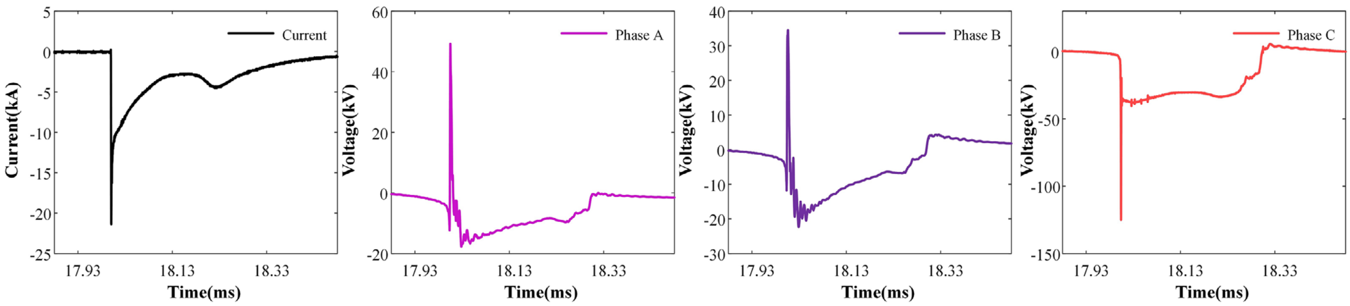

FIGURE 4 Amplified waveform of lightning current and three-phase overvoltage corresponding to RS1

The residual voltage is around −35 kV, with an average value of −35.1 kV. For zero-crossing time, when the return stroke current is from 3.3 to 14.8 kA, it is between 25.3 and 54.3 μs, and when the current is from 21.4 to 32.9 kA, it is between 75.3 and 298.1 μs. In Mata' s record [16], the plateau lasted 29 μs corresponding to a lightning current being −13 kA approximately, much shorter than that we have measured.

3.3 | Overvoltage waveform of indirect struck phase

The overvoltage waveforms of phase A and phase B are shown in Figure 8 with their positive peak overlapped. They correspond to return stroke current from 3.3 to 32.9 kA, with 50 kV spacing between adjacent waveforms in the left sub-graph and 60 kV spacing in the right sub-graph.

On the whole, the waveforms of indirect struck phases show two characteristics. For the same return stroke, the waveforms of phase A and phase B are similar, but totally different from that of phase C, which is the direct struck phase. For different return strokes, the waveforms of indirect phase are similar. The voltage drops slowly from zero to form a small negative peak, followed by a rapid polarity reversal to a large positive peak. Then the voltage drops again slowly, crossing zero and attenuating back to zero with oscillations. The largest negative peak formed during the oscillation process could be larger than the initial negative peak in some cases.

In Eriksson's observation [19], about 2–3% of the total voltages showed the characteristics of early negative impulse and

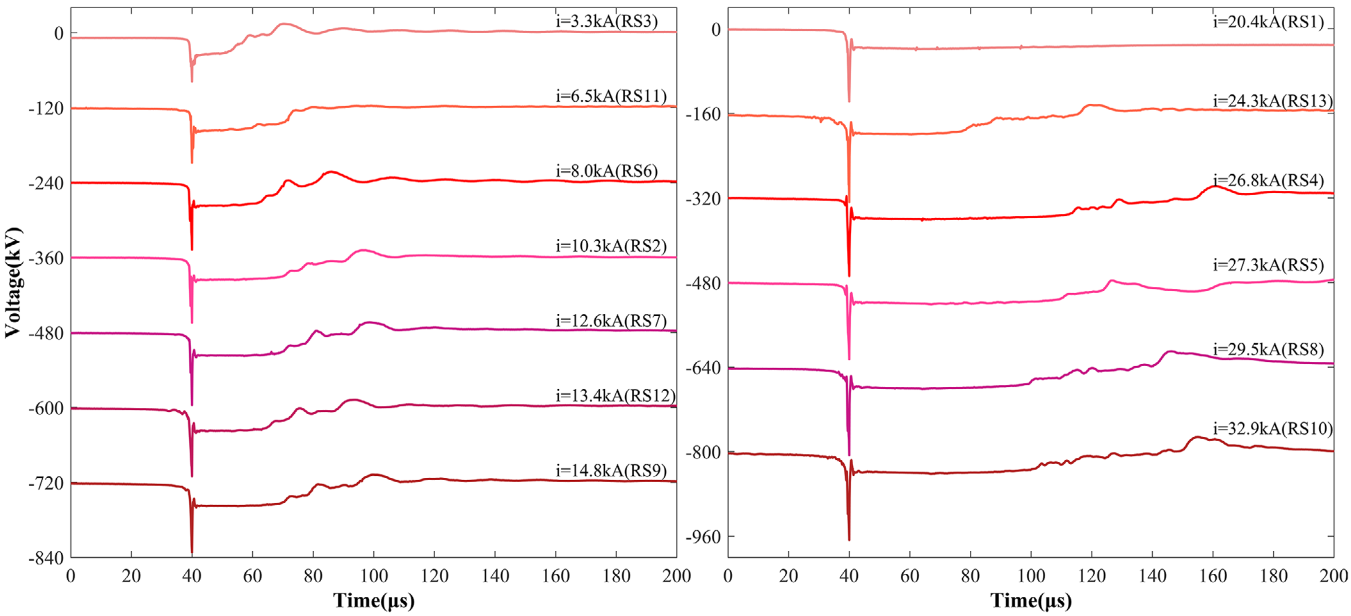

FIGURE 5 Overvoltage waveform of phase C corresponding to event F1807261411

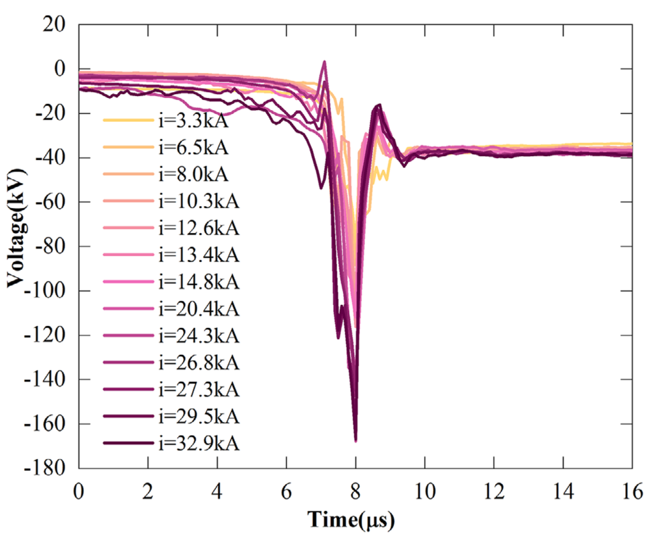

FIGURE 6 Amplified overvoltage wavefront waveform of phase C

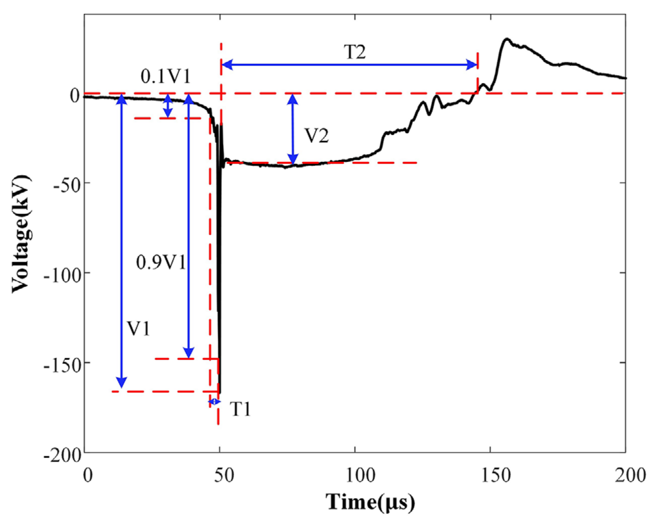

FIGURE 7 Overvoltage waveform parameters definition of direct struck phase

later positive-going transition, classified as nearby induced type. Some of these cases corresponded to ground flashes within 200 m of the line in their record. The waveform of indirect struck phase is also similar to that shown by Rachidi et al. [20]. Their calculation results show that the formation of the initial negative peak is associated with the leader, and the transition from the initial negative peak to the positive peak is related to return stroke. However, the voltage in [20] decays from positive peak to zero with the tail being positive polarity in the whole process, different from ours. The reason might be the overvoltage of indirect struck phase here is not only affected by the leader and return stroke, but also affected by the overvoltage of direct struck phase. In [21], they describe that the initial spike voltage of non-lightning-striking phases is generated by the return stroke current in the lightning channel and they have opposite polarity. The spike was also observed in [22]. Among 13 overvoltage waveforms, the waveforms are similar for phase A and phase B in Figure 8, but there is difference only in the wave tail for RS12 (13.4 kA) and in the magnitude and the wave tail for RS10 (32.9 kA), which may be related with the action time difference of gapped arresters in these two RSs. Effects of gap action time on the response characteristics of overvoltage deserves attention in further simulation [23].

To better analyse the effect of direct struck phase on the wave tail of indirect struck phase, the waveforms of three phases are overlapped with the negative peak being the baseline, as shown in Figure 9. The attenuation process after the positive peak for

TABLE 1 Voltage parameters of direct struck phase

Return stroke number	Peak value of return stroke current (kA)	Negative peak value of overvoltage (kV)	Negative rise time of overvoltage (μs)	The residual voltage value (kV)	Zero-crossing time (μs)
F1807261411-RS3	3.3	−78.1	1.1	−34.8	25.3
F1807261411-RS11	6.5	−88.4	1.0	−36.8	38.4
F1807261411-RS6	8.0	−107.3	1.1	−36.5	39.9
F1807261411-RS2	10.3	−104.2	1.0	−33.4	51.3
F1807261411-RS7	12.6	−116.1	1.4	−36.1	52.6
F1807261411-RS12	13.4	−110.0	1.7	−36.1	48.0
F1807261411-RS9	14.8	−111.9	2.2	−35.1	54.3
F1807261411-RS1	20.4	−137.8	1.1	−31.9	298.1
F1807261411-RS13	24.3	−167.8	4.9	−35.6	75.3
F1807261411-RS4	26.8	−147.5	1.0	−33.8	113.6
F1807261411-RS5	27.3	−145.1	1.5	−34.3	85.0
F1807261411-RS8	29.5	−166.7	2.2	−36.1	93.8
F1807261411-S10	32.9	−166.9	3.2	−36.3	102.5

indirect struck phase includes two processes. Firstly, the voltage decays rapidly and oscillates in negative polarity corresponding to the period of residual voltage for direct struck phase. After that, the voltage returns to zero slowly with oscillation in positive polarity corresponding to positive wave tail oscillation for direct struck phase. This could explain the negative wave tail of indirect struck phase.

The waveform parameters of indirect struck phase overvoltage are defined in Figure 10, including V1, T1, T2, as defined in phase C, positive peak value V3, peak-to-peak value V4 and time interval from negative peak to positive peak T3. The results are shown in Table 2.

In terms of indirect struck phases, the negative peak value of phase A is from −4.6 to −24.1 kV. This is close to that of phase B, with the maximum difference only being 1.6 kV. The negative peak rise time of indirect phase is about six times that of phase C, with the average values for phase A and phase B being 35.2 and 28.0 μs. The positive peak value of phase A and phase B are from 1.9 to 49.8 kV and from 0.2 to 38.3 kV respectively. As for peak-to-peak value, for phase A, it is between 7.6 and 64.1 kV while for phase B, it is from 7.0 to 63.5 kV. The order of positive peak value and peak-to-peak value of indirect struck phases in most return strokes is phase A > phase B. The positive and negative peaks of induced voltage recorded by Wang

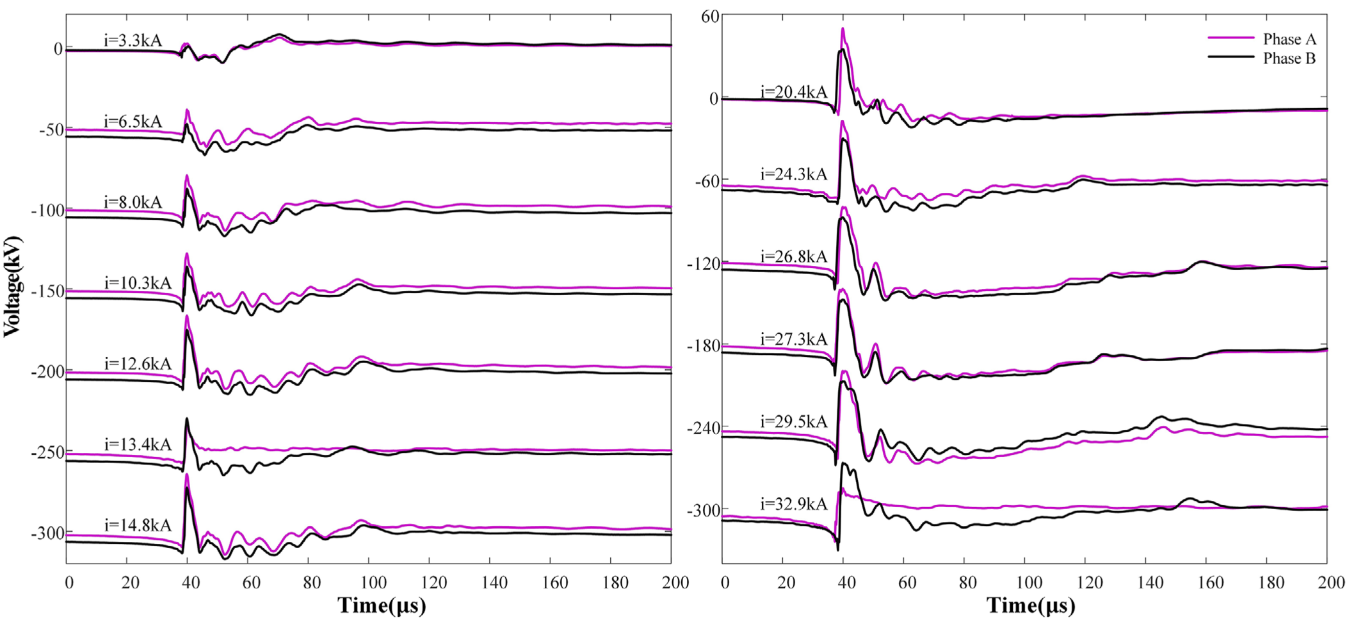

FIGURE 8 Overvoltage waveform of phase A and phase B at lightning strike point

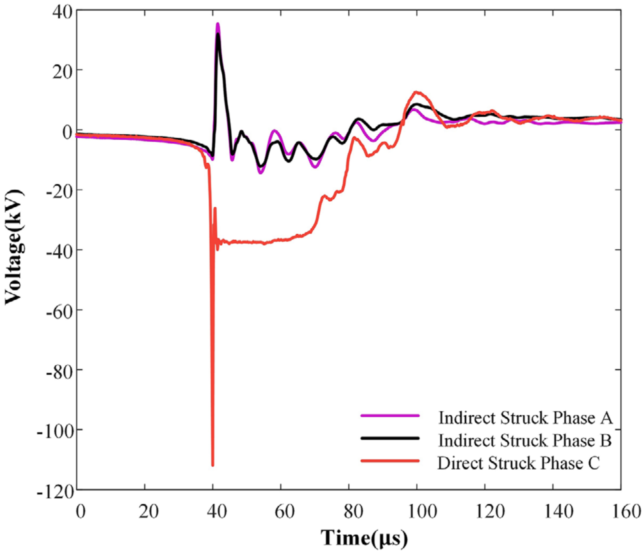

FIGURE 9 Overlapping voltage waveforms of indirect struck phase and direct struck phase at lightning strike point

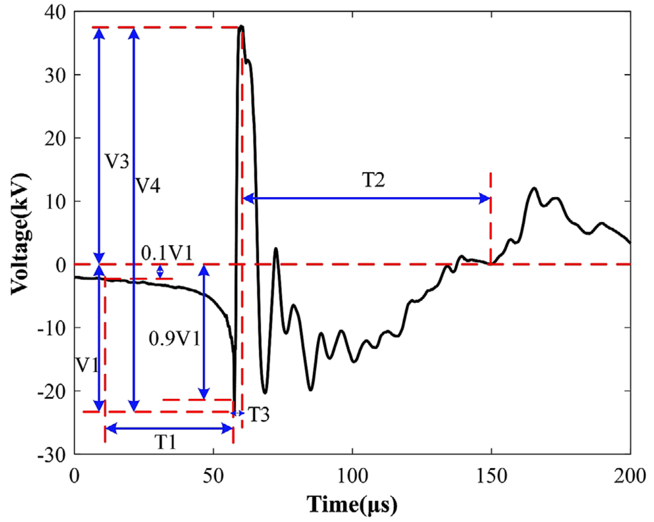

FIGURE 10 Overvoltage waveform parameters definitions of indirect struck phase

[14] were similar. Maybe it is because their lighting strike point is farther from the line, about 40 m, and their observation station is at the end of the line. The negative to positive peak time interval is around 2 μs for both phases. However, zero-crossing time has a wide range. For phase A, it is from 21.9 to 313.4 μs, and this value for phase B is between 16.6 and 293.3 μs. Besides, this parameter for phase A is larger than that of phase B in most return strokes because the wave tail amplitude of phase B in most return strokes is larger than that of phase A as shown in Figure 8. Since the conductor of phase B is closer to the strike point, it is more affected by the electromagnetic coupling effect of the direct struck phase.

3.4 | The relation between overvoltage parameters and return stroke current parameters

Figures 11, 12 and 13 show the relation between the parameters of overvoltage and those of lightning return stroke current. The negative peak value and the peak-to-peak value of voltage and the negative peak value of current are replaced by their absolute

TABLE 2 Voltage parameters of indirect struck phase

Return stroke number	Peak value of return stroke current (kA)	Negative peak value of overvoltage (kV)		Negative rise time of overvoltage (μs)		Positive peak value of overvoltage (kV)		Peak-to-peak value of overvoltage (kV)		Negative to positive peak time interval (μs)		Zero-crossing time (μs)	
		A	B	A	B	A	B	A	B	A	B	A	B
F1807261411-RS3	3.3	−5.7	−6.8	15.1	5.3	1.9	0.2	7.6	7.0	2.7	2.1	21.9	16.6
F1807261411-RS11	6.5	−4.6	−4.1	49.8	41.4	10.9	7.1	15.5	11.2	1.1	1.5	33.3	32.1
F1807261411-RS6	8.0	−7.5	−6.7	25.3	20.0	20.2	16.9	27.7	23.6	0.7	1.6	31.4	30.4
F1807261411-RS2	10.3	−8.6	−8.8	19.3	13.7	22.0	18.7	30.6	27.5	1.5	1.4	50.2	38.9
F1807261411-RS7	12.6	−7.8	−7.4	29.9	19.9	33.3	29.7	41.1	37.1	1.5	1.4	48.0	38.5
F1807261411-RS12	13.4	−8.2	−8.2	42.3	34.8	17.5	24.8	25.7	33.0	1.0	1.5	60.2	32.6
F1807261411-RS9	14.8	−9.8	−8.6	35.3	29.9	35.4	32.0	45.2	40.6	1.6	1.6	49.3	45.7
F1807261411-RS1	20.4	−13.4	−11.8	40.8	36.7	49.8	34.6	63.2	46.4	1.7	2.9	313.4	293.3
F1807261411-RS13	24.3	−14.7	−13.2	53.9	52.2	42.2	34.5	56.9	47.7	1.7	1.9	76.7	75.4
F1807261411-RS4	26.8	−16.0	−15.3	32.1	27.0	39.7	37.0	55.7	52.3	1.8	2.7	118.4	114.5
F1807261411-RS5	27.3	−18.7	−18.0	26.5	28.3	39.9	37.3	58.6	55.3	2.6	2.6	172.1	125.5
F1807261411-RS8	29.5	−23.7	−23.2	35.5	23.8	40.4	37.7	64.1	60.9	1.7	2.4	106.0	77.7
F1807261411-RS10	32.9	−24.1	−25.2	51.7	30.9	14.9	38.3	39.0	63.5	2.6	1.6	147.0	73.9

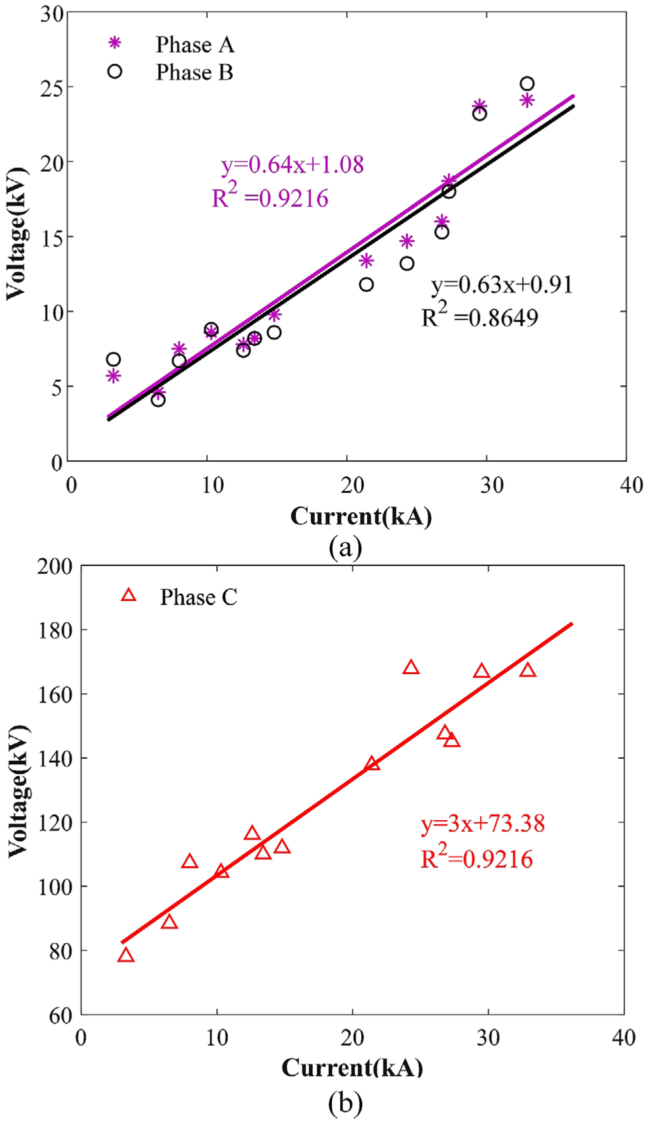

FIGURE 11 Relation between negative peak value of voltage and peak value of lightning return stroke current. (a) Relation between negative peak value of voltage of indirect struck phases and current. (b) Relation between negative peak value of voltage of direct struck phases and current

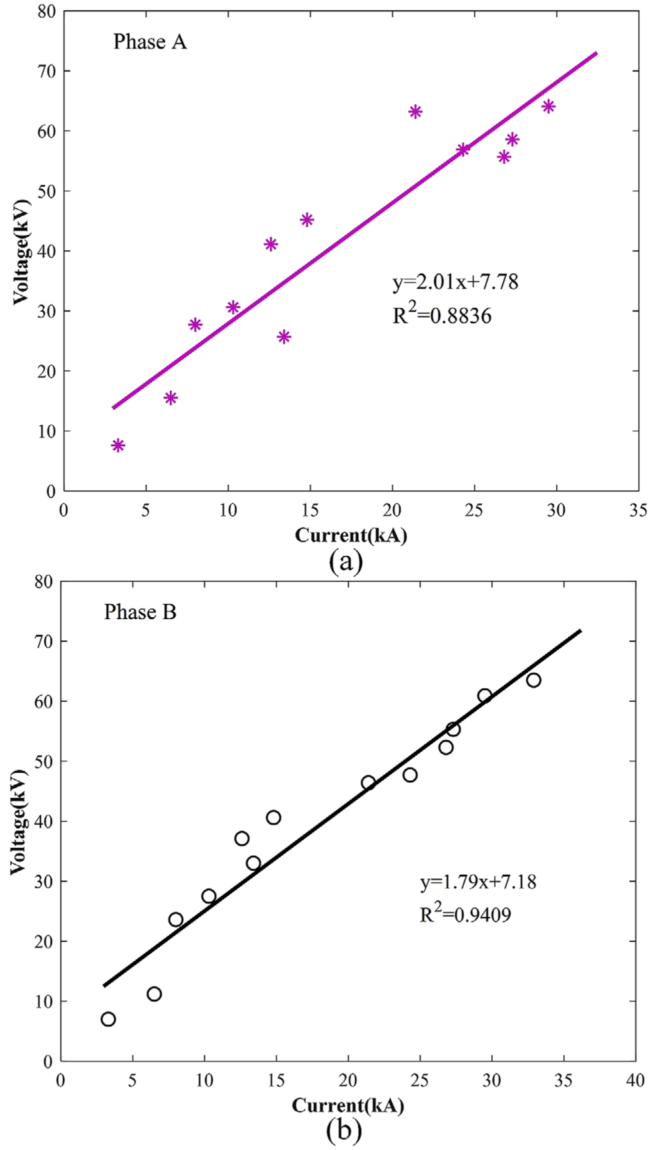

FIGURE 12 Relation between peak-to-peak value of indirect struck phase overvoltage and peak value of lightning return stroke current. (a) Relation between peak-to-peak value of overvoltage of phase A and current. (b) Relation between peak-to-peak value of overvoltage of phase B and current

value for convenience. There is a good linear relation between the negative peak value of voltage and the peak value of current, with the correlation coefficient being 0.92, 0.86 and 0.92 for phase A, B, and C respectively. This regulation was also reported by Barker et al. [23]. For zero-crossing time, it also has a linear relation with the peak value of current, especially for phase C, the correlation coefficient being 0.90. Considering the overlapping waveforms of three phases in Figure 9, the same rule can be found in indirect struck phase, and the correlation coefficient for phase A and B are 0.82 and 0.72. The linear relation between the peak-to-peak value of indirect struck phase and the peak value of return stroke current is obvious, with the correlation coefficient being 0.88 and 0.94 for phase A and phase B respectively. However, there is no linear relation between the rise time of the negative peak value of voltage, the positive to negative peak interval time and the rise time of return stroke current.

4 | SUMMARY AND CONCLUSION

The observation of overvoltage caused by direct lightning on distribution line is scarce. In this paper, we enrich this field by implementing triggered lightning experiment in the middle of a 1.5 km, 10 kV distribution line. The lightning directly struck the phase conductor and the three-phase overvoltage characteristics were clearly revealed at the closest pole to the lightning strike point. The arrester installed between direct struck phase and the ground down lead operated in every return stroke. There was no flashover occurred at this pole in all return strokes, meaning that

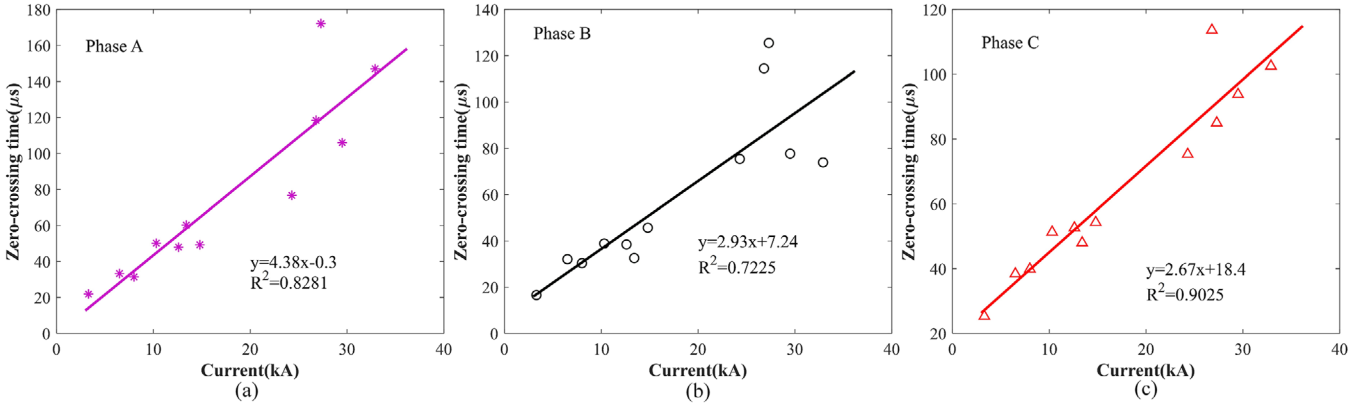

FIGURE 13 Relation between zero-crossing time of voltage and peak value of lightning return stroke current. (a) Relation between zero-crossing time of voltage of phase A and that of lightning return stroke current. (b) Relation between zero-crossing time of voltage of phase B and that of lightning return stroke current. (c) Relation between zero-crossing time of voltage of phase C and that of lightning return stroke current

this pole was well protected by the arrester during the flash, with the current from 3.3 to 32.9 kA. The results are summarized as follows:

The overvoltage waveforms of the direct struck phase of all return strokes are similar. The waveform characteristics were revealed, including voltage dropping from zero to negative peak, operation area of metal oxide varistor, and the wave tail with positive attenuation and oscillation. The overvoltage waveforms of indirect struck phase of all return strokes are also similar, but different from those of direct struck phase. The features include a micro initial negative peak, a rapid and large positive transition, and the final negative oscillation process.

The three-phase overvoltage waveform parameters are statistically analysed. The negative peak value of the indirect struck phase is between −4.1 and −25.2 kV, and that of direct struck phase is between −78.1 and −166.9 kV with return stroke current ranging from 3.3 to 32.9 kA. This value for direct struck phase is much larger than that for indirect struck phase. The order of negative peak rise time of three-phase overvoltage is phase A > phase B > phase C, and the order of positive peak value and peak-to-peak value of indirect struck phases in most return strokes is phase A > phase B. The negative peak of three-phase overvoltage, zero-crossing time of three-phase voltage and the peak-to-peak value of voltage of indirect struck phase all show a linear relation with the peak value of lightning return stroke current.

To be noted, the phase conductor would be directly struck by natural lightning only due to shielding-failure, which is rare event for distribution line with overhead shielding wire. The waveforms of the voltage caused by direct strokes deserve more investigations, thus revealing deeper mechanism.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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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