Observation of Overvoltage at the Terminal of 10 kV Distribution Line by Direct Triggered Lightning

Jianguo Wang, Yating Zhao, Yuquan Fang, Li Cai, Shoupeng Wang, Zhiling Xu, and Si Cheng

***Abstract*—This paper reports the waveform characteristics and parameters of the overvoltage at the terminal of a 1.5 km 10 kV distribution line by direct triggered lightning. The three-phase overvoltage exhibited three kinds of waveforms, all including the initial rising process of the negative peak, the transition from negative peak to the positive peak or the residual voltage, and the subsequent oscillation process. It is observed that the negative peak value of the three-phase overvoltage is between −8.2 kV and −96.1 kV and the rise time of negative peak is between 3.2 μs and 31.7 μs, while the corresponding peak value of the return stroke current is between 3.3 kA and 32.9 kA. When the return stroke current is relatively small, the negative peak value of the direct struck phase overvoltage is twice or more than that of the indirect struck phase. When it is larger, the negative peak value of the indirect struck phase overvoltage is much closer to that of direct struck phase. There is good linear relation between the negative peak value of the indirect struck phase overvoltage and the peak value of the lightning return stroke current, with correlation coefficient being 0.98 and 0.90.**

***Index Terms*—10 kV distribution lines, triggered lightning, lightning current, overvoltage.**

I. Introduction

LIGHTNING overvoltage is one of the main causes of power distribution line failure and electrical equipment damage. Distribution lines generally have a lower voltage insulation level compared to high voltage transmission line. When the distribution line is struck by direct struck lightning, accidents such as flashover of line insulator and lightning-caused breaking of the conductor are likely to occur. In Japan, more than 50% of power system failures are caused by lightning [1]. In areas where the trip-out rate is relatively high in China, the total number of trips of high voltage line caused by lightning accounts for about 40% to 70% [2]. At present, researches about lightning overvoltage on distribution lines mainly focus on the lightning induced voltage. Experimental studies about direct lightning overvoltage are few, and the study on the effect of lightning protection measures for distribution lines is still needed.

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Researches on the induced overvoltage on distribution line caused by natural lightning have been made in Japan, the United States, China, etc. In Japan, Yokoyama *et al.* [3]–[5] measured the induced voltage on an 820 m long distribution line supported by 17 poles when lightning struck a high stack 200 m away from the line. The correspondence between the polarity of lightning current and that of the induced voltage was reported. In the United States, Master *et al.* [6] reported that the electromagnetic field and lightning strike position were related to the polarity of the induced voltage. Georgiadis *et al.* [7] measured the electromagnetic field generated by a ground flash 5 km away and the induced voltage at both ends of 448 m long distribution line. In China, Zhou *et al.* [8] and Cai *et al.* [9] observed the induced voltage on a 220 V distribution line caused by nearby natural lightning strikes, where the SPD can significantly limit the induced voltage to its protection level.

Rocket triggered lightning technique can be used for artificial lightning, thus playing an important role in the study of lightning physics [10]. Wang *et al.* [11] studied the electric field waveforms at a distance of 68 km to 126 km by rocket-triggered lightning. De Carlo *et al.* [12] examined the division of the injected lightning current between the grounding system when triggered lightning current was injected into a structural lightning protection system. Wang *et al.* [13] measured the induced voltage on a 280 m long, 10 kV distribution line with 5 poles and the lightning current 40 m away from the line by rocket-triggered lightning. Rubinstein *et al.* [14] observed two types of induced voltage waveforms at both ends of a 448 m long distribution line caused by triggered lightning 20 m away, which are oscillation type and pulse type. Schoene *et al.* [15], [16] and Mata *et al.* [17] studied the division of current among the arresters and groundings of two 800 m long distribution lines when triggered lightning directly struck phase conductor. Wang *et al.*[18] reported the induced overvoltage generated by lightning 40 m away from the line at the end of a 10 kV, 1.5 km long distribution line, finding that the peak value of return stroke current has a good linear relation with the negative peak of induced voltage. In Florida, Paolone *et al.* [19] measured the current at the ends of a buried coaxial cable induced by triggered and natural lightning. Huang *et al.* [20] reported that the voltage on the signal line induced by triggered lightning had the characteristic of V shape, and was linearly correlated with the gradient of the triggered lightning.

In addition to experimental research, the calculation of induced voltage and direct lightning overvoltage on the distribution lines is also studied [21]–[26]. Recently, Ishimoto *et al.* [27] proved that the flashover rate is remarkable when taking

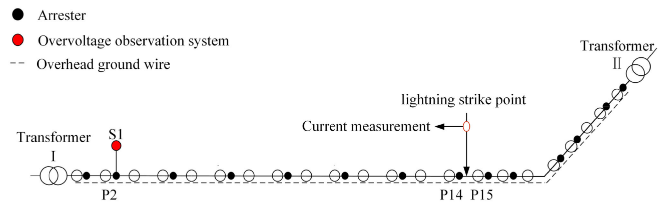

Fig. 1. Distribution line with a vertical configuration, measurement point S1 and the location of lightning current injection between pole 14 and pole 15.

lightning electromagnetic pulse effect into consideration in the calculation of the overvoltage caused by direct lightning.

This paper carried out the overvoltage observation at the terminal of a 1.5 km, 10 kV distribution line, when the rocket-triggered lightning directly struck the phase conductor. The overvoltage waveform characteristics and parameters are analyzed. The contribution of this paper are listed as follows:

1) The experiments about direct triggered lightning are scarce. This paper provides the insight into the observation of overvoltage at the terminal of a 10 kV distribution line by direct triggered lightning. As we know, it is the first direct struck triggered lightning to over 1 km length distribution line with three phase industrial arrangement. The distribution line was constructed according to the typical design of 10 kV distribution lines in Southern China.
2) This paper analyzes the voltage waveforms not only on the direct struck phase but also the indirect struck phase on the distribution line. The results were compared, which is helpful to reveal the behavior of voltage response to direct lightning.
3) Three kinds of waveforms of overvoltage were concluded to embody on three phases simultaneously, and present the coupling between them. Details of overvoltage waveforms could be found for electromagnetic simulation comparison, thus providing reference for calculation and simulation.

II. Method and Data

A 10 kV unenergized distribution line with overhead ground wire was established in a hilly area in Conghua, Guangzhou City, Guangdong Province, China, as shown in Fig. 1. It was constructed according to the typical design of 10 kV distribution lines in Southern China. The line is 1.5 km and supported by 22 reinforced concrete poles with circular section, and the average span between adjacent poles is about 70 m. Due to topographic constraint, the distribution line shows an "L" shape. 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 three-phase wires are arranged vertically. Phase A is located at the top of the line which is 11.8 m above the ground, and the spacing between phase conductors is 0.9 m. Cross arms of insulators are all stiffening angle iron. The overhead ground wire is located 1 m directly over the upper phase A, and it is grounded at each pole through the LGJ-185mm^2 down conductor to two vertical grounding electrodes with 3 m length in the soil. The grounding resistance is around 3.1Ω to 22.0Ω and its value at each pole is shown in Table I. The soil resistance ranges from 180$\Omega \cdot$ m to 200$\Omega \cdot$ m. The transformers with 10 kV/200 kVA capacity are installed at both ends of the distribution line.

TABLE I
Grounding Resistance at Each Pole

pole	1	2	3	4	5	6	7	8
Rg(Ω)	10.3	12.5	10.5	5.5	8.6	4.8	4.9	5.1
pole	9	10	11	12	13	14	15	16
Rg(Ω)	12.5	16.2	22.0	10.2	\	8.0	6.3	9.2
pole	17	18	19	20	21	22		
Rg(Ω)	21.0	21.7	19.0	21.9	20.5	3.1		

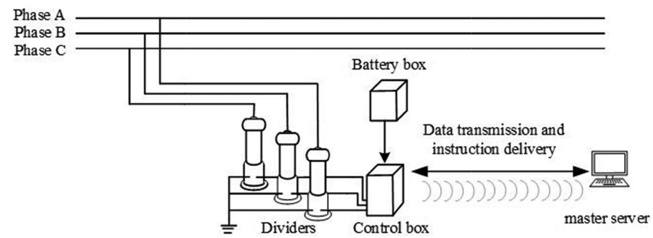

Fig. 2. Layout of overvoltage observation system.

Arresters are installed between the phase conductor and grounding down conductor of pole 1, 2, 4, 6, 8, 10, 12, 14, 15, 16, 18, 19, 21, and 22. Arresters without gaps are installed at pole 1 and pole 22, while arresters with gaps are installed at other poles. The type of gapped arresters is YH5CJ5-17/50D, whose lightning impulse residual voltage is less than 50 kV and the lightning impulse discharge voltage is 95 kV. The line is mainly equipped with porcelain-arm insulator S-210, whose 50% impulse flashover voltage measured in the test is 240 kV of positive polarity and 296.4 kV of negative polarity. Rocket triggered lightning technology was used to inject lightning current into the conductor of phase C between pole 14 and pole 15 in the experiment. An overvoltage observation station was installed on pole 2, 70 m away from the end of the line to collect the data of three-phase overvoltage, as indicated by the red circle in Fig. 1. Fig. 2 shows the layout of overvoltage observation system. The lightning current injected into the line conductor is measured by coaxial shunt. In [18], there are photos of the overvoltage observation system and the line configuration. The overvoltage on the distribution line concerns a lightning event named as F1807261411.

III. Observation Results and Analysis

A. Return Stroke Current Parameters

The rocket triggered lightning event happened at 14:11:24 on July 26, 2018, containing thirteen return strokes, as shown in Fig. 3. The return stroke current rises sharply in the wave front and decays slowly in the wave tail. Based on the waveform of the return stroke current, the waveform parameters of current are defined, including peak value, 10%-90% rise time, half peak width, 10%-10% peak width and interval time of adjacent return strokes.

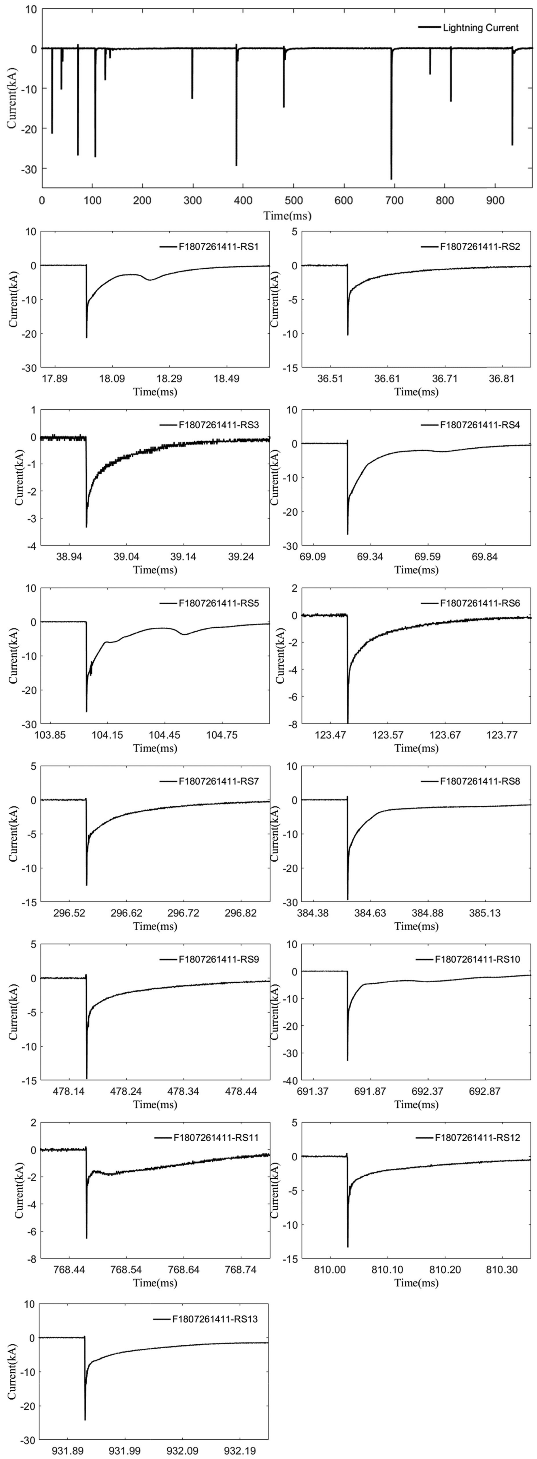

Fig. 3. Lightning current waveforms at injected point of the F1807261411.

Table II provides the parameters of return stroke current waveform of event F1807261411. The peak value of return stroke current has a wide range, with the maximum and minimum values being 32.9 kA and 3.3 kA, corresponding to RS10 and RS3. The charge drained by each return stroke in 1ms is between 0.2 C and 4.4 C, and its geometric mean value is 1.5 C. This parameter measured in [28] was from 0.2 C to 4.7 C with its

TABLE II
PARAMETERS OF RETURN STROKE CURRENT

Lightning event	Return stroke number	Charge in 1ms (C)	Peak value of return stroke current (kA)	10%-90% rise time of return stroke current (μs)	Half peak width of return stroke current (μs)	Duration of return stroke current (μs)	Interval time of adjacent return strokes (ms)
F1807261411	RS1	1.7	21.4	0.5	6.7	312.8	\
	RS2	0.4	10.3	0.5	1.1	101.0	18.5
	RS3	0.2	3.3	0.7	12.4	142.4	2.4
	RS4	2.5	26.8	0.5	24.5	207.0	30.3
	RS5	3.3	27.3	0.5	19.5	580.4	34.8
	RS6	0.4	8.0	0.6	4.1	112.6	19.5
	RS7	0.6	12.6	0.5	3.2	126.4	173.1
	RS8	2.8	29.5	0.5	6.9	180.2	88.0
	RS9	0.7	14.8	0.5	1.1	132.6	93.6
	RS10	4.4	32.9	0.5	5.6	902.2	213.5
	RS11	0.5	6.5	0.5	0.8	243.8	76.8
	RS12	0.7	13.4	0.3	1.0	151.8	41.6
	RS13	1.7	24.3	0.5	1.8	167.4	121.9
Arithmetic Mean		1.5	17.8	0.5	6.8	258.5	76.2
Geometric Mean		1.0	14.8	0.5	3.8	203.5	46.7

geometric mean value being 0.89C. The rise time of return stroke current is between 0.3 μs and 0.7 μs, and the half- peak width is between 0.8 μs and 24.5 μs. The time interval between adjacent return strokes is between 2.4ms and 213.5ms. The arithmetic and geometric mean of return stroke current peak value are 17.8 kA and 14.8 kA, larger than those of 144 return stroke current in direct strike experiment from 1999 to 2004 at International Center for Lightning Research and Testing in Florida (arithmetic mean: 13 kA, geometric mean: 12.0 kA) reported by Schoene [29]. The arithmetic and geometric mean of 10%-90% rise time of 63 return strokes provided in [29] is 1.4 μs and 1.2 μs, which is larger than that in this paper. The arithmetic and geometric mean of half peak width in Table I is 6.8 μs and 3.8 μs. Over 50% cases in [30] show that the rise time for the first stroke in natural lightning exceeds 5.5 μs. In [31], it was mentioned that the first return strokes in natural lightning is more intense than other return strokes. Data in Table II can prove that the return strokes caused by the rocket-triggered lightning are similar with subsequent return strokes in natural lightning.

B. Overvoltage Waveform of Three Phase

Data of three phase overvoltage corresponding to 12 return strokes except RS11 of the event F1807261411 is recorded in the overvoltage observation station installed at pole 2. The three-phase overvoltage waveforms and the corresponding return stroke current are shown in Fig. 4. When the current is injected into the conductor of phase C, the overvoltage not only occurs in phase C but also in phase A and B. The time interval of overvoltage caused by two adjacent return strokes is basically same to that between return stroke current. The overvoltage is associated with the corresponding return stroke current, and is independent of other return strokes in the event.

In terms of the voltage waveform, the three phase overvoltage all rises to negative peak from zero level rapidly. After the

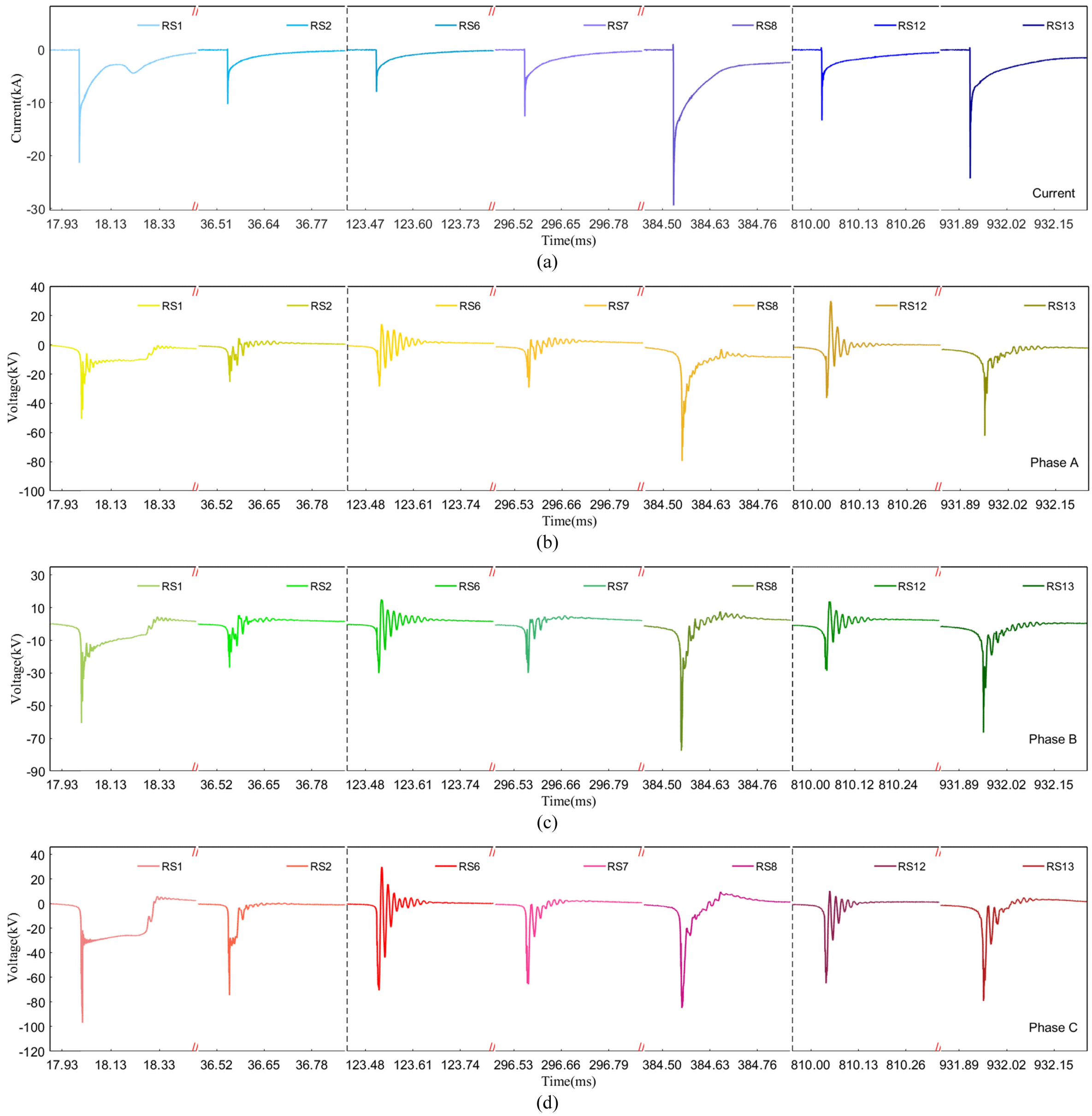

Fig. 4. Amplified waveform of lightning return stroke current and three-phase overvoltage corresponding to RS1, RS2, RS6, RS7, RS8, RS12, RS13. (a) Lightning current. (b) Voltage of phase A. (c) Voltage of phase B. (d) Voltage of phase C.

first attenuation from the negative peak, the voltage eventually returns to zero after a process of attenuation. The differences of overvoltage waveforms are the attenuation process after the first attenuation from the negative peak.

Comparing the overvoltage amplitudes of the same phase in different return strokes, the three-phase overvoltage amplitude corresponding to RS1, RS8, RS13 is relatively large compared with other return strokes. In relation to the return stroke current, the current amplitude of RS1, RS8, RS13 is relatively large compared with other return stroke current. The negative peak value of the overvoltage has a relation with the peak value of the lightning current.

The order of return strokes will be disrupted in the following analysis, and the overvoltage waveform will be studied in the order of current peak value from small to large, as shown in Fig. 5. The overvoltage waveforms can be divided into three types in Fig. 5. The first type is that the voltage increases rapidly to the negative peak in the front, and then a polarity conversion from negative peak to positive peak occurs followed by the attenuated oscillations for more than 100 microseconds. The oscillation time interval after the negative peak of each return stroke is almost the same. Only the amplitude of the oscillation is different. The corresponding return strokes are RS3, RS6, RS7, RS9, RS12 of the event F1807261411 and the current peak value is between 3.3 kA and 14.8 kA, which is relatively small compared to the whole. Arresters installed at pole 2 didn't operate in these return strokes since its gap discharge voltage is 95 kV. The attenuated oscillations of the first type of overvoltage are related to the reflection and refraction of traveling wave on the line.

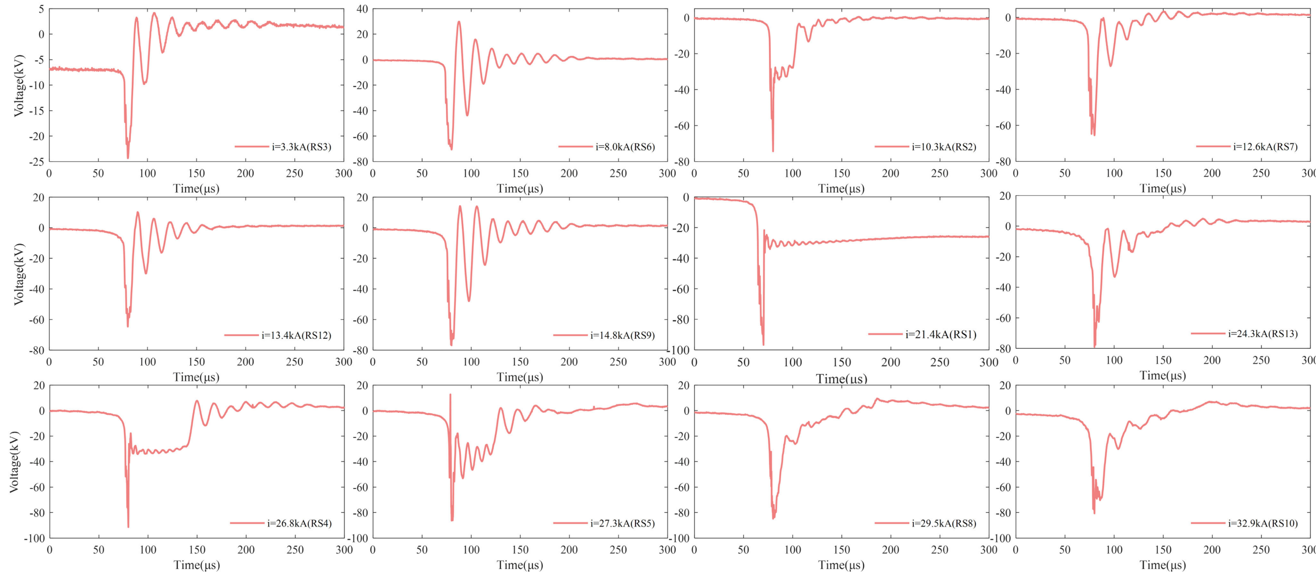

Fig. 5. Overvoltage waveforms of phase C in the order of the peak value of return stroke current from small to large.

The second type of voltage waveform has the characteristics including rising rapidly before the initial negative voltage pulse, operation of valve disc related to the nonlinear volt-ampere characteristic of the arrester, and sharply crossing zero and showing the positive oscillation. The return strokes corresponding with the second type of overvoltage are RS1, RS2, RS4 and RS5. The relatively large peak values of current are 26.8 kA and 27.3 kA, and relatively small peak current is only 10.3 kA. Arresters installed at pole 2 operated in these return strokes and residual voltage appears in the second type of overvoltage waveform.

The third type of voltage waveform has many short time interval oscillations after negative peak. Voltage rapidly attenuates to 0 to -20 kV after brief oscillations of few microseconds, followed by oscillations of low amplitude at intervals of 20 μs approximately. The corresponding return stroke is RS8, RS10, RS13 and the peak value of current is between 24.3 kA and 32.9 kA which is relatively large compared to the whole.

The overvoltage waveforms of the indirect struck phase can also be divided into three types as shown in Fig. 4. The first type of waveform has a rapid polarity conversion from negative peak to positive peak, and the attenuated oscillations following the positive peak which is similar with the first type of waveform of phase C. The second type of waveform corresponds to the four return strokes in which arresters of phase C at pole 2 operated. There is a slow attenuation period after the negative peak in these four return strokes, corresponding to the residual voltage waveform of the second type of direct struck phase. It is the coupling component of arrester residual voltage. The third type of voltage is similar with direct struck phase, but has more oscillations after negative peak. Although the peak value of return stroke current is relatively large, there isn't residual voltage in the third type of overvoltage which is related to the operation of arresters.

For the first type of overvoltage, it is the waveform of arrester without gap operation, with the current ranging from 3.3 kA to 14.8 kA. The oscillation at the end of the waveform is due to wave reflection. The average value for the oscillation period is 16 μs. Assuming that wave travels at the speed of light, and considering other effects such as corona etc., the actual distance is about 2880 m. The whole length of the line is about 1500 m, the distance of wave reflection is about 3000 m (1500 m$\times$2). This may prove that the oscillation at the end of the waveform is due to reflection.

For the second type of overvoltage, it is the waveform of arrester with operation because of the obvious residual voltage. The oscillation period at the end of it is also about 16 μs, caused by wave reflection.

The third type of the waveform almost has no oscillation in the end. By checking the condition of arresters after test, we found that the arrester at phase C at pole14 (the left hand of the strike point) is broken and the arresters at pole 2 are intact. Three types of overvoltage waveforms are related with the response of gapped arresters in different return strokes corresponding to different current injection.

C. Overvoltage Parameters of Three-Phase

Different parameters for three types of overvoltage waveforms are defined, as shown in Fig. 6. For the first type of overvoltage, parameters are defined including negative peak V1, rise time of negative peak T1, half peak width of overvoltage T2, oscillation period T3 and the duration of oscillation T4. For the second type of overvoltage, the parameters are defined including V1, T1, T2, the residual voltage value V2 and duration of residual voltage T5. For the third type of overvoltage, the parameters are defined including V1, T1, T2 and 10%-10% width of overvoltage T6. Table III, IV and V show the parameters of three types.

For the first type of overvoltage, its negative peak value of phase A is between -10.4 kV and -36.5 kV, and that of phase B is between -8.2 kV and -35.0 kV, and that of phase C is between -24.5 kV and -76.4 kV. The negative peak rise time of the direct struck phase C is between 3.2 μs and 8.2 μs, while

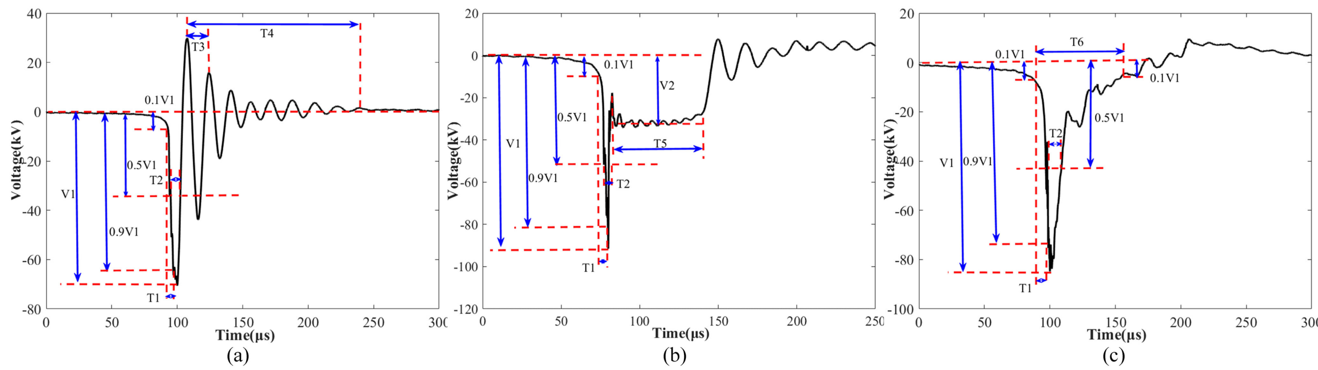

Fig. 6. Waveform parameters definitions of overvoltage. (a) The definition of the first type of overvoltage. (b) The definition of the second type of overvoltage. (c) The definition of the third type of overvoltage.

TABLE III
FIRST TYPE OF OVERVOLTAGE WAVEFORM PARAMETERS

Return stroke number	Peak value of return stroke current(kA)	Negative peak value of overvoltage(kV)			Negative rise time of overvoltage(μs)			Half peak width of overvoltage (μs)			Oscillation period (μs)			Duration of oscillation (μs)		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
F1807261411RS3	3.3	-10.4	-8.2	-24.5	18.7	16.9	3.2	9.5	9.4	7.6	17.1	17.1	17.2	154.1	153.5	135.8
F1807261411RS6	8.0	-28.6	-30.1	-70.4	12.6	9.4	4.9	6.7	6.6	7.2	16.3	16.9	16.5	146.8	151.7	131.8
F1807261411RS7	12.6	-29.2	-29.9	-65.4	17.4	12.4	6.6	7.5	7.8	8.6	16.4	16.6	15.6	147.9	134.8	122.6
F1807261411RS12	13.4	-36.5	-28.6	-64.3	24.8	22.0	8.2	4.9	6.9	7.7	17.3	17.1	16.7	173.3	171.4	156.8
F1807261411RS9	14.8	-33.8	-35.0	-76.4	30.0	17.3	5.8	7.5	7.7	8.1	16.2	16.9	16.1	180.0	209.1	208.7

TABLE IV
SECOND TYPE OF OVERVOLTAGE WAVEFORM PARAMETERS

Return stroke number	Peak value of return stroke current(kA)	Negative peak value of voltage(kV)			Negative rise time of voltage(μs)			Half peak width of overvoltage (μs)			The residual voltage value (kV)			Duration of residual voltage(μs)		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
F1807261411RS2	10.3	-25.4	-26.7	-82.1	15.5	9.2	3.9	2.6	2.6	2.4	8.9	8.7	30.6	19.3	19.3	17.9
F1807261411RS1	20.4	-50.7	-60.6	-96.1	11.3	6.2	6.5	6.1	5.9	6.0	11.7	14.4	30.2	262.8	263.4	263.3
F1807261411RS4	26.8	-74.2	-76.8	-90.5	7.9	6.8	5.6	3.5	3.5	3.2	20.2	18.8	31.5	57.5	57.5	58.6
F1807261411RS5	27.3	-71.5	-77.6	-85.6	9.8	6.8	6.0	5.7	5.5	5.6	24.3	20.5	34.1	35.6	35.5	33.3

TABLE V
THIRD TYPE OF OVERVOLTAGE WAVEFORM PARAMETERS

Return stroke number	Peak value of return stroke current(kA)	Negative peak value of voltage(kV)			Negative rise time of voltage(μs)			Half peak width of overvoltage (μs)			10%-10% width of overvoltage (μs)		
		A	B	C	A	B	C	A	B	C	A	B	C
F1807261411RS13	24.3	-62.3	-66.5	-74.8	31.7	15.3	12.1	7.0	7.7	8.4	73.9	71.0	56.3
F1807261411RS8	29.5	-79.6	-77.6	-83.9	13.2	7.5	7.0	5.3	4.8	12.0	105.0	43.7	58.6
F1807261411RS10	32.9	-92.1	-67.2	-78.5	5.2	16.7	11.6	2.4	3.8	13.8	39.0	36.5	68.8

for phase A, it is between 12.6 μs and 30.0 μs, and for phase B, it is between 9.4 μs and 22.0 μs. The oscillation period of three phases are close, which is between 15.6 μs and 17.3 μs. Duration of oscillation of three phases are from 122.6 μs to 209.1 μs.

The waveform characteristics of the first type of overvoltage are very similar with the induced voltage waveform at the terminal of the same distribution line by triggered lightning 40 m away reported by Wang *et al.* [18]. The average negative peak value of the three-phase induced voltage at the terminal of the 10 kV distribution line are very close and below 30 kV. The average values of the three phase 10%-90% rise time of negative peak are 36.2 μs, 25.1 μs, and 20.4 μs.

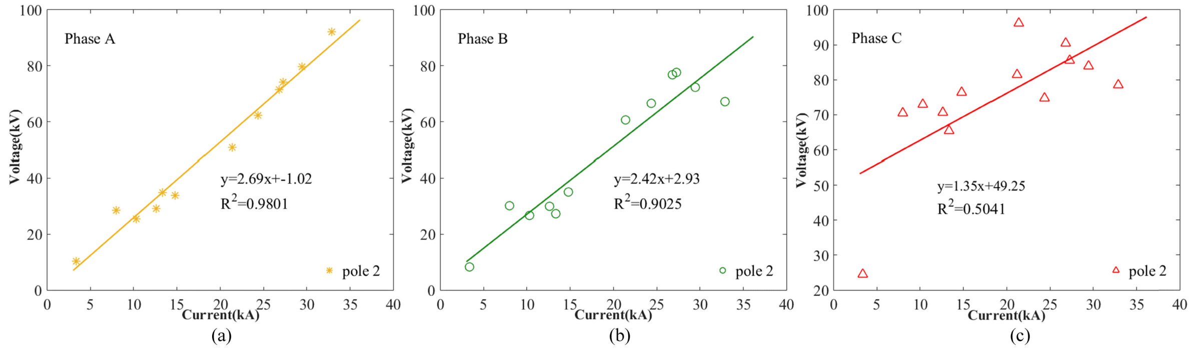

Fig. 7. Relationship between negative peak value of three phase overvoltage and peak value of return stroke current. (a) The relation between the overvoltage of phase A and peak value of return stroke current. (b) The relation between the overvoltage of phase B and peak value of return stroke current. (c) The relation between the overvoltage of phase C and peak value of return stroke current.

The second type of negative peak value of phase A is between −25.4 kV and −71.5 kV, that of phase B is between −26.7 kV and −77.6 kV, and that of phase C is between −82.1 kV and −96.1 kV. The rise time of negative peak of the direct struck phase C is between 3.9 μs and 6.5 μs. This value for phase A is between 7.9 μs and 15.5 μs, and for phase B, it is between 6.2 μs and 9.2 μs. Half peak width and duration of residual voltage of three-phase overvoltage are close. The former is between 2.4 μs and 6.1 μs and the latter is between 17.9 μs and 273.4 μs. The residual voltage value of indirect struck phase increases with the return stroke current, but that of direct struck phase stabilizes at about 30 kV. Compared with the voltage caused by induced lightning, it can be found that the rise time of the overvoltage by direct lightning strike is smaller than the induced voltage in [18], and the rise time of negative peak of the direct struck phase is smaller than that of the indirect struck phase.

For the third type of overvoltage, the negative peak value of phase A is between −62.3 kV and −92.1 kV, that of phase B is between −66.5 kV and −77.6 kV, and that of phase C is between −74.8 kV and −83.9 kV. The rise time of negative peak of the direct struck phase C is between 8.8 μs and 15.1 μs. For phase A and phase B, it ranges from 6.5 μs to 39.6 μs, and from 9.4 μs to 20.9 μs respectively. Half peak width of indirect struck phase is close, ranging from 2.4 μs to 7.7 μs, and that of direct struck phase is between 8.4 μs and 13.8 μs. It can be seen that the order of negative peak value in most return strokes is phase C > phase B > phase A. When return stroke current is between 3.3 kA and 32.9 kA, the ratio of the overvoltage negative peak values between indirect struck phase and direct struck phase is about 1/3 to 1/2. When the return stroke current is larger, the negative peak values of three-phase overvoltage are very close, and the ratio of the negative peak value between indirect struck phase and direct struck phase is larger than 1/2. The order of negative peak rise time in most return strokes is phase A > phase B > phase C. The rise time of negative peak of the three-phase overvoltage of second type is smaller than the other two types.

D. The Relation Between Parameters of Return Stroke Current and Overvoltage

Fig. 7 shows the relation between the negative peak value of three-phase overvoltage and the peak value of the lightning return stroke current. The overvoltage negative peak values of phase A and phase B both have a good linear relation with the peak value of lightning current, and the correlation coefficients are 0.98, 0.90 respectively. Because of the operation of arrester at phase C in four return strokes and the nonlinear volt-ampere characteristics of the arrester, the linear relation is not obvious between the negative peak value of phase C overvoltage and peak value of return stroke current. Only the negative peak value of the first type of overvoltage has a good linear relationship with the peak value of return stroke current. There is nearly no linear relation between the rise time of negative peak of the overvoltage and the rise time of the lightning return stroke current.

The relation between the waveform parameters of the three-phase induced voltage at the end of the line and the lightning return stroke current parameters is also reported in [18]. The results show that the negative peak value of the three-phase induced voltage has a very good linear relation with the lightning current, and the correlation coefficients are 0.925, 0.968, and 0.984. There is also no clear linear relation between the rise time of negative peak of the induced voltage and the rise time of the lightning current in [18], which is the same as the phenomenon reported in this paper.

IV. Summary

A 1.5 km, 10 kV distribution line equipped with overhead ground wire was struck directly on the phase conductor C by triggered lightning, where the arresters were installed at every other pole. The three-phase overvoltage at the terminal of the distribution line are observed as follows:

The overvoltages were observed not only on direct struck phase but also the indirect struck phase at the terminal of the distribution line, corresponding to 13 return strokes with the peak current from 3.3 kA to 32.9 kA. For the negative peak value of overvoltage, in most return strokes, it shows the rule of phase C > phase B >phase A. The ratio of the negative peak values of overvoltage between indirect struck phase and direct struck phase increases with the peak value of the current. The linear relation between the negative peak value of the indirect struck phase overvoltage and the peak value of the lightning return stroke current is obvious.

There are three types of overvoltage waveforms for the direct struck phase. For the first type, the overvoltage increases rapidly to the negative peak from zero and then experiences polarity conversion followed by the oscillation decay process. The second type of overvoltage features the operation of valve disc of arrester and the positive oscillation. The third type of waveform has a short oscillation of a few microseconds after the negative peak and then gradually decays to zero. The overvoltage waveforms of indirect struck phases are very similar with the direct struck phase and can also be divided into three types.

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

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