Lightning protection of multi-fracture arc-quenching lightning protection gap for 35 kV distribution lines

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Abstract
Owing to the low insulation level of 35 kV distribution lines, lightning outage accidents and huge economic losses occur frequently. Therefore, a multi-fracture arc-quenching lightning protection gap (MFALPG) for 35 kV distribution lines is developed to ensure the safety and stability of power supply. Here, the principle of MFALPG is presented through the electromagnetic self-contraction effect and qualitative modelling theory. In order to investigate the coupling effect between high-energy compressional waves and arcs, a mathematical model of airflow coupled arc was developed to simulate and analyse the arc-quenching process. Theoretical analysis and simulation results show that the high-energy compressional wave is triggered by the impulse arc rapidly, and the arc conductivity drops abruptly in a short time. Finally, a lightning impulse discharge test and the power frequency withstand voltage test are performed to determine the 35 kV power frequency continuous current interruption test parameters. Under the action of the MFALPG, the entire time of arc duration is less than 3 ms, and reignition phenomenon of the arc is not found after the subsequent power frequency voltage is restored.

1 | INTRODUCTION

As an important issue, the service unavailability caused by lightning often occurs in the power systems, particularly in the mountainous areas where there is a high probability of lightning strike to the power electric network [1]. Since the overall insulation level of the 35 kV distribution network lines is low, when lightning strikes occur, follow-up power frequency arcs may damage electrical equipment such as distribution lines and insulators. A number of studies have showed that lightning protection devices, such as shielding wires and surge arresters, avoid lightning flashovers by maintaining the voltage across insulators on a transmission line below the insulation withstand capability [2–4]. However, due to economic reasons, it may not be possible to equip the line with surge arresters at each transmission structure [4, 5]. Meanwhile, adding surge arresters against direct strokes is difficult because of the high currents, steep rates of rise, and large energy content in lightning flashes [6]. Therefore, for 35 kV distribution network lines, it is urgent to propose new lightning protection measures to effectively protect them.

In order to prevent the outages of covered conductors in distribution system caused by lightning flashes, different technologies and devices have been researched and developed in many countries [7]. Weijiang Chen team analyses the protection principle of installing parallel gaps on lines, designs the series–parallel gap structure of 35 kV line insulators, and calculates the effect of parallel gap on the lightning trip rate of the line, the developed parallel gap lightning protection devices have been widely used, and the operation effect is good [8]. Due to the weak self-extinguishing ability of the parallel gap, when the line is struck by lightning, the parallel gap is prone to a stable power frequency freewheeling arc after the flashover, which causes frequent trips of the line and limits its application [9–11].

In Japan, arcing horns are installed between the two ends of insulators, this method can prevent surface ablation of the...
insulators caused by lightning flash [12]. The principle is to use the electric arc to enter the pipeline, and the arc heats up in the arc extinguishing pipeline, and the organic material in the arc extinguishing pipeline generates high-speed and high-pressure airflow to extinguish the arc [13–16]. Russian scientists Georgij Podporkin developed a special type of self-extinguishing arc clearance to protect insulators from being burnt [17–21]. Russian scientist A.V. Glushenka studied the effect of the energy spent in the discharge gap on the spatiotemporal characteristics of the shock wave, which is extremely important not only for fundamental science, but also for applications [22].

In this article, a 35 kV multi-fracture arc-quenching lightning protection gap (MFAPLG) was presented to reduce the lightning outage rate. Furthermore, we developed a mathematical model of airflow coupled arc to simulate and analyse the arc-quenching process. A 35 kV power frequency continuous current interruption test was performed to investigate the self-extinguishing characteristic of arc under the action of high-energy compressional wave.

2 | OPERATION PRINCIPLE

2.1 | Structure of the MFAPLG

The structural diagram of MFAPLG for 35 kV distribution lines is shown in Figure 1. As presented in the figure, the MFAPLG consists of two arc-quenching gap devices, main gap, and lightning flash electrodes. The arc-quenching gap devices are installed on the grounding tower and 35 kV distribution lines, respectively. Multiple arc-guided electrodes and arc-quenching chambers are placed inside the MFAPLG, which are arranged as a semi-enclosed space to facilitate the generation of high-energy compressional waves to extinguish the arcs.

2.2 | Mechanism of arc compression

Since lightning overvoltage was generated on the distribution lines caused by the lightning flashes, the lightning flashover occurs at main gap. Lightning impulse arc starts to build up, which is compressed in the arc-quenching chamber; meanwhile, the arc will be compressed again due to the self-magnetic compressional effect, and the arc will be extremely compressed. Since the temperature at the centre of the arc radius is the highest, the energy of the impulse arc at this time is more likely to spread to the surrounding cold air. Finally, the high-energy compressional waves are formed and coupled with the arc. The analysis process of arc self-magnetic compression is as follows:

The equilibrium equation of the central strength of the arc column is as follows:

$$\frac{dP}{dr} + j_r \cdot B_\phi = 0,$$

(1)

where $P$ is the radial pressure of arc column, $j_r$ is the axial current density, and $B_\phi$ is the magnetic field strength of the arc column.

Since the arc column is axisymmetric, the ampere law is as follows:

$$\oint B \cdot dl = \mu_0 \sum I,$$

(2)

where $\mu_0$ is the vacuum permeability, $l$ is the integral length of arc column diameter, $\sum I$ is the sum of all currents in closed loop $l$.

The integral path is set as a circle with radius $r$. At this time the magnetic induction intensity $B$ and the integral element length are in the same direction, and $|B| = B_\phi$:

$$B_\phi = \frac{\mu_0}{r} \int_0^r j_r r dr.$$

(3)

The simultaneous Equations (1) and (3) are simplified

$$\frac{dP}{dr} + \frac{\mu_0}{r} \int_0^r j_r r dr = 0,$$

(4)

$$dP = -\mu_0 \left( \frac{j_r}{r} \int_0^r j_r r dr \right) dr,$$

(5)

$$\Delta P(r) = P(r) - P_0 = -\mu_0 \int_0^r \frac{j_r}{r} \int_0^r j_r r dr,$$

(6)

$$j_r = \frac{I}{\pi r_1^2},$$

(7)

$$\Delta P(r) = \frac{\mu_0}{4\pi} \frac{I^2}{r_1^2} \left( 1 - \frac{r^2}{r_1^2} \right),$$

(8)

$$P_{max} = \frac{\mu_0}{4\pi} \frac{I^2}{\mu_1^2 r_1^2}.$$
where \( j_r \) is the current distribution of the arc column, \( I \) is the arc current and \( r_i \) is the arc radius. \( P_0 \) is the pressure at the edge of an arc column, and \( P_{\text{max}} \) is the maximum value of the pressure in the arc-quenching chamber.

The maximum value of the pressure in the arc-quenching chamber is related to the square value of the arc current and arc radius. When the arc is compressed, the arc radius decreases. In addition, the maximum value of the pressure in the arc-quenching chamber increases. The cold air around the arc is heated by the arc column, and strong airflow will be formed to act on the arc. Consequently, the arc energy channel is cut off and the arc is extinguished.

### 2.3 Coupling mechanism of airflow and arc

Since the process of air-coupled arc is complicated, the simplified air-coupled arc control equations are proposed to solve the qualitative analysis of the arc conductivity, temperature, and other parameters in this process. The simplified conditions of the coupling model are as follows: (1) Viscous dissipation term (\( \Phi_{\text{diss}} \)) and gravity are negligible; (2) The stagnation enthalpy can usually be simplified to enthalpy.

#### Arc magnetic fluid model control equations:

**Mass conservation equation:**

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,
\]

where \( \rho \) is the density of arc column; \( \mathbf{v} \) is the airflow velocity.

**Momentum conservation equation:**

\[
\rho \frac{d\mathbf{v}}{dt} = -\nabla P + \mathbf{J} \times \mathbf{B} - \frac{2}{3} \nabla (\mu \text{div} \mathbf{v}) + 2 \text{div} (\mu S),
\]

where \( P \) is the gas pressure; \( \nabla P \) is the pressure gradient; \( \mathbf{J} \) and \( \mathbf{B} \) are the current density and magnetic induction strength; \( \mu \) is the dynamic viscosity coefficient; and \( S \) is the velocity deformation tensor.

**Energy conservation equation:**

\[
\rho \frac{\partial T}{\partial t} = \frac{\partial J}{\partial t} \left( b + \frac{u^2}{2} \right) - \frac{\partial \rho}{\partial t} = \frac{\partial E}{\partial t} \cdot \mathbf{v} + \text{div} (\lambda \text{grad} T) + E \cdot \mathbf{J} - \varepsilon_{\text{rad}} + \Phi_{\text{diss}},
\]

where \( b \) is the enthalpy of the arc field coupled by the airflow; \( \varepsilon_{\text{rad}} \) denotes the ohmic heat effect term generated by the current through the arc; \( \text{div} (\lambda \text{grad} T) \) is the medium thermal conductivity term; and \( \Phi_{\text{diss}} \) is the radiative heat caused by fluid viscosity.

Maxwell's equation:

\[
\nabla \times \mathbf{A} = B \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \nabla \times \mathbf{B} = 0,
\]

where \( \mathbf{A} \) is the magnetic potential.

Ohm's law equation:

\[
J = \sigma E,
\]

where \( \sigma \) is the electrical conductivity.

Gas equation of state:

\[
P = \rho RT,
\]

The boundary layer control equations for the arc column are as follows:

**Mass conservation equation:**

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \frac{1}{r} \frac{\partial (r \rho v_r)}{\partial r} = 0,
\]

where \( v_r \) and \( v_\zeta \) are the radial velocity and the axial velocity, respectively.

**Axial momentum conservation equation:**

\[
\rho \left( v_\zeta \frac{\partial v_\zeta}{\partial \zeta} + v_r \frac{\partial v_r}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \mu r \frac{\partial v_\zeta}{\partial r} \right) = 0,
\]

**Radial momentum conservation equation**

\[
\frac{\partial \rho}{\partial r} + j_r B_\phi = 0,
\]

where \( j_r \) is the radial current density.

**Energy conservation equation:**

\[
\rho \left( v_\zeta \frac{\partial b}{\partial \zeta} + v_r \frac{\partial b}{\partial r} \right) = \sigma E^2 - Q + \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right),
\]

where \( b \) is the enthalpy of arc column; \( \sigma \) is the arc conductivity of the arc; \( Q \) is radiant energy; \( T \) is temperature.

Maxwell equation:

\[
\frac{1}{r} \frac{\partial}{\partial r} (r \Phi_{\phi}) = j_r.
\]

Figure 2 shows variation of arc temperature and current with time under the effect of airflow. It is clear that the arc temperature curve lags behind the arc current curve, because the arc energy transmission process is a continuous process and its value will not mutate. The arc current has a maximum output value of approximately 18kA at \( t = 50 \mu s \), and the arc temperature a maximum output value for the first time at \( t = 300 \mu s \). The arc temperature shows a gradual upward trend from 50 to 300 \( \mu s \), resulting in rapid conversion of arc energy, which affects the arc self-extinguishing behaviour in the arc-quenching chamber. Furthermore, the high-energy compressional waves generated by impulse arc moves toward the exit of the arc-quenching chamber. However, the arc and the high-energy compressional waves are coupled, so the arc current value presents a sharp drop trend during this time period. Since the subsequent power
frequency arc and impulse arc will be coupled and decoupled, the arc temperature will fluctuate many times from 300 to 1500 μs.

To analyse the changing behaviour of subsequent arc current, the amplification curve of the arc current from 400 to 1500 μs is draw in Figure 3. Owing to the subsequent power frequency arc energy injection, the value of arc current did not decay to zero at t = 500 μs, but began to gradually rise, and has an output maximum current for the second time. Meanwhile, as can be seen from Figure 2, the arc temperature increases during this time. It is clear that the arc current growth rate is significantly reduced after 1050 μs. After that, although the arc current increased slowly due to reignition, the peak value of the arc current was less than 20 A, and the arc could not maintain at all. Under strong suppression, the signs of arc reignition are very weak, and the probability of reignition is almost zero. Consequently, the arc current value decreases to zero at t = 1500 μs.

3 SIMULATION OF ARC-QUENCHING PROCESS

The flow control equations are established.

Mass conservation equation:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0, \tag{21}
\]
where \(\rho\) is the density of airflow; \(v\) is the speed of airflow; \(t\) is time.

Momentum conservation equation:
\[
\rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla) v = -\nabla p + J \times B, \tag{22}
\]
where \(p\) is the pressure of airflow; \(T\) is the temperature of airflow; \(J\) is the current density; \(B\) is the magnetic induction intensity.

Energy conservation equation:
\[
\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho H v - \lambda \nabla T') = \frac{\partial p}{\partial t} + J \cdot E - \nabla \cdot F, \tag{23}
\]
where \(E\) is the electric field strength; \(H\) is the enthalpy; \(F\) is radiant energy; \(T\) is the viscous stress tensor.

Current conservation equation:
\[
J = \sigma (E + v \times B), \tag{24}
\]
where \(\sigma\) is the arc conductivity.

Magnetic field equation:
\[
\nabla \times B = \mu_0 J, \tag{25}
\]
\[ \partial_t B + \nabla \times E = 0, \]  

(26)

where \( \mu_0 \) is vacuum permeability.

The structure of simulation model of an arc-quenching chamber (semi-enclosed space) established in COMSOL is shown in Figure 4. The lower part of the structure is the arc entrance, and the upper part is the arc exit. Furthermore, the direction of the arc-quenching airflow outlet is consistent with the direction of the arc outlet. The walls adopt high temperature resistant and insulating materials. The material of electrode is copper, which is of good conductivity.

The simulation results of the temperature field of the arc-coupling airflow during the generation stage of the impulse arc are shown in Figure 5. As can be observed from Figure 5a, the temperature of the arc-quenching chamber increases sharply and the radius of the arc is relatively small. The moment is the early stage of the generation of the impulse arc. The gases in the arc extinguishing chamber are heated by the high temperature. It is clear that the maximum temperature of the arc column centre can reach 35,000 K at \( t = 1 \) \( \mu s \). As seen from Figure 5b, arc radius gradually increases. However, the high-temperature gas mainly gathers at the exit of the arc-quenching chamber from 40 to 100 \( \mu s \), which is shown in Figure 5c and 5d. This is because the arc-quenching airflow is triggered to blow the arc at the initial stage of the impulse arc.

4 | EXPERIMENTAL VERIFICATION

4.1 | Lightning impulse discharge volt-second characteristic test

In order to better perform the power frequency continuous current interruption test, the installation parameters of the MFAPLG must be determined in advance, so a lightning impulse discharge volt-second characteristic test must be performed, which can more comprehensively investigate the protection degree of the MFAPLG to the insulator under the action of impulse voltage. The parameter value of the main gap of the MFAPLG is finally determined by the repeated discharge tests.

Figure 6 shows the impulse voltage test circuit diagram. The rated voltage of the surge voltage generator is 3000 kV, and the rated energy is 675 kJ. The impulse generator can generate standard lightning waves to simulate the impulse arc generation process. The H.V/L.V (High Voltage/Low Voltage) arm capacitance is used to measure the discharge voltage at both ends of the specimen, which can lay the foundation for the subsequent calculation of \( U_{50\%} \) discharge voltage.

Table 1 shows the parameters of IG system. The charging voltage of IG system can be set to conduct repetitive discharge test on the test article; meanwhile, the distance of the main gap
The impulse voltage test circuit diagram is shown in Figure 6. SG, sphere gap; IG, impulse generator; C, capacitor of impulse generator; $R_f$, front resistance; $R_t$, tail resistance; TO, test object; $C_1/C_2$, H.V./L.V arm capacitance; $R$, damping resistance; AS, acquisition device.

The action picture of the MFAPLG in the impulse discharge test is shown in Figure 7. As seen from the figure, the MFAPLG are installed at both ends of the 35 kV composite insulator in parallel. Furthermore, the bottom simulates 35 kV distribution line, and the upper end simulates grounding tower. When the lightning flash occurs, the multi-fracture arc extinguishing device installed on the high-voltage distribution line is first triggered and jet phenomenon appears at the exit of the arc-quenching chamber. At the same time, the impulse arc causes instantaneous heating in the arc-quenching chamber, which in turn causes the air in the arc-quenching chamber to suddenly heat and expand. Since the arc-quenching chamber is a rigid object, the generated high-speed airflow will flow along the axial direction to the outlet. Meanwhile, the arc is segmented into short arcs and the arc fracture begins to form. Consequently, the short arc energy of each arc-quenching chamber is greatly weakened, which eventually leads to the extinguishment of the arc.

The 50% discharge voltage of lightning impulse is determined according to the lifting method mentioned in the national standard GB/T 16927.1. The data in Table 2 are obtained through 30 repetitive lightning impulse discharge tests. And when the main gap distance is 37.6 cm, the success rate of arc path control on the device side reaches 100%. However, when the main gap distance is 39.6 cm, the success rate of arc path control on the device side is less than 40%. Consequently, the parameter value of main gap is finally determined to be 37.6 cm and in the subsequent power frequency continuous current breaking test, the impulse voltage setting value needs to exceed 325.1 kV to ensure that the main gap between the arc-quenching devices is broken down, and the arc flashover path is controlled in the device side.

The $V$–$t$ curves of the insulator and device are shown in Figure 8. As seen from the figure, the blue and red curves represent the amplitude-second characteristic curves of the insulator and the device, respectively. The device plays a certain role in the protection of insulators. The raw test data and test environment parameters are shown in Table 3.
TABLE 3  Data of the volt-second characteristics test

| Test sequence (\(T = 29.2^\circ\text{C}, P = 95.7\text{ kPa}, \) \(RH = 61\%\)) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|---------------------------------------------------------------|----|----|----|----|----|----|----|----|----|
| Insulator Breakdown voltage (kV)                             | 538.6 | 497.4 | 466.2 | 455.3 | 422.9 | 418.3 | 402.6 | 394.6 | 389.3 |
| Breakdown time (\(\mu\text{s}\))                            | 1.64 | 2.60 | 2.76 | 3.15 | 4.07 | 5.01 | 6.05 | 6.52 | 8.26 |
| Device Breakdown voltage (kV)                                | 464.1 | 426.5 | 375.7 | 364.8 | 332.5 | 327.9 | 313.2 | 306.2 | 301.4 |
| Breakdown time (\(\mu\text{s}\))                            | 1.96 | 2.74 | 2.84 | 3.23 | 4.19 | 4.95 | 6.04 | 6.61 | 8.30 |

4.2  Power frequency withstand voltage test

According to the IEC60060-1-2010 standard, the power frequency withstand voltage value of the 35 kV line power frequency continuous current interruption test should be selected as 40.5 kV, so it is necessary to perform a power frequency withstand voltage test, to test the power frequency voltage withstand capability of the MFAPLG.

Figure 9 shows the construction drawing of power frequency withstand voltage test.

Figure 10 shows the industrial frequency withstand voltage test circuit. As seen from the figure, the MFAPLG was subjected to a power frequency voltage of 40.5 kV for 1 min, no power frequency breakdown occurred. Effective verification of the safety of the device applied to 35 kV lines was carried out, and the parameters of subsequent power frequency continuous current interruption test were determined.

Table 4 shows the parameters of TT system. The rated voltage of the industrial frequency test transformer can meet the voltage resistance test voltage required for this test. Table 5 shows the parameters of IG and TT system.

4.3  Power frequency continuous current interruption test

In order to verify the effectiveness of arc-quenching of the MFAPLG, a power frequency continuous current interruption test was performed.

The installation drawing of power frequency continuous current interruption test is shown in Figure 11. The left part of the picture is the power frequency test transformer, the right part is the impulse voltage generator, and the middle part is the 35 kV MFAPLG.

Figure 12 shows the power frequency continuous current interruption test circuit. A number of lightning arresters, protective gaps, capacitors, and inductors are arranged between the power frequency transformer and the impulse voltage generator, which are chosen for overvoltage protection and coupling. The ground wire runs through the current transformer, so that the current can be sensitively detected. The main gap distance is set to 37.6 cm, which is according to measured data of the lightning impulse discharge experiment.
The test process is as follows:

1. Impulse voltage generator and power frequency test transformer parameters are set. The power frequency test transformer is boosted to 40.5 kV for 1 min, which is the test data obtained in the power frequency withstand voltage test.

2. We trigger the impulse voltage generator device after the MFAPLG is subjected to the power frequency voltage for a period of time. Furthermore, the main gap is broken down, and the impulse voltage and the power frequency voltage are coupled to act on the MFAPLG.

3. Oscilloscope is used to record the discharge voltage waveform. We perform grounding operations and observe whether there are signs of damage to the external insulation on the surface of the MFAPLG.

Figures 13 and 14 show the arc voltage waveform in coupling experiment and the arc current waveform, respectively. According to the arc current waveform, the whole arc duration is 3 ms and the arc current amplitude is 2.2 kA. The experiment results show that when the impulse voltage is used in combination with the power frequency voltage for the MFAPLG, the main gap between the devices is broken down, and the voltage value at both ends of the device suddenly decreases. After the arc-quenching mechanism is activated, after 3 ms, the power frequency voltage waveform reappears, which indicates that the arc has been extinguished at this time. During this process, the impulse arc induces high-energy compressional waves to act on the arc in the early stage of the arc. Owing to the space structure design of the arc-quenching chamber, the arc energy channel is cut off. The arc is extinguished and did not rekindle with the effect of the subsequent power frequency voltage.

5 | CONCLUSION

Here, the arc-quenching principle and effectiveness of 35 kV MFAPLG for distribution lines is presented.

1. The counter-blow structure is beneficial for the arc to be cut off. At the same time, it is combined with the main gap to ensure that the device does not break down under the action of the rated power frequency voltage for 35 kV distribution lines.

2. In the power frequency continuous current interruption test, under the action of the self-extinguishing device, the entire time of arc duration was 3 ms, the arc current amplitude is 2.2 kA and the arc did not rekindle with the effect of the subsequent power frequency voltage.

3. The study of the MFAPLG lays the foundation for the subsequent application of the device to 35 kV distribution lines.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (51467002), Doctoral Research Initiation Fund of Guilin University of Technology (GUTQDJJ2018068), and 2020 Guangxi University Middle-aged and Young Teachers’ Basic Research Ability Improvement Project (2020KY06024).
The authors wish to thank the staff of high-voltage laboratory at Guangxi University.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

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How to cite this article: Wu, D., Wang, J.-f.: Lightning protection of multi-fracture arc-quenching lightning protection gap for 35 kV distribution lines. IET Gener. Transm. Distrib. 15, 2277–2285 (2021). https://doi.org/10.1049/gtd2.12193