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Identification of Transmission Line Lightning based on HHT

Cheng Zixia, Pei Haowei and Teng Chenyuan

School of Electric Engineering, Zhengzhou University, Zhengzhou 450001, China
chzx@zzu.edu.cn

Abstract

Lightning groundwire or tower without fault, back striking, shielding failure without fault and shielding failure with fault are simulated and analyzed in this paper based on the electromagnetic transient simulation software of ATP-EMTP. The results show that the current waveform of lightning strikes the ground or tower without fault is generated by the coupling of lighting current from lighting groundwire and oscillates around the axis of the steady state. Back striking contains processes of couple and flashover, its current waveform has characteristics of reverse polarity pulse and sudden current drop. The current of shielding failure without fault is the lighting current. The current waveform of shielding failure with fault is characterized by the truncation. On this basis, the Hilbert Huang transform (HHT) was introduced to do further analysis of the simulation results. The solution of end effect is also proposed in this paper. And thus the marginal spectrum was obtained by dealing with the simulated current waveform of lightning stroke. Then, calculating the energy distribution in different frequency bands and normalizing them. Therefore, a method for recognizing 4 types of lightning stroke is proposed which is on the basis of the energy proportion in different frequency bands. In addition, a large number of simulations are conducted to verify the effectiveness of this method by changing the parameters of the lightning current, grounding resistance and lightning distance.

***Keywords**: Identification of lightning stroke; ATP-EMTP; HHT*

1. Introduction

The flashover caused by lightning stroke are 31.64% of the total according to the operating statistics from State Grid Corporation during 2005-2010 [1], while the lightning trip in transmission lines is mainly resulted from direct lightning [2]. Direct lightning can be split into two categories: back striking and shielding failure, whose mechanism, process and protective measures are different [3]. Therefore, it is difficult to take reasonable measures for lightning protection if the back striking and shielding failure fail to be accurately identified. In addition, direct lightning will lead to the misoperation or misstrip of transmission line traveling wave protection devices if lightning fault and lightning stroke without fault can not be accurately identified [6]. Therefore, the accurate identification of 4 kinds of lightning stroke, such as lightning groundwire or tower without fault, back striking, shielding failure without fault and shielding failure with fault can not only take the specific lightning protection , greatly improving the effect of lightning protection, but also provide criterion for travelling wave protection and promote its application.

The domestic and foreign researchers have done a lot of research on the lightning identification problem, and obtained some achievements. Wang Yongzhi in reference [4] proposed two lightning stroke fault and non fault identification criterions if there is the mutations phenomenon that traveling wave signal is truncated, and if the correlation coefficient polarity are the same as the original DC component, then combinated these two criteria to improve its reliability. Zhang Guangbin in the literature

[5] proposed the shielding failure fault and back striking identification method by using wavelet transform to obtain the polarity of zero mode voltage surge. Zhang Bin in the literature [6] proposed to calculate the correlation degree of the former 2ms sampling data and the average of later 3ms sampling data, and then inosculate these two calculation results by extension theory to identify lightning interference, which has a function of fault selection. However, these methods above can only identify one or two of the 4 lightning cases, failing to put forward a unified identification method. In addition, they are studied from the aspect of voltage traveling wave, which is against the actual situation that on-line monitoring devices of transmission line use current traveling waves for locating and identifying faults.

Therefore, in this paper, lightning simulation model of transmission line is built based on ATP-EMTP from the aspect of current traveling wave, and 4 kinds of lightning conditions in 220 kV transmission lines were simulated, then simulation current waveforms obtained is compared and analysed. HHT is used to do further analysis of the current waveforms in this paper, which is suitable to deal with the non-steady state and nonlinear signal, which . A HHT end effect solution is also proposed in this paper based on the characteristics of lightning transient waveform. Then, HHT was used to deal with current waveform to obtain the marginal spectrum, and 4 kinds of lightning were identified according to the frequency domain energy distribution in the marginal spectrum.

2. 220 kV Transmission Line Lightning Simulation

2.1. Simulation Model

Lightning transmission line model includes lightning source model, transmission line model, tower model, grounding resistance and insulator model, as shown in Figure 1.

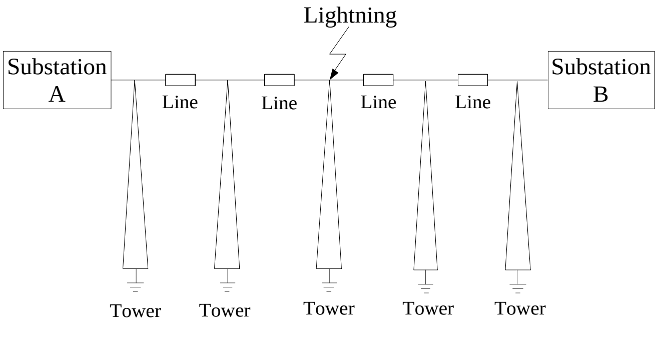

Figure 1. Lightning Stroke of Transmission Line Sketch Map

According to the measured data from different countries, the negative polarity lightning accounts for 75% ~ 90% of the total lightning[7]. Therefore, negative lightning wave is introduced as lightning source in the simulation research in this paper, as shown in Figure 2. The double exponential wave model is selected as the lightning current model, which is closest to the actual lightning current waveform[8], and its mathematical expression is:

$$i = I_0(e^{-\alpha t} - e^{-\beta t}) \tag{1}$$

In this formula, I_0 is the amplitude of lightning current; α and β are the time coefficient of wavefront and wave tail respectively. The wave impedance Z_0 of Lightning channel is 300Ω.

Transmission line model uses Jmarti frequency dependent model. Line span is 400 m, and a 40 km long line is provided at both ends respectively to avoid the refraction and reflection effects of traveling wave in end of the line. Towers choose 2F1Wa-ZM1-27 type cathead tower, which is actually used in the 220 kV transmission lines, and is simulated using multi-wave impedance model [9]. The actual tower structure and the established multi-wave impedance model can be seen in Figure 3. The Z_A is the wave impedance of the tower crossarm; Z_T is the wave impedance of main material in the main body of the tower; Z_L is the wave impedance of fine materials. R is the impulse grounding resistance, its value is 10Ω.

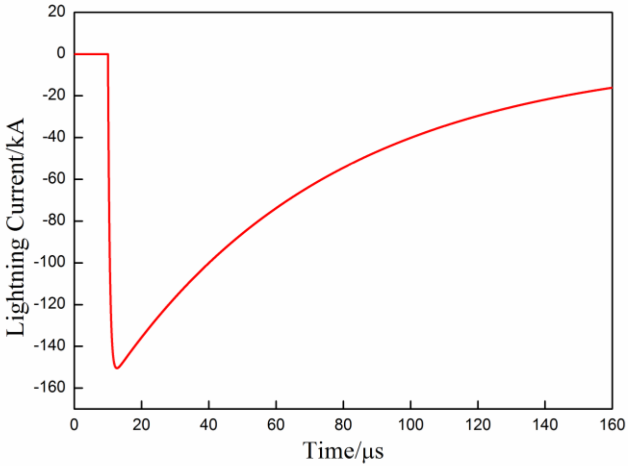

Figure 2. Lightning Current Source Waveform

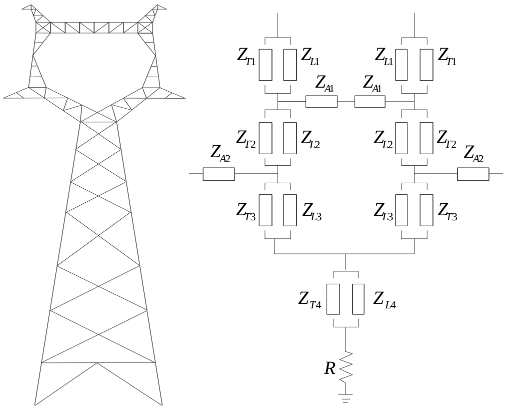

Figure 3. Tower Structure and its Multi-Wave Impedance Model

The insulator flashover model uses pilot flashover model [10]. Insulator string flashover can be judged by whether the development of pilot is throughout the gap, and the rate formula of pilot development recommended by CIGRE WG33.01[11] is:

$$\frac{dL}{dt} = ku(t)\left[\frac{u(t)}{D-L} - E_0\right] \qquad (2)$$

In this formula, L is the pilot development length (m); $u(t)$ is the voltage (kV) of the insulator string; D is the gap length (m); the E_0 is the starting field strength of the pilot (kV/m). According to the volt-second characteristic curve which IEC recommended, we can push back that k=1.1, E0 = 500 kV/m.

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2.2. Results and Analysis of Simulation

4 kinds of lightning cases are simulated respectively using the transmission lines lightning model, which is established in *1.1*. The results are shown in Figure 4.

In the Figure 4 (a), the current travelling wave in lightning strikes the groundwire or tower without fault is caused by the induction of the lightning current in grounding line. And because of the influence of lightning current's refraction and reflection between the towers, the waveform fluctuates around the steady state current values, and decay gradually, ultimately back to the axis of the steady state. In the Figure 4 (b), the formation of current traveling wave includes two processes:

(1) Current wave is inducted in the grounding wire by the lightning current before the insulator flashover, this process generates the reverse polarity pulse and is the same as the induction process of lightning grounding wire or tower without fault.

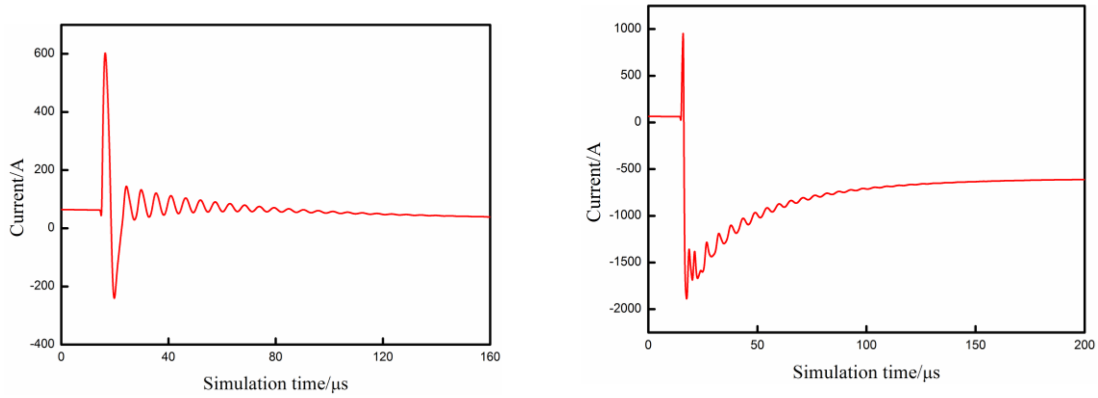
(2) Lightning injects the wire through flashover channel after insulator flashover, this process generates the current wave which is behind the reverse polarity pulse and its general shape is similar to the standard lightning waveform, for the lightning current is fed directly to the wire. However, because the reflection waveform of the lightning between the toweris fed to the wire through the flashover channel as well as the induction of the lightning current in the grounding wires, the wave tail shows a oscillation sight.

In Figure 4 (c), the current wave of the shielding failure without fault is the lightning current transmitting in the wire and is as same as the standard lightning wave. In Figure 4 (d), similar to the back striking, the formation of current waveform of shielding failure with fault also includes two processes:

(1) The transmission process of lightning current in the wire before the insulator flashover.

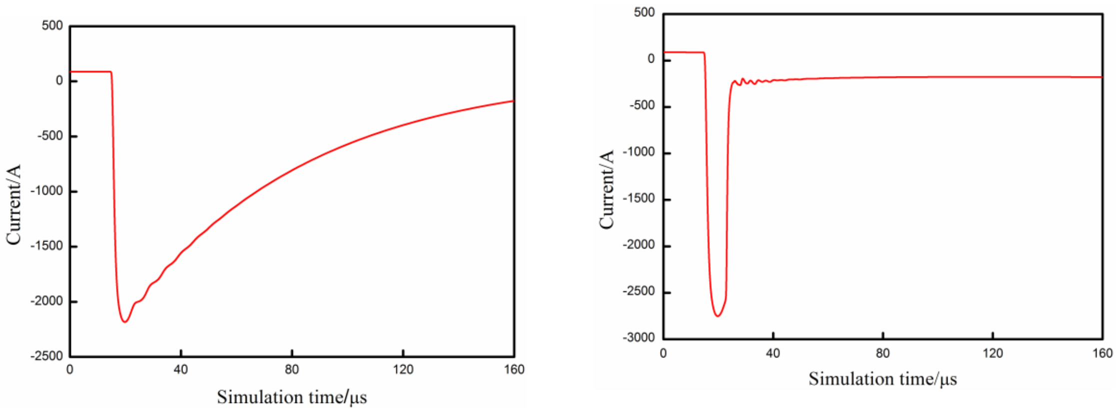
(2) The wave, which is reflected by lighting current in the tower, injected into the wire through the flashover channel after insulator flashover. The sum of the wave in the second process and the lightning wave in the wire makes the final wave cuted, and the wave tail steepness is approximately equal to the wavefront steepness.

As is seen from the analysis above, the different physical generation mechanism of the transient current in transmission line results their different waveform characteristics. Lightning groundwire or tower without fault and back striking are greatly effected by the induction of the lightning current in the groundwire, presenting oscillation characteristics. But lightning groundwire or tower without fault has no flashover and current dump process, its wave oscillate along the axis of steady state. Before the flashover, back striking inducts a pulse whose polarity is opposite to the lightning current. After the flashover, lightning wave injects conductor and causes the sudden drop of current. At the same time, the current inducted by the lightning current in the groundwire mixes with the lightning current that injects the wire, and oscillates along



(a) lightning groundwire or tower without fault

(b)back striking



(c)shielding failure without fault

(d)shielding failure with fault

Figure 4 Wire Current in Different Lightning Stroke Cases

the lightning current waveform. The shielding failure without fault and shielding failure with fault is less affected by the induction current, and its waveform is mainly influenced by the flashover process. The shielding failure without fault has no flashover process, and the current on the wire is the lightning wave. In the shielding failure with fault, the reflection wave stacks with the lightning wave when flashover happens, and thus it is cut off. Its wave tail steepness is approximately equal to the wavefront steepness.

3. Identification Method of Lightning based HHT

In order to do further research on the transient characteristics of the current wave of four lightning cases and obtain transient characteristic value quantitatively, Hilbert-Huang transform [12,13] (HHT) is introduced to analyze the simulation waveform in this paper, acquiring the description of its frequency domain and thus to reveal their transient characteristic differences more comprehensively and accurately.

3.1. HHT Principle and Implementation Method

HHT is an analysis method for nonlinear and non-stationary signals, which is used to do adaptive decomposition of signals based on local time-change feature. It can overcome the shortcoming like traditional methods that uses meaningless harmonic component to represent non-stationary signals, having a good local adaptability. HHT process consists of two parts: empirical mode decomposition (EMD) and Hilbert Spectrum analysis[14].

The EMD is to obtain the intrinsic mode function (IMF) by sieving the raw signal, so that each IMF only contains a single frequency component at each time, making the instantaneous frequency meaningful.

The original signal can be expressed by the following formula after EMD processing:

$$s(t)=\sum_{i=1}^{n}c_i+r_n \tag{3}$$

In this formula, c_I is the ith IMF component, and r_n is the residual vector.

With Hilbert transform to the IMF, it can obtain:

$$c_i(t)=\frac{1}{\pi}P\int_{-\infty}^{\infty}\frac{c_i(t')}{t-t'}dt' \tag{4}$$

Where, P is Cauchy principle value.

Then analytic signal $z_i(t)$ is bulit:

Its amplitude function, phase function and instantaneous frequency functions are as follows:

$$a_i(t) = \sqrt{c_i^2(t) + \hat{c}_i^2(t)} \tag{6}$$

$$\phi_i(t) = \arctan(\hat{c}_i(t) / c_i(t)) \tag{7}$$

$$f_i(t) = \frac{1}{2\pi}\omega_i(t) = \frac{1}{2\pi}\frac{d\phi_i(t)}{dt} \tag{8}$$

Furthermore, Hilbert marginal spectrum can be obtained, and its expression is:

$$h(\omega) = \int_0^T \mathrm{Re}\sum_{i=1}^{n} a_i(t) e^{j\int \omega_i(t)dt} \tag{9}$$

Marginal Spectrum describes the energy distribution of original signal in the frequency domain. And the energy on marginal spectrum means that the wave with corresponding frequency appears at a specific time during the time signal continous.

3.2. The End Effect Problem and its Solutions

When do the EMD decomposition of the original signal, cubic spline function is needed to approximate the extreme point to get the envelope. However, not all the endpoints of the signals is the extreme point, making the envelopes distorted inevitably at the endpoints, and thus affects the effect of the EMD decomposition. Taking the lightning ground wire or tower without fault waveform for example, ,cubic spline interpolation appears a serious wing phenomenon at the beginning and end of a signal which can be seen in Figure 5.

A lot of researches have studied the endpoint effect of HHT, and have proposed several end effect treatment, such as extension method based the neural network [15], the mirror extending method [16], ARMA model extension method [17], ARIMA model extension method [18], Volterra model extension method [19] and polynomial fitting extension method[20], and so on. These methods above predict the extreme points beyond the endpoints based on the known extreme points, and then fit the envelope

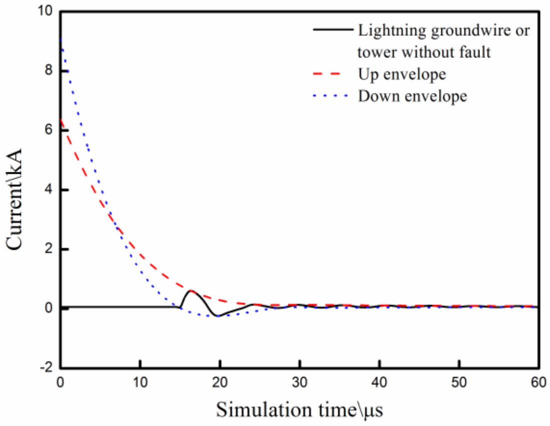


Figure 5. End Effect

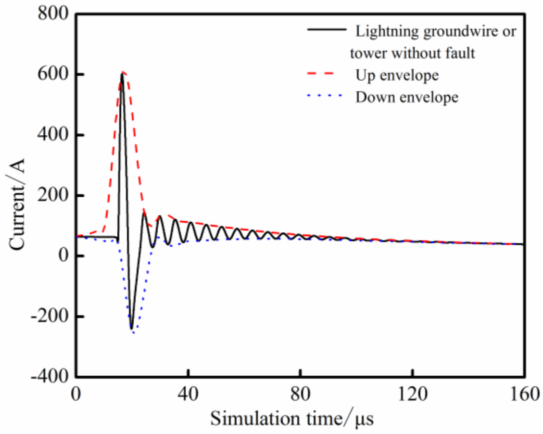


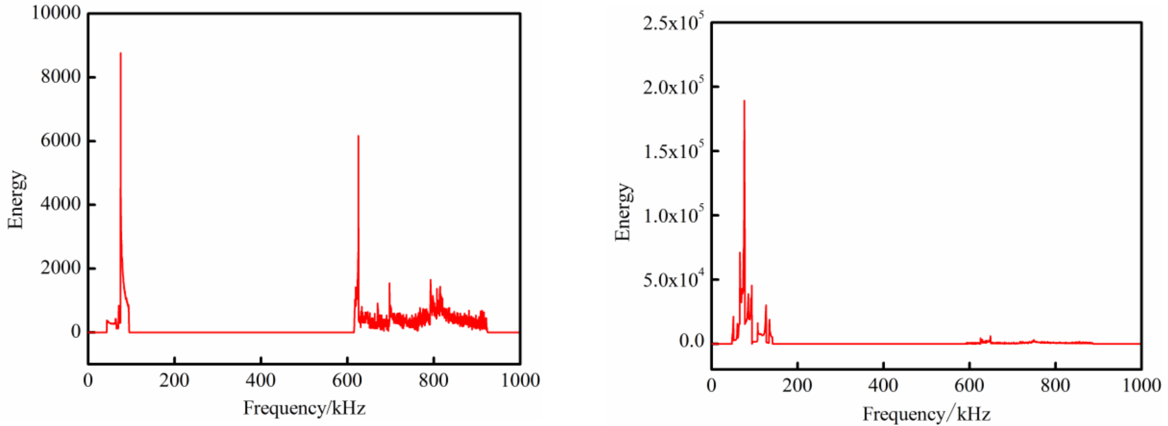
Figure 6. Envelope Line based on the Characteristics of Lightning Stroke

curve, which solve the end effect of HHT to some extent. However, the extreme points amplitude of lightning transient waveform vary greatly and lack in regularity especially in the head of the waveform where may appear extreme points abruptly, causing large errors when using methods above to predict.

The current generated by lightning stroke is transient traveling wave. They all go back to a steady state before they arise and after they disappear, namely the two termianls changing state of waveform is known. And as shown in Figure 6, this characteristics is used to extend the extreme points at both terminals based on the gradient of the waveform in this paper, making the envelope tends to steady axis, which successfully solves the endpoint effect.

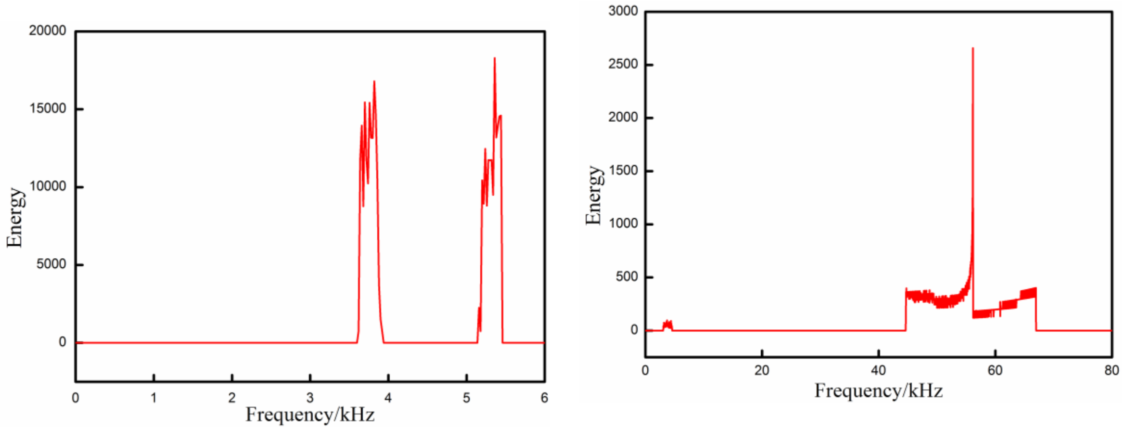
3.3. Lightning Identification Criterion

4 types of lightning waveforms are processed by HHT, and the Hilbert marginal spectrum is calculated after the obtaining of IMF component, which is shown in Figure 7. As is seen from the picture, the energy distribution of the 4 lightning waveforms ranges from the 0 to 1 MHz, but the specific distribution and energy value are different. Some current energy of lightning groundwire or tower without fault and back striking all



(a) the marginal spectrum of lightning groundwire

(b) the marginal spectrum of backing striking or tower without fault



(c) The marginal spectrum of shielding failure with fault

(d) The marginal spectrum of shielding failure without fault

Figure 7. The Marginal Spectrum of Current Waveforms in 4 Cases of Lightning Stroke

distribute from 500 kHz to 1 MHz and there is little difference in the amount of energy. However, the energy of the back striking is more than 20 times of the lightning groundwire or tower without fault energy in the frequency band below 500 kHz. The energy of current waveform of shielding failure without fault only distributes in the frequency range below 10 kHz, but its energy is large, which is more than 10 times of the shielding failure with fault current waveform. The energy of shielding failure with fault current waveform mainly distributes at the range from 40 kHz to 70kHz, and has a very small amount of distribution below 10 kHz.

Considering the analysis above, the frequency band from 0 to 1 MHz is divided into low, medium and low frequency band, medium and high frequency band, high frequency band respectively. Their frequency range are below respectively: 0 ~ 25 kHz, 25 to 40 kHz, 40 kHz to 500 kHz and 500 kHz to 1 MHz.

Then, calculating the total energy of each frequency band using the equation (10) :

$$W_i = \int_{f_1}^{f_2} w_i df \tag{10}$$

Where, W_i is the total energy of a frequency band; w_i is the energy of a certain frequency; i= 1,2,3,4, represent the low frequency, medium and low frequency, medium and high frequency, high frequency respectively.

Thus, the energy distribution of the Hilbert marginal spectrum can be expressed as:

$$W = [W_1, W_2, W_3, W_4] \tag{11}$$

The feature vector can be obtained by the normalization processing of the formulation (11) :

$$W^* = [W_1^*, W_2^*, W_3^*, W_4^*] \tag{12}$$

Where, $W_i^* = W_i / \sum_{i=1}^{4} W_i$, i=1, 2, 3, 4。

After the normalization, the frequency domain energy distribution of current traveling waves of 4 lightning cases is shown in Figure 8, and the sum of energy frequency is 1.

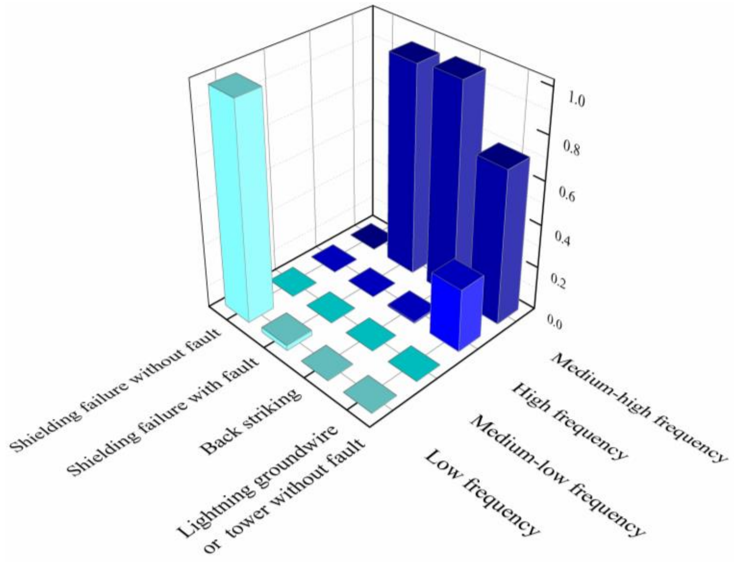


Figure 8. Energy Distribution of each Frequency Band in 4 Cases of Lightning Stroke

As is shown in Figure 8, high frequency band only contains energy of lightning groundwire or the tower without fault and back striking, but their proportion differ large, and the high-frequency energy proportion of lightning groundwire or tower without fault is more than 0.2, while the back striking is less than 0.01. The energy distribution of shielding failure without fault all distributes in the low frequency band, and the energy of shielding failure with fault mainly distributes in the medium and high frequency band, and a small amount distributes in the low frequency band.

Considering the analysis above and leaving a certain margin, the criterions to identify these 4 types of lightning strikes are as follows:

(1) When there has high frequency energy, if the energy is less than 0.03, it can be judged as back striking; if the energy is larger than 0.03, it can be judged as lightning groundwire or the tower without fault.

(2) When there has no high frequency energy, if the proportion of medium and high frequency energy is larger than the low frequency energy, it can be judged as shielding failure with fault, otherwise, it can be judged as shielding failure without fault.

4. Simulation Verification

The actual statistics show that most wave head time of the lightning current is about 1~5us, and the average wavelength is about 2.6 us [21]. While the wavelength of the lightning current is about 20 ~ 100 us, the average wavelength is about 50 us. The normal grounding resistance is about 10 Ω according to the measured data from the power supply company, and it is poorly grounded when the grounding resistance is greater than 10 Ω. The distance of the transmission line online monitoring devices is usually less than 30 km. Therefore, the distance between lightning point and monitoring devices is less than 15 km. In this paper, these factors above are considered and thus a variety of situations are simulated to verify the identification criteria of lightning proposed in *2.3*. The verification results are shown in Table 1 ~ 4. The number 1, 2, 3, 4 in judgment column represent lightning groundwire or tower without fault, back striking, shielding failure without fault, shielding failure with fault respectively.

Table 1 The verification results of lightning ground-wire or tower without fault

Lightning parameter	Grounding resistance/Ω	Lightning distance/km	W_1^*	W_2^*	W_3^*	W_4^*	Judgement
1/20	10	0.5	0	0.4172	0.5494	0.0334	1
		15	0	0.0018	0.3206	0.6777	1
	20	0.5	0	0.0101	0.9373	0.0526	1
		15	0	0.1057	0.184	0.7103	1
2.6/50	10	0.5	0	0.0604	0.8305	0.1091	1
		15	0	0	0.4618	0.5382	1
	20	0.5	0.1672	0.1812	0.2395	0.4121	1
		15	0	0	0.9595	0.0405	1
5/100	10	0.5	0	0.054	0.8286	0.1175	1
		15	0	0.737	0.0618	0.2012	1
	20	0.5	0.1446	0.4805	0.2407	0.1343	1
		15	0	0.6825	0.2153	0.1022	1

Table 2 The verification results of back striking

Lightning parameter	Grounding resistance/Ω	Lightning distance/km	W_1^*	W_2^*	W_3^*	W_4^*	Judgement
1/20	10	0.5	0.5773	0.3439	0.0779	0.0009	2
		15	0.0136	0.3471	0.6257	0.0134	2
	20	0.5	0.0380	0	0.9573	0.0048	2
		15	0.009	0.8879	0.076	0.0271	2
2.6/50	10	0.5	0.5154	0.2588	0.2198	0.0061	2
		15	0.7934	0.0240	0.1810	0.0016	2
	20	0.5	0	0	0.9825	0.0175	2
		15	0.3202	0.2747	0.3973	0.0078	2
5/100	10	0.5	0.008	0.9637	0	0.0284	2
		15	0.8628	0.0304	0.0855	0.0213	2
	20	0.5	0	0.0017	0.9883	0.0100	2
		15	0	0.1037	0.8902	0.0061	2

Table 3 The verification results of shielding failure without fault

Lightning parameter	Grounding resistance/Ω	Lightning distance/km	W_1^*	W_2^*	W_3^*	W_4^*	Judgement
1/20	10	0.5	1	0	0	0	3
		15	0.1702	0.796	0.0339	0	3
	20	0.5	0.1085	0.8915	0	0	3
		15	1	0	0	0	3
2.6/50	10	0.5	1	0	0	0	3
		15	1	0	0	0	3
	20	0.5	1	0	0	0	3
		15	0.9477	0.0523	0	0	3
5/100	10	0.5	0	0	0	0	3
		15	1	0	0	0	3
	20	0.5	0	0	0	0	3
		15	1	0	0	0	3

Table 4 The verification results of shielding failure with fault

Lightning parameter	Grounding resistance/Ω	Lightning distance/km	W_1^*	W_2^*	W_3^*	W_4^*	Judgement
1/20	10	0.5	0.5773	0.3439	0.0779	0.0009	2
		15	0.0136	0.3471	0.6257	0.0134	2
	20	0.5	0.0380	0	0.9573	0.0048	2
		15	0.009	0.8879	0.076	0.0271	2

2.6/50	10	0.5	0.5154	0.2588	0.2198	0.0061	2
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5/100	10	0.5	0.008	0.9637	0	0.0284	2
		15	0.8628	0.0304	0.0855	0.0213	2
	20	0.5	0	0.0017	0.9883	0.0100	2
		15	0	0.1037	0.8902	0.0061	2

5. Conclusion

Four kinds of lightning stroke in 220kV transmission line is simulated and analyzed in this paper, and the HHT is used to process the simulating current waveform, resulting in following conclusions:

1) The current waveform of lightning groundwire or tower without fault is generated by the induction of lightning current in the groundwire which has reflected multiple times, and has the characteristic of high frequency oscillation. The current waveform of back striking has reverse polarity pulse which is inducted by lightning current before flashover. Its waveform trend is similar to the lightning wave after flashover, but has oscillation characteristic. The waveform of shielding failure with fault contains the reflection wave of the tower when flashover happens, showing a truncation phenomenon, and the steepness of wavefront and wavetail is approximately equal. The waveform of shielding failure without fault is similar to the lightning waveform.

2) Energy distribution of transient current waveform of 4 lighting stroke in HHT marginal spectrum is different, and thus the frequency band is divided into low frequency band, medium and low frequency band, medium and high frequency band and high frequency band. After normalization of the frequency domain energy, it is able to identify the lightning groundwire or tower without fault if the high frequency energy ratio is greater than 0.03; if the high frequency energy ratio is in the range of 0 ~ 0.03, it can be judged as back striking.

The identifying of the shielding failure with fault and shielding failure without fault is based on the comparison between the proportion of the medium and high frequency energy and the proportion of the low frequency energy. If the former is greater than the latter, it can be judged as shielding failure with fault. Otherwise, it can be judged as shielding failure without fault. This method has highly reliability after the simulation verification.

Acknowledgements

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