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Protective effect of compressing arc extinguishing lightning protection device on superimposed lightning strikes①

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Abstract

Traditional lightning protection measures can not solve the problem of superimposed lightning strikes. This paper presents a compressing arc extinguishing lightning protection device, which can solve the problem of superimposed lightning strikes. This device can extinguish the power frequency continuous current arc quickly in 1 – 2 ms. It is far less than the response time of relay protection, which can avoid lightning trips and improve the reliability of power supply. The computer simulation and engineering practice show that the compressing arc extinguishing device has good protection effect on superimposed lightning strikes.

Key words: compressing arc extinguishing, superimposed lightning strike, simulation, lightning trip, power frequency continuous

0 Introduction

According to the statistics, the lightning accident is a common serious accident in the power system, and relevant statistics show that the number of trips caused by lightning strikes on transmission lines accounts for 40% – 70% of the total number of trips[1-2]. The lightning trip has become an important factor threatening the safe and stable operation of power grid.

At present, China's wind farms adopt 35 kV line for power transmission. Different from 35 kV power distribution lines in the traditional power systems, overhead ground wires are installed in all lines of wind farm in structural design. In order to avoid lightning damages, a large sum of money has been spent on the traditional lightning protection measures, such as strengthening insulation, reducing tower grounding resistance, installing double overhead ground wires and installing line lightning arresters. However, the trip accidents caused by lightning still account for more than 76% of the wind farm accidents[3], so the traditional lightning protection measures cannot fundamentally solve the problem of the lightning trips.

According to the trip statistics of a 25 kV high-speed railway line from 2015 to 2017, lightning strike is the main trip accidents of reason for the high-speed railway line.

One of the main reasons for the frequent lightning trip accidents is that the traditional lightning protection measures cannot cope with the superimposed lightning strikes. According to the International Conference on Large Grid (CIGRE)[4], more than 75% of the lightning strikes are superimposed lightning strikes. Superimposed lightning strikes include multiple return strokes with discharge interval in microseconds and repeated lightning strikes in milliseconds. The superimposed lightning strikes are very harmful. The superimposed lightning strikes present the superposition of current and lead to the superposition of overvoltage. The insulation requirements are higher in this case. However, the result of one-sided strengthening insulation is high-cost and poor-effect. Currently, there is no consideration for protecting the superimposed lightning strikes in the design of arresters[5]. None of the existing lightning rules and theories deals with the protection against the superimposed lightnings.

Currently, there are no protective devices against superimposed lightning strikes at home and abroad, and there are no relevant analytical articles. In the high-voltage team, the articles on protection against superimposed lightning strikes are only limited to solid phase arc extinguishing devices of 110 kV and above[6]. There are no articles on superimposed lightning protection on high voltage distribution lines of 35 kV and be-

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low. All the traditional lightning protection measures have great shortcomings[7], and hardly play any role in protecting against superimposed lightning strikes.

The high-voltage team where the author works has developed a new lightning protection product based on a brand new concept, namely compressing arc extinguishing lightning protection device[8], which has been successfully applied in the distribution network of 35 kV and lower voltage grades. The compressing arc extinguishing device realizes the protection against the superimposed lightning strikes, and fundamentally solves the problem of the lightning trip.

1 Compressing arc extinguishing lightning protection device

The compressing arc extinguishing lightning protection device[8] is applied to the high-speed railway lines and transmission lines of 10 – 35 kV distribution network (Fig. 1). When the transmission line is struck by the lightning, the lightning overvoltage generated will first break the gap of the insulator string in parallel, and the lightning current will discharge into the earth across the gap. At the same time, the compressing arc extinguishing device starts to work quickly, the high-speed airflow generated by the device quickly extinguishes the initial power frequency continuous current, completely blocking the power frequency arc construction process.

Fig. 1 On-site installation picture of compressing arc-extinguishing device

Fig. 2 is the schematic diagram of compressing arc extinguishing device. Fig. 3 is the schematic diagram of overall space arc extinguishing structure. The whole arc extinguishing structure is composed of a series of arc extinguishing compressing tubes, which are arranged in spiral. The compressing tube has a very small diameter and is made of rigid material that can withstand the high temperature of the arc.

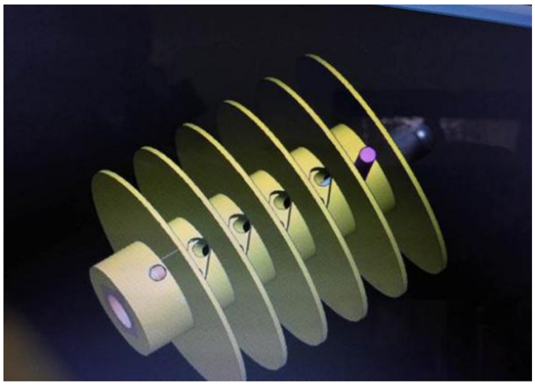


Fig. 2 Schematic diagram of compressing arc extinguishing lightning protection device

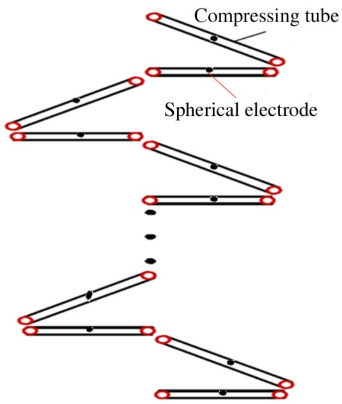


Fig. 3 The spatial structure of compressing arc-extinguishing device

The following is a theoretical analysis of the triple compression effect of the compressing arc extinguishing device on the arc through its own unique structure. Simulation was performed to verify the protective effect of the compressing arc extinguishing device against superimposed lightning strikes. Then, the arc extinguishing capability of the compressed arc extinguishing device was verified by the high-current arc extinguishing experiment. The application effect of compressing arc extinguishing device in engineering practice is shown. On the basis of the above analysis, the paper summarizes the main innovation points.

2 The compression effect of arc

The diameter of the arc is compressed and becomes smaller, which is called the compression effect of the arc. The arc in the tube is mainly compressed in the following three ways[9].

(1) The mechanical compression. The cold passage wall is used to restrict and compress arc column, so that the diameter of arc column is reduced and the pressure is increased.

(2) The self-magnetic compression. Refer to the compression force caused by the arc current and its own magnetic field. If the arc column is considered to be composed of numerous small currents, each small current is subjected to a Lorentz force. The direction of these Lorentz forces is mutual attraction and pointing to the center of the arc column (Fig. 4.), and the diameter of the arc column is reduced by this magnetic compression force. The pressure equation satisfied is $\Delta P_0 = \frac{5}{3}\frac{\mu_0}{4\pi}\frac{I^2}{\pi r_*^2} = \Delta P_{max}$. Here, ΔP_0 and ΔP_{max} refer to the variation of pressure, I refers to the arc current, and μ_0 refers to the permeability the medium. r_* is the radius of the arc.

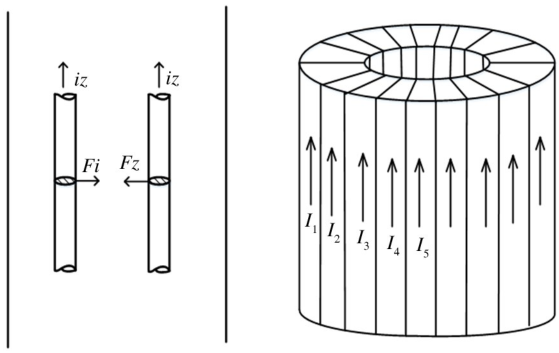


Fig. 4 Schematic diagram of arc's self-magnetic compression effect

It can be seen from the expression that the pressure P of the self-magnetic compression is proportional to the square of arc current I and inversely proportional to the square of the arc radius. The decrease of arc column diameter will lead to the enhancement of self-magnetic compression and further increase the temperature of arc center.

(3) The fluid compression. The arc column diameter is reduced by air blowing through the arc column longitudinally or horizontally.

In engineering practice, when the gap of the compressing lightning protection device is broken down by the impulse voltage, the power frequency continuous arc will be generated, and the power frequency continuous arc will be subjected to extreme compression effect in each compressing tube.

In the process of arc compression, the arc column is subjected to radial pressure of mechanical and self-magnetic compression. At this time, the cold air around the conductive pole at the end of the tube will be sucked into the arc column in large quantities, and a large amount of air will accumulate in the compressing tube. This phenomenon is called magnetic suction phenomenon. Meanwhile, in the process of arc compression, the arc column in the compressing tube develops into a high temperature heat source. The air in each compressing tube is heated by a high temperature heat source and expands. The expanded air generates a longitudinal airflow, which accelerates the arc movement and spews out at a high speed along both ends (see Fig. 5).

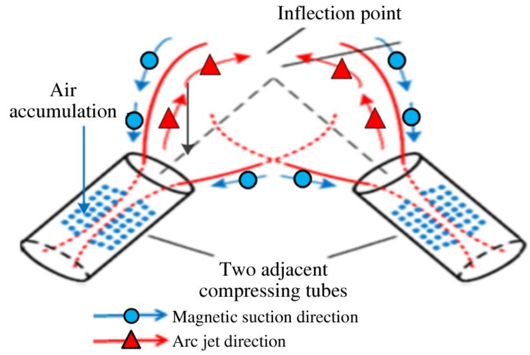


Fig. 5 Arc-column jet hedging between adjacent tubes

The maximum velocity of the arc at inflection point can be expressed as $V_{max} = \sqrt{\frac{2p_1}{\rho}}$ (p_1 is pressure, ρ is density) according to the data in Ref. [10], the maximum velocity can be obtained as hundreds of meters per second.

Under the action of longitudinal air flow, the arc current will decrease greatly, and the break point of the arc current will appear at the abrupt inflection point. Each compression tube contains only isolated energy segmental arc column, and the energy of segmental arc gradually disappears. In a very short time, the power frequency continuous current is completely interrupted, and the whole arc extinguishing process is completed.

The protection effect of compressing arc extinguishing device against superimposed lightning strikes will be analyzed in detail through simulation below. It is assumed that arc building process of power frequency occurs after every lightning strike.

3 The simulation analysis

The arc temperature is the basic basis to measure whether the arc is extinguished. If the arc temperature is less than 3000 – 4000 K, the arc in the compressing tube can be judged to have been extinguished[11-12].

Fluent software[13] was used to carry out geometric modeling and simulation calculation of the compressing tube in the compressing lightning protection device, and the cloud diagram of temperature field and pressure field changes of arc coupled airflow was obtained, further obtaining the internal pressure, temperature, speed and other data of the device during operation. These data serve as a prerequisite for further analysis of the device's response to superimposed lightning strikes.

3.1 Geometric model and simulation model

According to the arc compression effect and magnetic suction phenomenon, the geometric model of two compressing tubes with infection point of 90 degrees is drawn, as shown in Fig. 6. According to the phenomenon of magnetic suction and the influence of air flow on arc longitudinal blowing, the geometric model has five air inlets, among which inlet 1 reflects the influence of magnetic suction air on the arc, and inlet 2, 3, 4 and 5 are used to simulate the influence of air flow on arc. The end of the compressing tube is a spherical electrode. The air temperature is set at 300 K and the temperature of the power frequency continuous arc is set at 20 000 K. It is assumed that the temperature of the power frequency continuous arc formed is the same after each superimposed lightning strike.

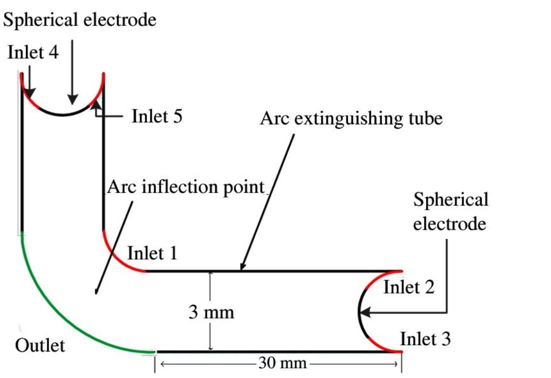


Fig. 6 Geometric model of compressing tube at inflection point

The simulation model was drawn with Gambit software, and the quadrilateral grid structure was adopted, as shown in Fig. 7.

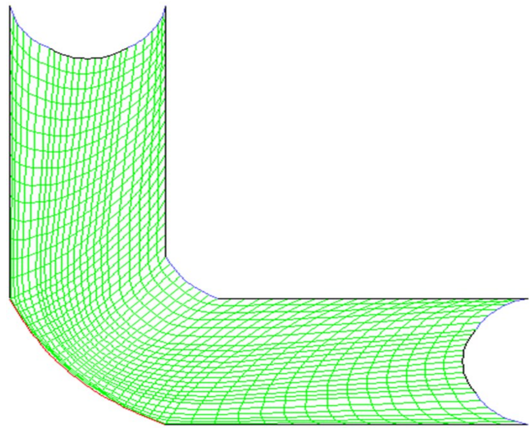


Fig. 7 Geometric simulation model of compressing arc extinguishing tube

3.2 The simulation process

In this process, there is a total of 1 main lightning strike ($t = 0$ ms), 2 return strokes (at $t = 0.11$ ms, $t = 0.26$ ms) and 1 repeated lightning strike (at $t = 2.01$ ms). After each lightning strike, the arc construction process of power frequency occurs, and a total of 4 power frequency arc construction processes take place. Each jet air completely blows the initial power frequency continuous arc. The simulated power frequency continuous current is about 10 - 20 kA, actually the power frequency continuous current which is extinguished in the compressing arc extinguishing device is far less than this value.

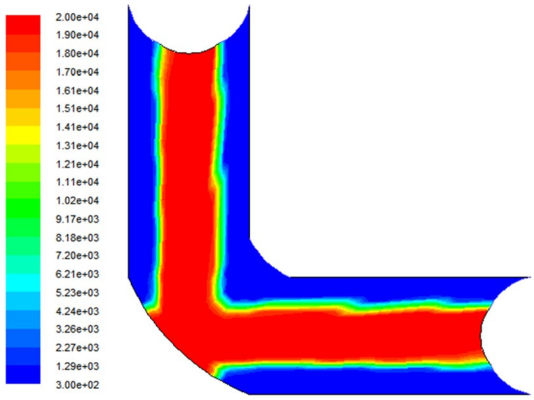
Fig. 8(a) - Fig. 8(k) show the temperature change in the compressing tube, and Fig. 9 shows the average temperature change curve at the outlet of the inflection point of the compression tube. According to the basic physical properties of the arc, when the temperature drops below 3000 - 4000 K, the arc can be judged to have been extinguished.

3.3 The analysis of simulation

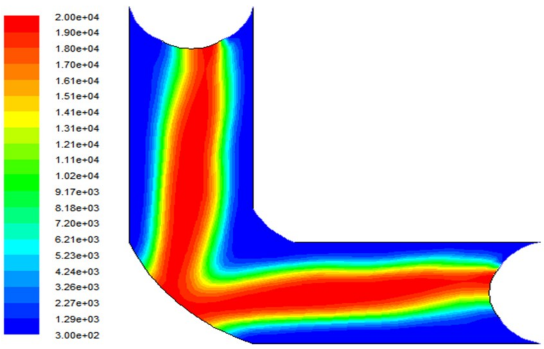
As can be seen from the temperature variation diagram in the compressing tube, during the first 2 ms, 1 main lightning strike and 2 return strokes occurred, and 3 power-frequency arc building processes occurred, respectively at $t = 0$ ms, $t = 0.11$ ms and $t = 0.26$ ms. When $t = 2$ ms, the goal of completely extinguishing the arc can be achieved, as shown in Fig. 8(a) - Fig. 8(g). In the temperature curve of Fig. 9, at the moment $t = 2$ ms, the average temperature at the outlet of the two compressing tubes had dropped below 3000 K, and the average temperature in the compressing tube is much lower than 3000 K. According to the temperature criterion of arc extinction, the arc had been extinguished.

A repeated lightning occurs at $t = 2.01$ ms, and the power frequency arc is extinguished again at $t = 4$ ms, as shown in Fig. 8(h) - Fig. 8(k). Theoretically speaking, through many simulation experiments, the compressing arc extinguishing device can protect against the repeated lightnings and return strokes for countless times.

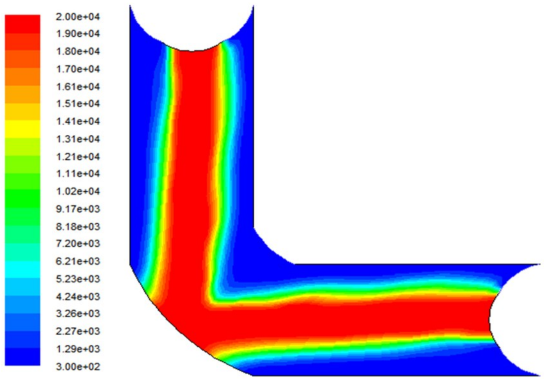
The time required for each arc extinction is about 2 ms, which is far less than the relay protection response time (more than 20 ms)[14], to avoid the occurrence of lightning trip accidents.



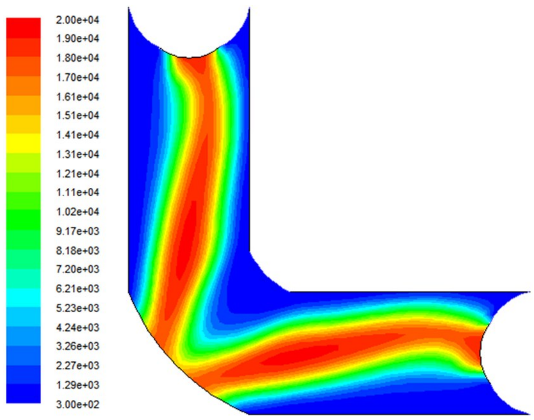
(a) At $t = 0$ ms. An power frequency current arc occurs when lightning strikes (unit: K)



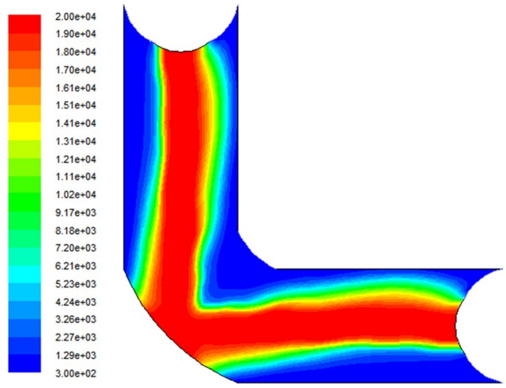
(b) At $t = 0.1$ ms. The arc is compressed and the air blows the arc (unit: K)



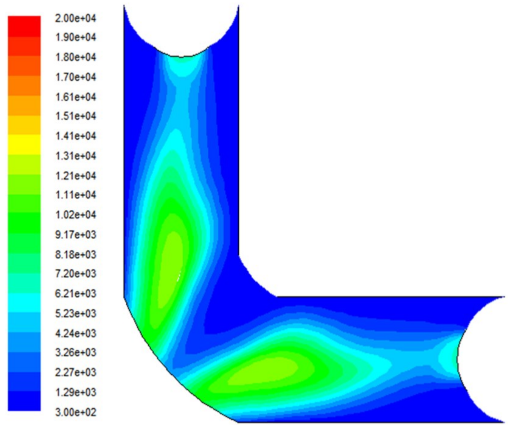
(c) At $t = 0.11$ ms. The first return stroke occurs and the power frequency arc appears again (unit: K)



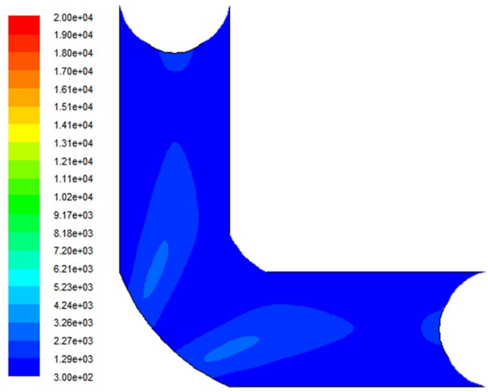
(d) At $t = 0.25$ ms. The arc is compressed and the air is blowing the arc (unit: K)



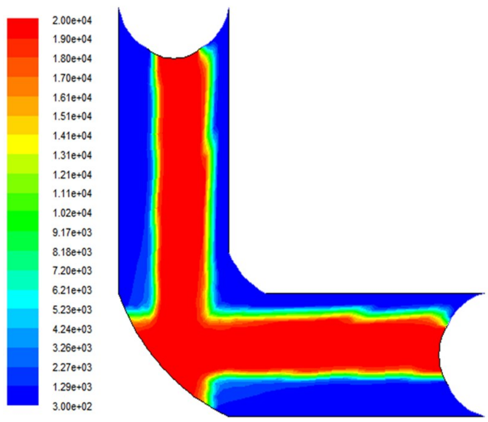
(e) At $t = 0.26$ ms. The second return stroke occurs and the power frequency arc appears again (unit: K)



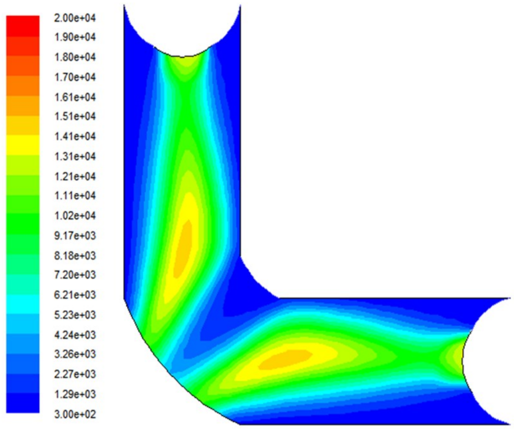
(f) At $t = 1.0$ ms. The phenomenon of air blowing is very obvious (unit: K)



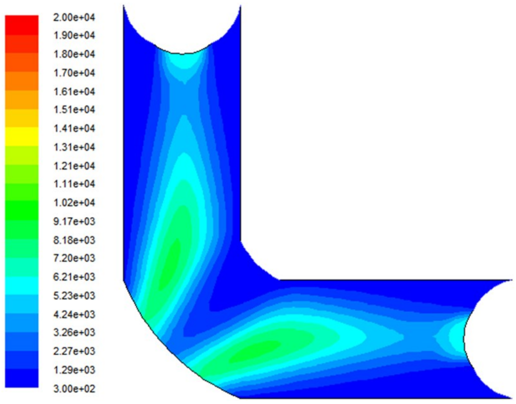
(g) At $t = 2.0$ ms. The arc was completely extinguished (unit: K)



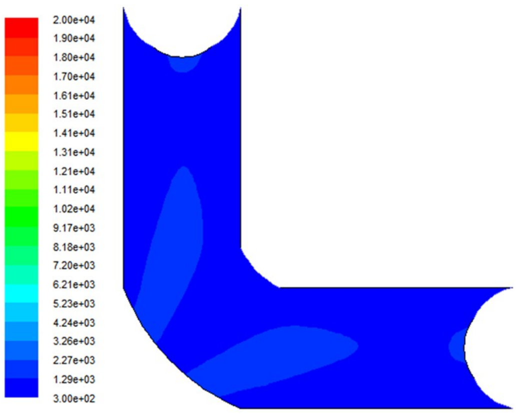
(h) At $t = 2.01$ ms. A repeated lightning strike occurs while thecompressing arc-extinguishing device is triggered again (unit: K)



(i) At $t = 2.5$ ms. The phenomenon of air blowing is very obvious (unit: K)



(j) At $t = 3.0$ ms (unit: K)



(k) At $t = 4.0$ ms. The arc was completely extinguished (unit: K)

Fig. 8 Temperature change in the compressing tube

3.4 Experimental verification

Because the time interval of superimposed lightning strikes is in milliseconds or microseconds, the protection experiments against the superimposed lightning strikes cannot be completed in high voltage laboratories at home and abroad at present. However, a single current arc extinguishing experiment can be conducted to verify the arc extinguishing ability of the compressing arc extinguishing device and obtain the arc extinguishing time of the compressing arc extinguishing device.

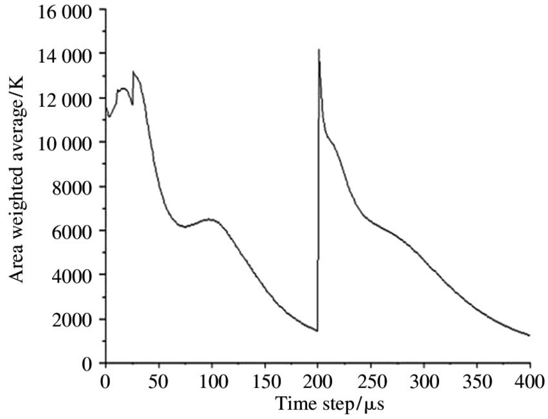
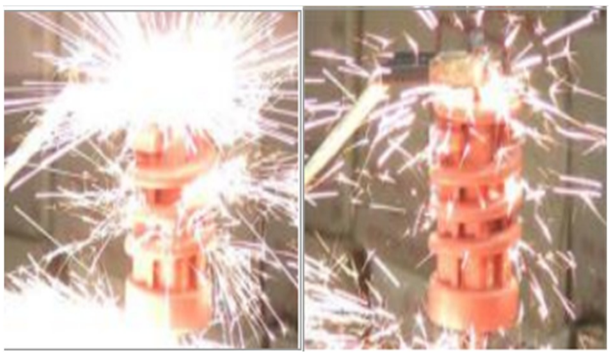
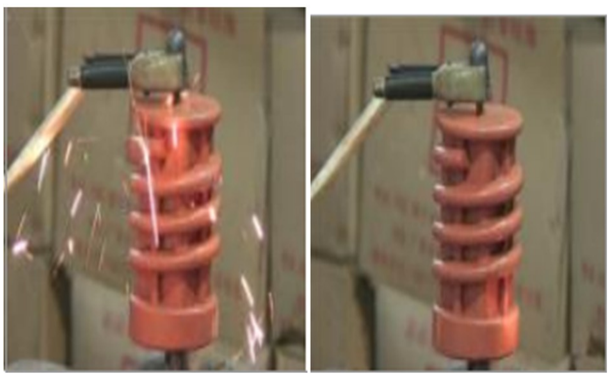


Fig. 9 The average temperature curve at the outlet of the two arc extinguishing tubes

During the whole experiment, the current amplitude of the arc reached 18 kA. Since the experimental site does not have the condition to trigger by lightning impulse wave, 0.01 mm fuse was used for arc guiding. Arc extinction time is 1.5 ms, and reignition will not occur, as shown in the Fig. 10(a) – Fig. 10(d) below. The arc extinguishing experiments were carried out hundreds of times, and the compressing arc extinguishing device worked normally and effectively.



(a) $t = 0.01$ ms (b) $t = 0.1$ ms



(c) $t = 0.5$ ms (d) $t = 1.5$ ms

Fig. 10 High-current arc-extinguishing experiment

In this single high-current arc extinguishing experiment, the arc extinguishing process diagram (Fig. 10(a) – Fig. 10(d)) shot by high-speed camera shows that the arc column loses the external injected energy and forms energy segmentation. It not only greatly accelerates the rate of energy dissipation, but also completely avoids the possibility of reignition. The whole arc extinguishing process is less than 1.5 ms, slightly lower than the simulation result and far less than the relay protection response time[14-15], which fully verifies the effectiveness of the compressing arc extinguishing device.

4 The practical operation effect

Currently, the compressing arc extinguishing devices can only be installed in distribution lines below 35 kV and high-speed railway lines. The compressing arc extinguishing device weighs only 0.3 kg and is very easy to install and maintain (Fig. 1). In a 10 kV transmission line in Guangxi, China, after installing the device on every pole in January 2016 (Fig. 1), the device can effectively protect against the superimposed lightning strikes, and the lightning trip rate tends to be almost zero (as shown in Table 1), which proves the effectiveness of the device and the excellent performance of the arc extinguishing, and greatly improves the power supply reliability of high-voltage transmission lines.

Another 10 kV transmission line in Guangxi, China, is located in a region with strong and multiple thunderstorms. The average annual thunderstorm day reaches 100 days, and the average annual lightning trip rate is more than 40 times before the compressing arc extinguishing device is installed. At the end of 2015, after installing the device on every pole in the whole line, as shown in Fig. 11 below, no trip accident occurred any more.

Table 1 User reports

Line name	A 10 kV line in Guangxi power grid, China
Gap device type	Compressing arc extinguishing lightning protection device
Before installation (lightning strike situation and loss)	The line is located in areas of strong and many lightning strikes, with 120 thunderstorm days per year. About 50 lightning trips are made each year, resulting in huge losses
After installation (lightning strike status)	No lightning trips or lightning accident occurred. The problem of lightning protection was solved

Fig. 11 A 10 kV transmission line with compressing arc extinguishing device in Guangxi, China

5 Conclusions

The compressing arc extinguishing device can effectively protect against the superimposed lightning strikes. Compared with other lightning protection devices, it has great advantages.

The time to extinguish power frequency continuous current arc is about 1-2 ms. Far less than the response time of relay protection, it can realize not tripping when struck by lightning.

Theoretically, the compressing arc extinguishing device is not limited by the number of triggers, and can realize countless arc extinguishing.

The initial investment of the compression arc extinguishing device is relatively high, but in the long run, it is cost-effective.

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