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Research on Resonance Overvoltage of EHV Transmission Lines Caused by Lightning Strike

XIAO LEI [1], TAO CUI [1], XIAOHUI WU [2], HONG ZENG [1], QIANG LIU [1], AND LINHUAN LI [3]

[1] State Grid Sichuan Electric Power Research Institute, Chengdu 610092, China
[2] State Grid Sichuan Electric Power Company, Chengdu 610041, China
[3] State Grid Sichuan Electric Measurement Center, Chengdu 610000, China

Corresponding author: Xiao Lei (qsrmm@163.com)

ABSTRACT This paper studies the mechanism and influencing factors of resonance overvoltage of EHV transmission lines caused by lightning. By analyzing the time domain steady state of the simplified resonance circuit, the physical mechanism of resonance is revealed. The characteristics of resonance transient process and overvoltage waveform are analyzed by using electromagnetic transient simulation. The main influencing factors of overvoltage amplitude are also studied. The results show that: 1) During uneven open-phase conditions, resonant circuit involving shunt inductors and line equivalent capacitor obtains energy from lightning strikes, which may lead to resonance. 2) the transient process of resonance can be divided into three stages, including lightning stage, lightning-resonance conversion stage and steady-state resonance stage, among which the voltage of the first two stages are higher; 3) the lightning strike time, lightning current parameters and subsequent lightning strike affect on the overvoltage amplitude, which leads to the random amplitude in overvoltage.

INDEX TERMS Resonance overvoltage, EHV transmission line, lightning strike, shunt inductor.

I. INTRODUCTION

In recent years, China has recorded several faults caused by resonance overvoltage occurred during uneven open-phase conditions in 500kV transmission lines with shunt compensation reactor. These resonances were stimulated by lightning strikes on the conductor of tripped phase, and differ from typical resonant overvoltage mechanism [1]. Transmission lines in areas prone to thunderstorms are vulnerable to lightning strikes. Due to the parameter design of shunt reactor and neutral reactor, the amplitude of induced voltage on fault phase line is low. However, the subsequent lightning strike that hits the faulty phase wire again provides energy for the resonant circuit. The working conditions of arrester, shunt reactance and neutral reactor are complicated because of lightning and resonance, which result in high risk of fault.

The resonance mechanism of high voltage transmission line is analyzed systematically [2]–[7]. Shunt reactors are usually applied to compensate for the effect of distributed line capacitance for long EHV transmission lines. Since the impedance values of reactor and line capacitor are similar at power frequency, resonance may occur during uneven open-phase conditions [8], [9]. Various methods have been used to mitigate resonance effect [1], [10], [11]. The common method is to install neutral reactor to make the equivalent phase-to-ground impedance of shunt reactor inductance and line capacitance capacitive. However, This resonance mechanism only considers the energy provided by the system power supply, and does not account for input of energy from external sources.

Lightning is the main external energy source of resonant circuit. According to the statistics of the State Grid Corporation, lightning trip accounts for 39.4% to 50.8% of the total trips in 330kV and above AC transmission lines [12]. Lightning trip out is more serious in the areas with more thunderstorms. The lightning trip rate of 500kV transmission lines in some provinces exceeds 0.3 times per 100 km per year. Lightning trip is not the final form of fault. According to lightning parameter statics among several countries, a typical cloud-to-ground flash is composed of 3-5 strikes [13]–[17]. The measured data of State Grid Corporation shows that the number of return strikes can reach up to 20. The amplitude of lightning current of subsequent return strike is low, so it won't easily cause insulation flashover again, which makes all energy injected into the resonant circuit. At present, there

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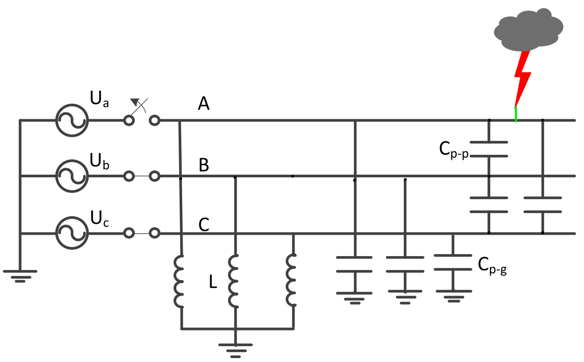

FIGURE 1. Simplified resonance circuit.

is no relevant research on transmission line resonant overvoltage induced by multiple lightning strikes.

In this paper, the resonance mechanism of transmission line with high reactance caused by lightning strike is given, and the characteristics and influencing factors of resonance overvoltage are studied. In the second section, the steady-state and transient processes of resonance are analyzed theoretically. In the third section, the influencing factors of resonant overvoltage are studied, including lightning parameters, lightning strike time and continuous return strikes. The forth section gives a case study.

II. RESONANCE MECHANISM

A. STEADY STATE ANALYSIS

In the case of external energy injection, a circuit with energy storage element might resonate. For the simplest resonant circuit composed of one capacitor and one inductor, the maximum capacitance voltage is as follows.

$$U_{\max} = \sqrt{\frac{2E}{C}} \tag{1}$$

where $U_{\max}$ is the maximum voltage, E is the injection energy, C is the capacitance. The time domain steady state expression of voltage is as follows.

$$U(t) = U_{\max} \sin(\frac{2\pi}{\sqrt{LC}} t) \tag{2}$$

Figure 1 shows the simplified circuit of 500 kV Line after phase A trip. According to Thevenin's theorem, the steady-state solution of reactor voltage can be decomposed into voltage caused by system power supply and voltage caused by external energy, as shown in Figure 2.

The calculation formula of voltage component U_1 caused by system power supply is as follows.

$$U_1(t) = \sqrt{2}U_A \sin(\omega_s t) \frac{\omega_s^2 \cdot L \cdot C_{p-p}}{1 - \omega_s^2 \cdot L \cdot (C_{p-g} + 2C_{p-p})} \tag{3}$$

where U_{A} is the RMS voltage of fault phase A, ω_s is the system angular frequency, L is the reactance of shunt reactor, C_{p-p} is the capacitance between lines, C_{p-g} is the capacitance between lines and ground.

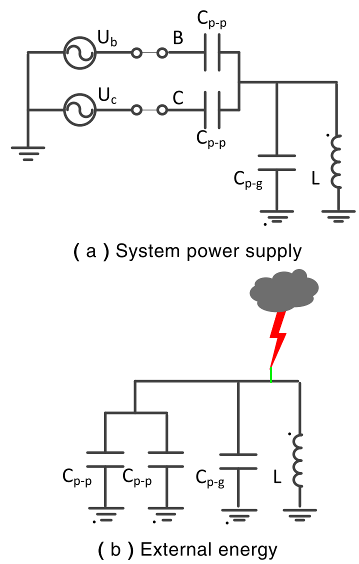

FIGURE 2. Equivalent subcircuit.

Whether the circuit resonates under the system power supply depends on whether the equivalent impedance Z is capacitive or inductive under the system power supply frequency. When Z is capacitive, the system will not resonate. The expression of Z is as follows.

$$Z_{eq} = \frac{1}{j(\omega_s \cdot C_0)} || j(\omega_s \cdot L) = \frac{j(\omega_s \cdot L)}{1 - \omega_s^2 \cdot L \cdot C_0} \tag{4}$$

The calculation formula of voltage component U_2 caused by external energy is as follows.

$$U_2(t) = \sqrt{\frac{2E}{(2C_{p-p}+C_{p-g})}} \sin(\frac{1}{\sqrt{L(2C_{p-p}+C_{p-g})}} t + \Delta\varphi) \tag{5}$$

where $\Delta\varphi$ is the phase difference between U_2 and U_1. It is determined by the external energy injection time.

Combining formula 3 and formula 5, the steady-state expression of reactor voltage is as follows.

$$\begin{aligned} U(t) &= U_1(t) + U_2(t) \\ &= \sqrt{2}U_A \sin(\omega_s t) \frac{\omega_s^2 \cdot L \cdot C_{p-p}}{1 - \omega_s^2 \cdot L \cdot (C_{p-g} + 2C_{p-p})} \\ &\quad + \sqrt{\frac{2E}{(2C_{p-p}+C_{p-g})}} \\ &\quad \times \sin(\frac{1}{\sqrt{L(2C_{p-p}+C_{p-g})}} t + \Delta\varphi) \end{aligned} \tag{6}$$

It can be seen from the above formula that even if the comprehensive impedance Z is capacitive, the circuit can resonate due to excessive external injection energy. In figure 1, set C_{p-p} as 0.5 μF, C_{p-g} as 2 μF, L as 6 H, and amplitude of power supply as 1 kV. When t is 10 ms, a square wave current with 1 ms pulse width and 4 A amplitude is injected. The voltage waveform of reactor is shown in Figure 3. Before

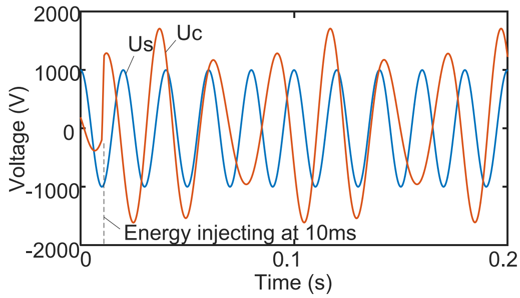

FIGURE 3. Voltage of simplified resonance circuit.

the external energy injection, the voltage amplitude is 381 V, which is less than the system power supply voltage amplitude. After external energy injection, the maximum amplitude is 1708 V. Since the natural oscillation frequency is 37.5 Hz, which is close to 50 Hz, the reactor voltage shows a beat frequency characteristics.

The premise of the above resonance mechanism is that the lightning energy is directly discharged from the lightning cloud to the tripping phase line. If the lightning strikes the ground wire and tower, the energy will go directly to the ground and will not cause resonance. The channel of subsequent lightning strike is generally the same as that of the first lightning strike. Therefore, in terms of line trip caused by the first lightning strike on the ground wire and tower, the subsequent lightning is unlikely to cause resonance. This paper only considers the case of lightning shielding failure.

B. TEMPORARY ANALYSIS

EMTP software is used for transient simulation. The resonant circuit is composed of power source at both ends, a transmission line, shunt reactor, neutral reactor and arrester. The ideal voltage source and series impedance are used to simulate the power source. The lightning strikes the middle point of the line after the B-phase is disconnected from the system to simulate a situation in which the lightning subsequent strike hits the conductor again after single-phase trip.

The length of the transmission line is set to 200 km. The line's geometry is flat construction and the line-phase distance is set to 15 m. The vertical height is set to 30 m. The soil resistivity is set to 100 Ω · m. The rated reactance of the shunt reactor and neutral reactance are 5318 mH and 2122 mH respectively. V-I characteristics of 500 kV arrester is shown in figure 5.

Generally, lightning is approximated by a Norton circuit, including an ideal current source equal to the lightning current in parallel with a lightning-channel impedance. Resistance is often used to simulate lightning-channel impedance. However, resistance will change the topology of resonant circuit. To solve this problem, a series switch is used to connect the resistor to the main circuit only during the lightning current time. The lightning channel impedance is estimated to be 600 Ω To 2.5 kΩ [13]. In this paper, it is set to 2 kΩ.

The lightning strike is negative, with amplitude of 10 kA, front time tf 10/90 of 2.6 μs and Tail Time to Half Value th of 50 μs. The overvoltage waveforms of transmission line with arresters and without arresters are shown in Figure 6. The resonance process can be roughly divided into three stages.

The first stage named "lightning stage" lasts a few microseconds. The lightning traveling wave propagates from the lightning strike point to the substation at both ends. The voltage on the line is lightning overvoltage. Due to the different impedance of reactor and line, traveling wave refracts and reflects in substation. Lightning overvoltage shows periodicity, which is related to the length of the line. Due to the existence of arrester, the amplitude of overvoltage is limited to the residual voltage. It can be seen from Figure 1 that the overvoltage without arrester is very high.

The second stage named "lightning-resonance conversion stage" occurs within tens of microseconds after the first stage. A part of the lightning energy is released by the arresters of the substations at both ends. The rest of the lightning energy is gradually released into the energy storage element of the resonant circuit. Due to the existence of resistance and impulse corona, the energy of resonant circuit is gradually consumed. It should be noted that the simulation does not simulate the corona loss. The overvoltage on the line is composed of lightning overvoltage and resonance overvoltage. It can be seen from Figure 1 that the voltage in the second stage decreases significantly due to the energy released by the arrester.

The third stage named "steady-state resonance stage" is pure resonance. At this time, the energy of lightning current has been completely released into the resonant circuit. When the resonance goes into steady state, the voltage shows an obvious periodicity. Compared with the second stage, the amplitude of line overvoltage is reduced.

Considering the higher voltage amplitude and longer duration, voltage in the first stage and second stage demand more attention. In this paper, the maximum values of the first and second stages are named V_{1max} and V_{2max}.

III. MATH INFLUENCE FACTORS

A. LIGHTNING STRIKE TIME

According to formula (6), even in the time domain steady state, the voltage waveform is closely related to the lightning strike time. In the transient process, the impact of lightning moment will be more complex. In order to study the influence of lightning strike time on overvoltage, a simulation of lightning strike occurring in the system power supply phase 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° is carried out. The lightning current amplitude is 5 kA and Tail Time to Half Value th is 50 μs. Other parameters are consistent with that in the second section.

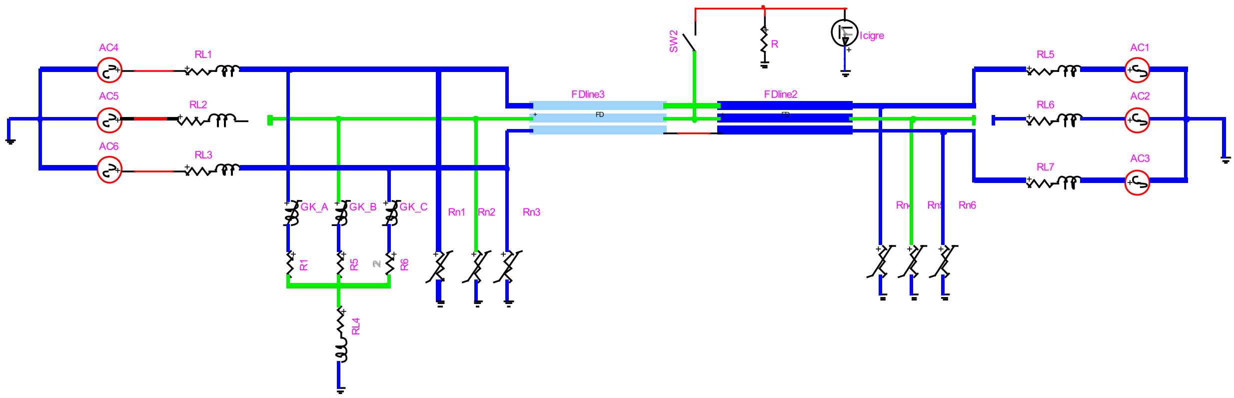

FIGURE 4. Simulation model.

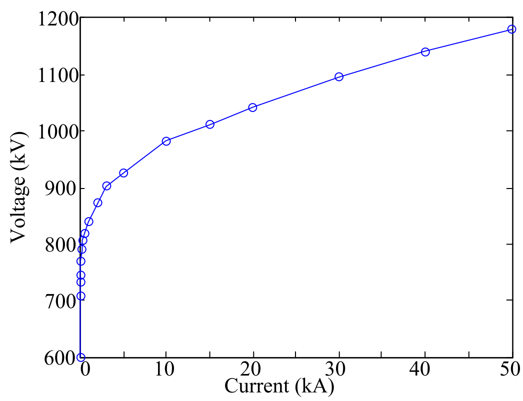

FIGURE 5. V-I characteristics of 500 kV arrester.

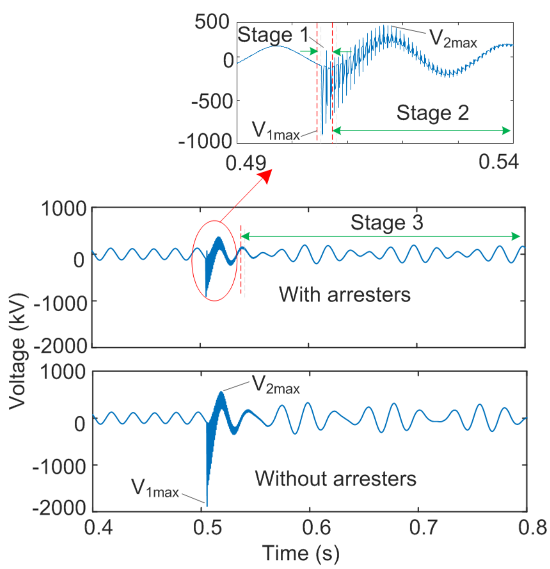

FIGURE 6. Voltage waveform using temporary analysis.

The relationship between voltage amplitude and lightning strike time is shown in Figure 7. The voltage amplitude is periodic. Figure 8 shows the voltage waveform when lightning strike occurs in the system power supply phase 0°, 90° and 180°. Due to the negative polarity of lightning strike, V_{1max} reaches its minimum at 90° and maximum at 270°. For V_{2max}, It has a maximum at 180°.

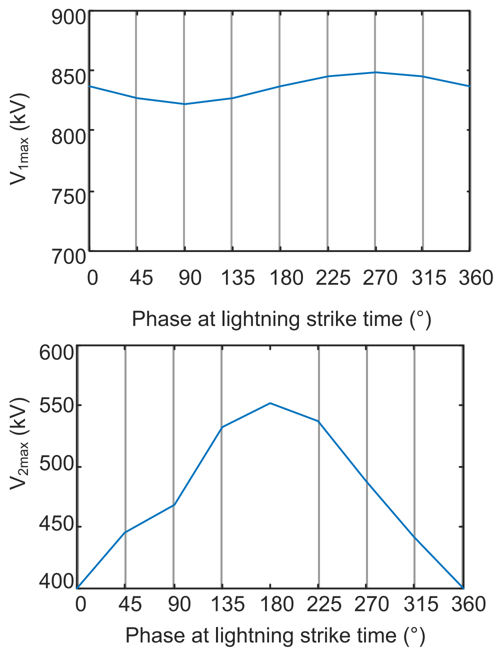

FIGURE 7. Relationship between voltage amplitude and lightning strike time.

B. LIGHTNING CURRENT WAVEFORM PARAMETERS

Lightning current waveform parameters in IEC 62305:2010 include current amplitude, front time, tail time to half value, etc. The main parameter affecting V_{1max} is the amplitude of lightning current. According to formula (2), it is the lightning energy that affects the later resonant voltage. The main parameters involved are current amplitude and tail time to half value.

When analyzing the impact of lightning duration, the current amplitude is set to 5 kA and the tail time to half value ranges from 50 μs to 450 μs. When analyzing the influence

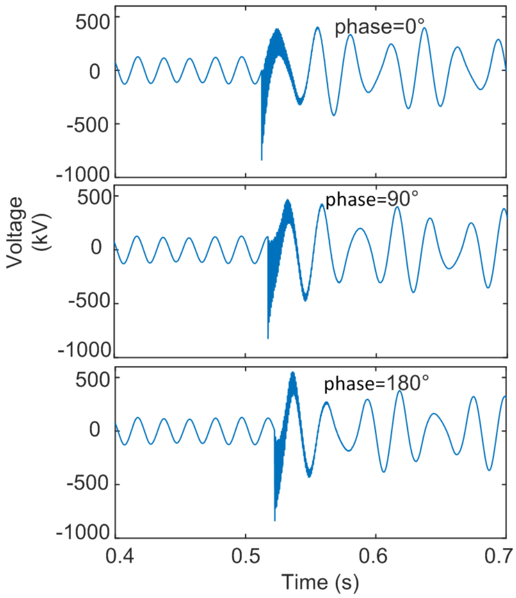

FIGURE 8. Voltage waveform with different lightning strike time.

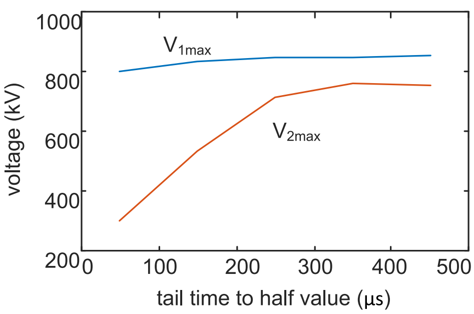

FIGURE 9. Relationship between voltage amplitude and tail time to half value.

of lightning current amplitude, the tail time to half value is set to 250 μs, and the current amplitude ranges from 5 kA to 20 kA. Lightning strike occurs in the system power supply phase 180°. Other parameters are consistent with the second section.

The relationship between voltage and tail time to half value th is shown in Figure 9. V_{1max} is almost independent of th. The longer the duration of lightning, the greater the energy injected into the resonant circuit and the higher the voltage amplitude. Due to the existence of arrester, part of the lightning energy does not enter the resonant circuit. Figure 10 shows the voltage waveform when th is 50 μs, 250 μs and 500 μs. According to CIGRE technical brochure [13], the median value of t_h is 30.2 μs. This statistical data shows that most of the subsequent lightning strikes are unlikely to cause resonance. However, in the areas prone to lightning strikes, with the increase in the number of lightning strikes, the possibility of resonance increases.

In addition, it can be seen that the longer the duration is, the smoother the voltage curve is, and the shorter the

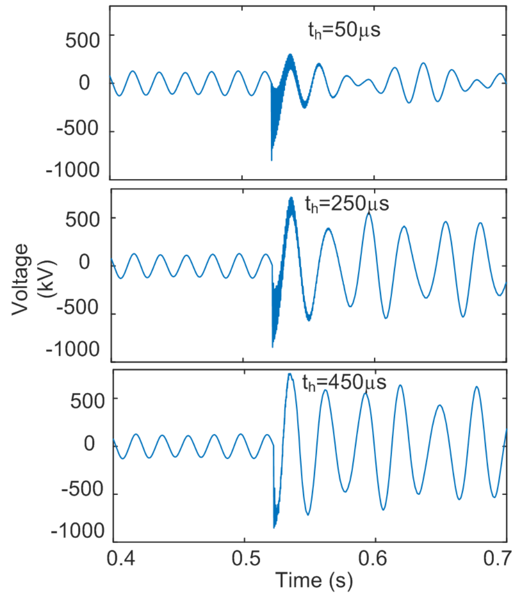

FIGURE 10. Voltage waveform with different tail time to half value.

time of lightning energy conversion to resonant circuit is. This is because the lightning energy mainly flows into the reactor in the form of current. The wider the waveform of lightning current is, the lower the high frequency component is, and the less energy is reflected back to the line each time.

The relationship between voltage and lightning current amplitude is shown in Figure 11. V_{1max} increases with the increase of lightning current amplitude. However, V_{2max} decreases with the increase of lightning current. This is because the arrester releases lightning energy, as shown in Figure 12. Under the condition of the same duration, the higher the amplitude of lightning current, the more energy released by the arrester, and the less energy converted to the resonant circuit. Figure 13 shows the voltage waveform when amplitude is 5 kA, 10 kA and 15 kA.

Although corona loss has an influence on the waveform of overvoltage rising part, V_{1max} is actually limited by the residual voltage of arrester. The distortion of lightning overvoltage waveform has little effect on V_{1max}. In terms of energy loss, the resistance loss effect of long-distance transmission line is more obvious than that of corona effect. Further, resistance loss is already reflected in the model. V_{2max} is also less affected by corona loss. In addition, the accuracy of corona model depends on experiments and is affected by many factors. In view of the above reasons, the corona loss is not take into account in the model.

C. SUBSEQUENT LIGHTNING STRIKE

According to the CIGRE report, the time interval between two subsequent lightning strikes may be very short, as short as 1ms. In view of the low probability of multiple return strikes within a few microseconds, the case of two successive strikes are studied. The current amplitude is set to 5 kA and tail time

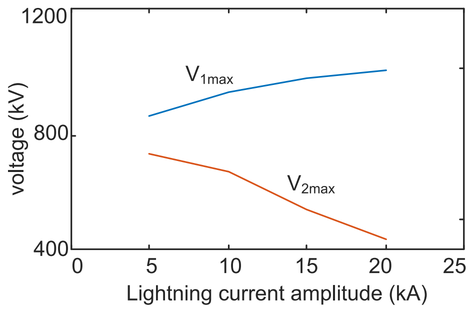

FIGURE 11. Relationship between voltage amplitude and lightning current amplitude.

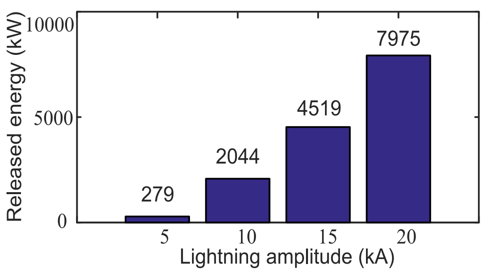

FIGURE 12. Relationship between lightning current amplitude and released energy.

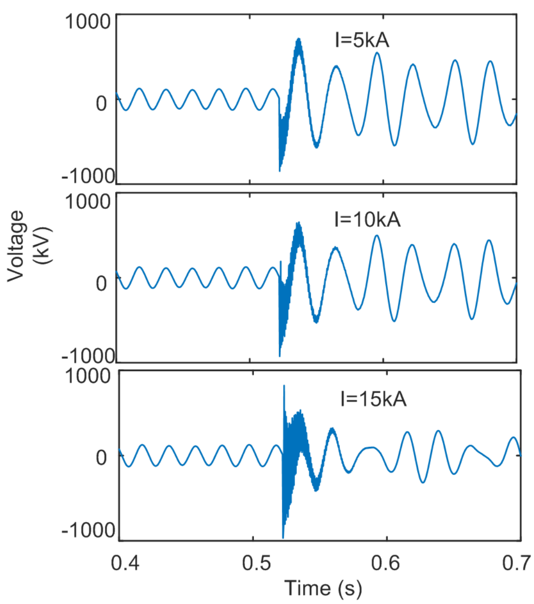

FIGURE 13. Voltage waveform with different lightning current amplitudes.

to half value is set to 150 μs. The interstroke interval ranges from 1ms to 10 ms.

The relationship between voltage and interstroke interval is shown in Figure 14. V_{1max} is the maximum value of the first lightning strike and the second lightning strike. The V_{1max} of the first lightning strike is 837kV. The voltage amplitude of the second lightning strike can be considered as the sum of

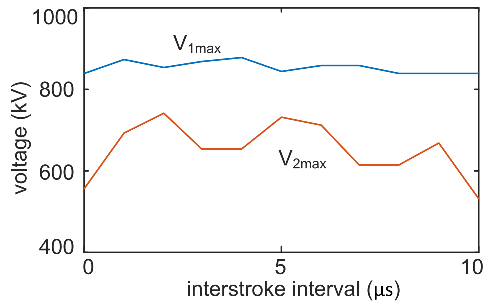

FIGURE 14. Relationship between voltage amplitude and interstroke interval.

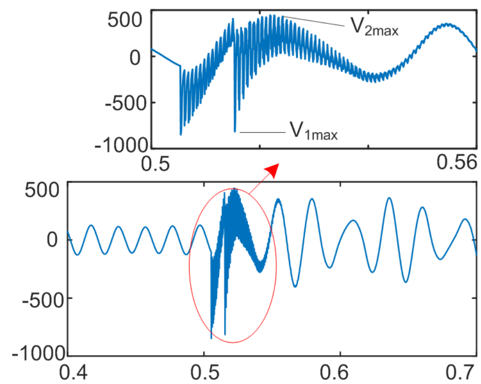

FIGURE 15. Voltage waveform with interstroke interval of 10ms.

lightning overvoltage and current voltage. If the current voltage is positive, the voltage amplitude of the second lightning strike will be smaller than that of the first. The waveform with interstroke interval of 10ms is shown in Figure 15.

V_{2max} did not increase linearly with the injection of the second lightning energy. On the one hand, the time-domain steady-state voltage is related to the time of energy injection. When there are two consecutive lightning strikes, formula (6) can be rewritten as (7). At some intervals, the polarity of U_2 and U_3 is opposite, and V_{2max} will be smaller than that without a second subsequent strikes. On the other hand, the arrester will release some energy of resonance circuit during the second lightning strike, which increases the complexity of voltage change. It is determined that when interstroke interval is very short, such as, less than 2 ms, the lightning energy of the two lightning strikes will be converted to resonance circuit almost at the same time, making V_{2max} larger.

$$\begin{aligned} U(t) &= U_1(t) + U_2(t) + U_3(t) \\ &= \sqrt{2}U_A \sin(\omega_s t)\frac{\omega_s^2 \cdot L \cdot C_{p-p}}{1-\omega_s^2 \cdot L \cdot (C_{p-g}+2C_{p-p})} \\ &\quad + \sqrt{\frac{2E_1}{(2C_{p-p}+C_{p-g})}}\sin(\frac{1}{\sqrt{L(2C_{p-p}+C_{p-g})}}t+\Delta\varphi_1) \end{aligned}$$

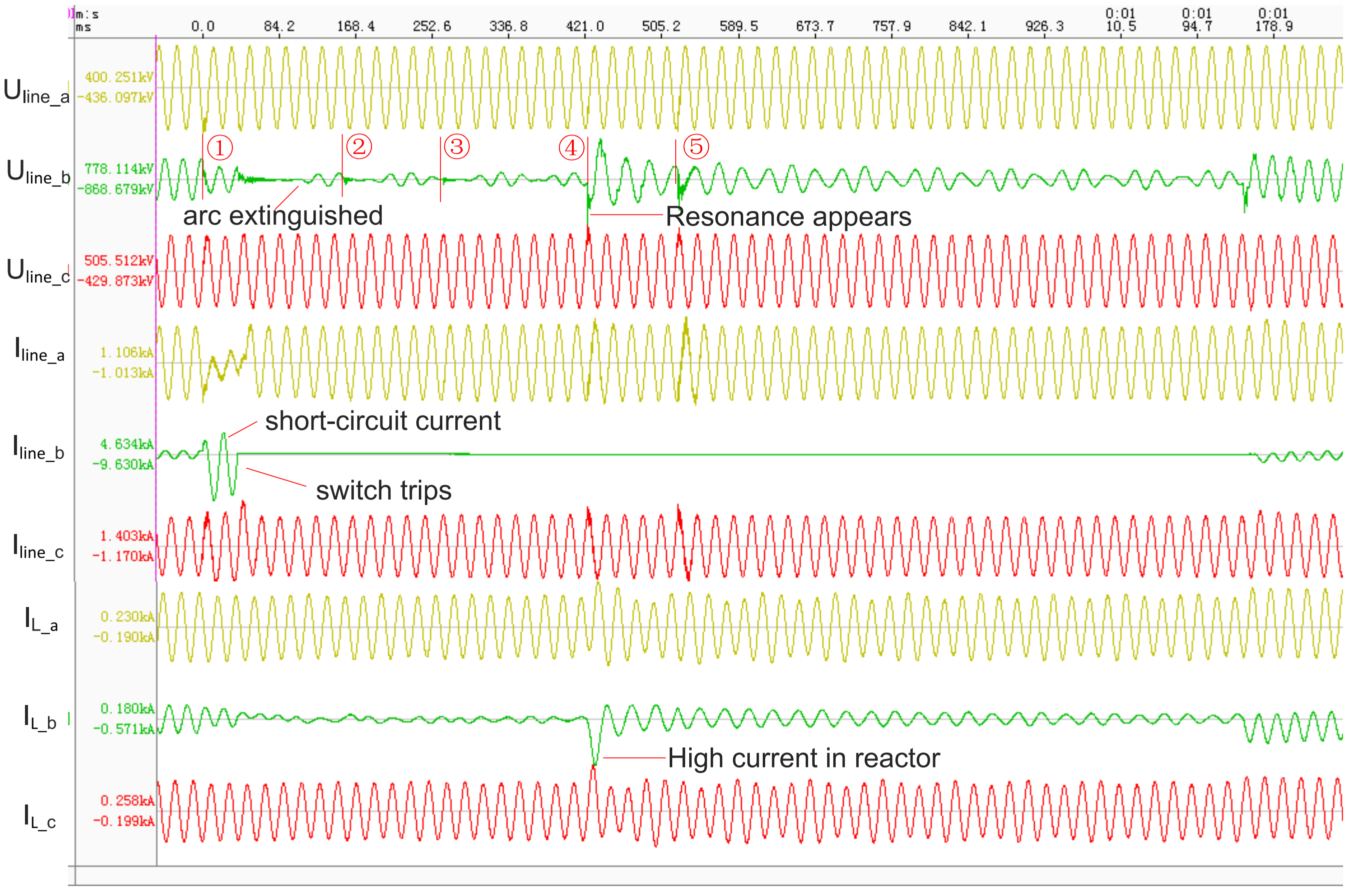

FIGURE 16. Recordings of voltage and current.

$$+\sqrt{\frac{2E_2}{(2C_{p-p}+C_{p-g})}}\sin(\frac{1}{\sqrt{L(2C_{p-p}+C_{p-g})}}t+\Delta\varphi_2) \quad (7)$$

IV. CASE STUDY

This section take a look at a typical case. A 500 kV transmission line in China has a total length of 150 km. Shunt reactor and neutral reactor have been installed. The rated reactance of the shunt reactor is 8029 mH, and the rated reactance of neutral reactance is 2866 mH. A lightning trip occurred in In August 7th 2020. According to the Field Recordings, resonance overvoltage occurred during single-phase outage, and large current flowed through the reactor.

Lightning information can be monitored by Lightning Location System (LLS) and Distributed Travelling Wave Location System (DTWLS). LLS can locate a lightning strike by measuring the electromagnetic field at multiple monitoring points, which can provide the lightning current amplitude, lightning strike location and lightning strike time. DTWLS uses the current monitoring device installed on the line for more accurate fault location. Lightning information is shown in Table 1.

The line voltage, line current and shunt inductor current during the trip are shown in Figure 16. When the first lightning struck, the line flashover and large short-circuit current appear. After about 38ms, the B-phase switch tripped and the line voltage dropped to zero. At this time, the arc at the fault point was not extinguished. After 72 ms, the arc at the fault point extinguished and the induced voltage appeared on the line. Overvoltage appeared at the time of the fourth strike. The negative peak value was 868 kV and the positive peak value was 778 kV. Looking deeper into the voltage wave, a few peaks appeared just around the moment of every lightning strike. Also, the high current of phase B high reactance appeared about 10 ms after the fourth lightning strike.

TABLE 1. Lightning strikes information.

No.	Strike time	Amplitude (kA)	Tower
1	05:11:48 418μs	16.4	#170
2	05:11:48 573μs	18.9	#170
3	05:11:48 68μs	9.9	#170
4	05:11:48 841μs	6.8	#170
5	05:11:48 941μs	8.6	#170

According to the consistency between the time of lightning strike and the time of voltage waveform change, the fact of resonance induced by lightning strike can be confirmed.

The second and third subsequent strikes did not cause resonance overvoltage, which was related to the energy of lightning. According to the analysis in Section 3.2, a lightning strike with low amplitude and long duration has larger energy and is less released by the arrester, which is more likely to cause resonance. The parameters of lightning current are uncertain, so there is randomness in resonance. The sampling rate of field recording was 5000 Hz, which resulted in the measurement error of lightning overvoltage peak value V_{1max}. The measurement of V_{2max} is considered to be close to the real value. This kind of overvoltage close to power frequency is a rigorous test for the energy holding of arrester. In fact, there have been several lightning arrester explosion failures in this kind of fault. In addition, the shunt reactor works on its saturation region at the initial stage of resonance, and is at risk of damage.

V. CONCLUSION

This paper introduces a kind of resonance phenomenon of transmission line with shunt reactor caused by lightning strike. The resonance mechanism is revealed in steady state and transient state. The influencing factors of resonant overvoltage are studied, and a typical overvoltage case is analyzed. The conclusions are as follows.

1) Even if the parameter optimization configuration of shunt reactor and neutral reactor can avoid resonance under the system power supply, lightning can still cause resonance. During uneven open-phase conditions, the resonant circuit gain energy when a lightning strikes the tripping phase line.

2) The resonant transient process can be divided into three stages. The first stage is the first few microseconds, in which the voltage on the line is lightning overvoltage. In the second stage, the lightning energy is gradually released to the energy storage element of the resonant circuit. The overvoltage on the line is composed of lightning overvoltage and harmonic overvoltage, characterized by high amplitude and wide waveform. In the third stage, the energy of lightning current has been completely released into the resonant circuit, and the overvoltage is resonant overvoltage with a lower amplitude.

3) The voltage amplitude V_{1max} of the first stage is mainly affected by the lightning current amplitude. The main factors affecting the voltage amplitude V_{2max} in the second stage are lightning strike time, lightning current waveform parameters and subsequent lightning strike. In view of the uncertainty of the above factors, the generation of high amplitude resonant overvoltage is random. However, it is highly probable for multiple lightning strikes to occur. When there are many lightning strikes, resonance overvoltage can't be clearly neglected.

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XIAO LEI was born in Dazhou, Sichuan, China, in 1988. He received the B.S. and Ph.D. degrees from Chongqing University, China, in 2009 and 2014, respectively. Since 2014, he has been a Senior Electrical Engineer with State Grid Sichuan Electric Power Research Institute. His research interests include overvoltage analysis, lightning process and protection, HVDC operation and maintenance, and transmission line disaster prevention and smart grid.

TAO CUI was born in Mianyang, Sichuan, China, in 1985. She received the B.S. and M.S. degrees from Huazhong University of Science and Technology, China, in 2007 and 2009, respectively. Since 2013, she has been a Senior Electrical Engineer with State Grid Sichuan Electric Power Research Institute. Her research interests include overvoltage analysis, lightning process and protection, neutral grounding, and transmission line disaster prevention.

XIAOHUI WU was born in Zizhong, Sichuan, China, in 1974. He received the B.S. degree from Shanghai Jiao Tong University, China, in 1996. He is currently a Senior Electrical Engineer with State Grid Sichuan Electric Power Company. He has been working in the research of power equipment operation and maintenance for 20 years.

HONG ZENG was born in Chengdu, Sichuan, China, in 1968. He received the B.S. degree from the Open University of Sichuan, China, in 2009. He has been working as a Senior Electrical Engineer with State Grid Sichuan Electric Power Research Institute, since 2000. His research interests include high voltage test technology, overvoltage analysis, cable test and fault diagnosis, and transmission line disaster prevention and smart grid.

QIANG LIU was born in Zigong, Sichuan, China, in 1987. He received the bachelor's and master's degrees from Xi'an Jiaotong University, China, in 2010 and 2012, respectively. Since 2012, he has been a Senior Electrical Engineer with State Grid Sichuan Electric Power Research Institute. His research interests include overvoltage analysis, lightning protection, and grounding technology.

LINHUAN LI was born in Dazhou, Sichuan, China, in 1991. She received the B.S. degree from China University of Mining and Technology, in 2012, and the M.S. degree from China University of Petroleum, in 2015. Since 2015, she has been a Senior Electrical Engineer with State Grid Sichuan Electric Measurement Center. Her research interests include quality supervision and on-site fault analysis and treatment of intelligent watt-hour meter, and acquisition terminal and communication unit.