Simulation Test Study on Combined Gap Structure of High-speed Railway Catenary

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Abstract. In order to deal with the lightning damage problem commonly existing in high-speed railway catenary, a combined multi-breakpoint arc-extinguishing and lightning protection gap device (CMALPGD) which can be applied to high-speed railway catenary is proposed in this paper. Based on the principle of gas production and arc quenching of the device, a three-dimensional dynamic (MHD) model of arc in the arc-extinguishing chamber is established. With the help of simulation software to simulate the changes of the temperature, conductivity and high-speed airflow velocity of the arc at the fracture of the arc-extinguishing chamber, it is known that the high-speed air flow generated by the arc-extinguishing device can quickly extinguish the arc and restrain the arc development, and the whole quenching time is about 2.5ms. At the same time, the arc-extinguishing test is carried out by setting up the test circuit under laboratory conditions, and it is found that the arc-extinguishing time of the device is about 3.0ms and the arc is not reignited for a period of time. The conclusions provide a scientific basis for the application of CMALPGD in high-speed railway catenary in the future.

1. Introduction

In recent years, China's high-speed railway construction coverage is increasing, the social development of high-speed railway dependence is also rising, which makes the social side of the catenary reliability requirements are higher. And high-speed railway in our country most using viaduct structure-res, such as high-speed railway in our country and the beijing-tianjin inter-city railway, the viaduct sections respectively account for 80.4% and 86.6% across the board, under the viaduct laying way, catenary wire close to even more than 110 kV transmission line to ground height[1-4], the lightning strike tripping accidents frequently, seriously affect the high-speed operation. According to statistics, in 2014, the number of high-speed railway tripping accidents was as high as 998, among which lightning caused more than 700 tripping accidents, accounting for over 70% [5]. Therefore, it is urgent to study the lightning protection of high-speed railway catenary.

At present, lightning protection measures of high-speed railway catenary in China are relatively simple, mainly based on relevant provisions of high-voltage transmission lines. Common methods include setting up lightning arrester, improving insulation, installing lightning arrester at important equip-
ment (power supply line nodes, electrical phase separation, disconnecting switch, primary side of suction transformer and both ends of long tunnel, etc.). However, the maintenance effect in practical operation is not ideal. For example, the lightning conductor will break the wire and lead to the bending and collapse of the poles and towers in the frozen state, and the lightning conductor cannot effectively protect the winding strike (the occurrence probability is very high). Using insulated tower to strengthen insulation cost is too high, large area implementation is not realistic; In addition, in many electrified railway, after several continuous lightning arrester actions, the substation tripping situation still exists. According to the data, the lightning arrester only protects the insulation of key equipment, and such a small range of protection cannot effectively reduce the catenary lightning damage problem [6].

In order to effectively solve the problem of high-speed catenary, the author team based on the idea of "channel" type lightning protection has been developed by a Combined multiple breakpoints arc-extinguishing from protection gap device (CMALPGD). The device effectively avoids the shortcomings of the traditional "drainage" lightning protection method (such as a pair of metal electrodes in parallel at both ends of the insulator, also known as the arc angle) [7,8]. It has the autonomous arc-extinguishing ability, which can quickly cut off the arc at both ends of the gap and effectively protect the high-speed railway insulator string from the ablation of lightning arc. So as to protect the insulator and prevent accidents.

This paper discusses the CMALPGD mechanism, established the CMALPGD arcing indoor arc three-dimensional Magneto-Hydro-Dynamical (MHD) model, and the process of high-speed airflow acting on the arc and extinguishing and suppressing the arc is studied and analyzed through COMSOL Multiphysics simulation software and arcing test. Finally, the feasibility of applying CMALPGD to high-speed railway catenary was fully verified.

2. Arc-extinguishing principle

Fig.1 is the schematic diagram of CMALPGD structure. The combined device is composed of two main bodies, and each main body is mainly composed of three parts, which are the main body of arc-extinguishing clearance, the graphite electrode and several arc-extinguishing chambers arranged in a spiral pattern. Each arc-extinguishing chamber contains a number of units of high-temperature compression pipes, which are built with arc guide balls and conductive electrodes to guide the arc path and form a semi-closed space (as shown in Fig.2). The outer surface of the main body is provided with three air blowing breaks.

Working principle: CMALPGD is connected in parallel with high-speed rail insulators, mainly including 1-high-voltage electrode, 2-low-voltage electrode and 3-extrusion gap main body, which is combined with high-speed rail insulator to form unbalanced insulation characteristics (as shown in Fig.3) When the high-speed catenary flashover lightning, lightning flows through composed of CMA-
Figure 2. Schematic diagram of the space structure of CMALPGD

Figure 3. Installation diagram of CMALPGD

Figure 4. Shape of arc in arc-extinguishing chamber
LPGD parallel priority clearance, ray arc under the induction of graphite electrode into the internal arcing gap, the arcing chamber of a series of compression pipe arc is compressed in the space and under the guide of conductive electrode arc of the ball and traction by subsection (as shown in Fig.2, 4). At the same time, the cold air around the arc is heated by the arc column, and a high-speed strong air flow is formed in the pipe to act on the arc, the temperature of the arc drops, and finally the arc energy is extinguished before it can be supplied.

2.1. Arc dynamic MHD model in CMALPGD arc-extinguishing chamber

In order to verify the validity and scientificity of CMALPGD, a dynamic arc mathematical model and arc-extinguishing simulation are established. In this paper, physical laws are used to establish the control equation [9-11] of arc Magneto-Hydro-Dynamical (MHD) model in arc-extinguishing chamber. The relevant governing equation is as follows:

(1) Mass conservation equation

The mass conservation equation is deformed by the O · Gauss formula to obtain the differential form of the equation in rectangular coordinate system, and the equations be described as follow:

\[
\frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \frac{\partial (\rho \mathbf{u})}{\partial x} + \mathbf{m} \cdot \frac{\partial (\rho \mathbf{m})}{\partial x} + \mathbf{w} \cdot \frac{\partial (\rho \mathbf{w})}{\partial x} = 0
\]  

(1)

Where: \( \rho \) is the density of the high-speed airflow in the arc-extinguishing room; \( \mathbf{u} \), \( \mathbf{m} \), and \( \mathbf{w} \) are respectively the velocity components of the indoor high-speed airflow in the direction of x, y, z axis; \( t \) is the time.

(2) Momentum conservation equations

In the known fluid system, the change of momentum with time is equal to the sum of the external forces on the fluid, and the differential equations can be described as follow:

\[
\begin{align*}
\rho \mathbf{F}_{bx} + \frac{\partial \mathbf{p}_{x}}{\partial x} + \frac{\partial \mathbf{p}_{y}}{\partial y} + \frac{\partial \mathbf{p}_{z}}{\partial z} &= \rho \frac{d\mathbf{u}}{dt} \\
\rho \mathbf{F}_{by} + \frac{\partial \mathbf{p}_{y}}{\partial x} + \frac{\partial \mathbf{p}_{y}}{\partial y} + \frac{\partial \mathbf{p}_{z}}{\partial z} &= \rho \frac{d\mathbf{m}}{dt} \\
\rho \mathbf{F}_{bz} + \frac{\partial \mathbf{p}_{z}}{\partial x} + \frac{\partial \mathbf{p}_{y}}{\partial y} + \frac{\partial \mathbf{p}_{z}}{\partial z} &= \rho \frac{d\mathbf{w}}{dt}
\end{align*}
\]  

(2)

Where \( \mathbf{p}_{x}, \mathbf{p}_{y}, \mathbf{p}_{z}, \mathbf{p}_{x}, \mathbf{p}_{y}, \mathbf{p}_{z} \) and \( \mathbf{p}_{z} \) are internal stress tensors of the fluid; \( \mathbf{F}_{bx}, \mathbf{F}_{by} \) and \( \mathbf{F}_{bz} \) are the components of the mass force on the axial directions of x, y, and z for each 1000g mass fluid.

(3) Energy conservation equation

In combination with the first law of thermodynamics, the corresponding energy conservation equation is obtained as follows:

\[
\frac{\partial (\rho h)}{\partial t} + \text{div}(\rho hv) = \nabla \cdot (k\nabla T) + \frac{\partial p}{\partial t} + Q - S_r
\]  

(3)

Where, T is the temperature of the high-speed airflow; \( \text{div}(\cdot) \) as the divergence; \( p = \eta RT \); \( P \) is the pressure of high-speed airflow, \( \eta \) is the gas correction coefficient, and \( R \) is the constant value; \( v_i \) is the velocity component of all parties upward (\( i = x, y, z \)); \( k \) is thermal conductivity; \( h \) as the heat enthalpy; \( Q \) is joule heat; \( S_r \) is the thermal radiation term.
(4) Electromagnetic field equation
The equation of the electromagnetic field on the $x, y, z$ axial component be described as follow:

$$\nabla^2 A_i = -\mu_0 J, i = x, y, z$$ \hspace{1cm} (4)

Where, $\mu_0$ is the permeability in vacuum; $A_i$ is the components of the magnetic vector in the $x, y, z$ axial direction; $J$ is the current density.

The following relationship exists between the current and potential, and the relevant equations be described as follow:

$$\begin{cases}
\text{div}(\sigma \text{grad}\, \varphi) = 0 \\
J = -\sigma \text{grad}\, \varphi
\end{cases}$$ \hspace{1cm} (5)

Where, $\sigma$ is the arc conductivity; $J$ is the current density of the arc; $\text{div}(\cdot)$ as the gradient; $\varphi$ as the potential.

2.2. Simulation model
Since CMALPGD consists of two identical structures, only one of them is modeled in the simulation. The author used COMSOL Multiphysics software to establish the two-dimensional geometric simulation model of CMALPGD, as shown in Fig.5.

The simulation parameters set by the author are as follows: the initial temperature of solid and fluid is 293.15k and the pressure is 0.1MPa; the potential of the grounding electrode is 0; the simulation uses a lightning current waveform of 10/350$\mu$s, and the amplitude of the lightning pulse is set to 15kA; The thermal conductivity of each metal conductor (such as high voltage electrode, ground electrode, etc.) is 328W/(m·K), the electrical conductivity is $3.856 \times 10^7$S/m, the density is 2800Kg/m$^3$, and the constant pressure heat capacity is 700J/(Kg·K); the thermal conductivity of the insulating material is very high Low (about 0.25W/(m·K)), constant pressure heat capacity is 2100J/(Kg·K), density is 1100Kg/m$^3$; the dielectric constant is 1 in the calculation process, there is no convection heat radiation and radiation in solid heat transfer. At the same time, the simulation ignores the impact of high temperature on insulation and other materials. The time step set in this simulation is 0.1ms, and the specific steps of simulation calculation are shown in Fig.6.
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2.3. Analysis of simulation results
Fig. 7 shows the velocity distribution of simulated lightning pulse triggering CMALPGD action. It can be clearly seen from the figure that the high-speed airflow is generated at the fracture of the arc extinguishing chamber, and the airflow speed is close to 1000 m/s. Such a high-speed air flow will provide conditions for accelerating the arc plasma diffusion. It also further demonstrates that when the arc extinguishing device operates and the lightning arc breaks through the air gap of the compression

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**Figure 5.** Two-dimensional geometric model of CMALPGD

**Figure 6.** Simulation calculation flow chart

1 - external air; 2 - arcing electrodes; 3 - insulating materials; 4 - fracture; 5 - high voltage electrode; 6 - ground electrode; 7 - arc-extinguishing channel; 8 - fracture depth; 9 - fracture width; deviation Angle; A, B, C, D, E- simulation monitoring points
pipe, high temperature will be generated in the compression channel and the internal air will be heated, but the narrow space greatly limits the internal high-temperature air flow and the external cold air. The conduction heat dissipation speed causes the internal air flow to rise continuously in a very short time. The instantaneous increase in temperature will be accompanied by a rapid decrease in air density, which forms a strong compressed high-speed air flow.

Under the action of high-speed air flow, the arc plasma will be released to the outside of the fracture. As shown in Fig.8, the arc is elongated and quickly forms a convection with the outside air, and the energy is continuously dissipated, as shown in Fig.9 of the simulation.

Figure 7. Speed cloud distribution at 0.1ms

Figure 8. Temperature cloud distribution at 0.1ms
Figure 9. Convective heat flux in the y direction at 0.1 ms.

Fig.10 shows the temperature change waveform of the fracture at the monitoring point A. Fig.11 shows the waveforms of conductivity and airflow velocity changes at the fracture at monitoring point A. Other waveforms collected by B, C, D and E are similar to those at point A, and point A is at the side of the high-voltage electrode, with the highest current density and the most difficult extinguishing environment. Data analysis at point A is more convincing.

From the analysis of Fig.10 and Fig.11, it can be seen that when the lightning pulse triggers the initial CMALPGD action (about 0ms-0.25ms), the internal air gap of the device is broken by the arc, and the conductivity increases rapidly. The temperature rise will form a high-speed arc extinguishing air flow at the beginning of the device operation. At about 0.4ms, it can be seen that the conductivity at this time drops quickly and is almost close to zero, indicating that the generated high-speed airflow fluid has acted on the arc thermal plasma and inhibited the arc construction. It can also be seen from the temperature change at point A that the temperature at this time has dropped to 3000K-4000K. According to the temperature criterion for extinguishing the arc [12,13], the arc is basically extinguished at this time. Although the temperature fluctuates to some extent over time, as can be seen from Fig.11, the conductivity remains stable and almost 0, indicating that the arc has not reignited. At the same time, it can be known from the process of 0.5ms-2ms that once the conductivity has increased, the high-speed airflow will increase, and then the conductivity will decrease, which has been maintained at a low value. After 2.5ms, the conductivity is basically unchanged and is 0, indicating that the arc has been completely extinguished at this time.

Figure 10. Changes in temperature at A monitoring site
Figure 11. Changes in conductivity and velocity at A monitoring site.

Comprehensive appeal theory and simulation analysis can show that CMALPGD can generate high-speed airflow and react to the arc in the early stage of the arc. It is a self-energy arc extinguishment and can effectively extinguish the arc and suppress the reignition of the arc. So, it is feasible to be applied to high-speed railway catenary.

3. Arc-extinguishing test

3.1. Test plan

In order to further verify the validity of the CMALPGD, the author conducted arc-extinguishing test under the conditions of a high-pressure laboratory. The simulated lightning current amplitude is 15kA, and two clearance distance (the distance between two graphite electrode) is 350mm. Since the power supply voltage cannot directly break through the gap, the gap is short-circuited by the short-circuit fuse $R_2$. When the power is turned on, the current will flow through the fuse. The fuse will be blown and form a lightning arc in the gap. The test circuit diagram is shown in Fig.12.

![Test Circuit Diagram](image)

AC - power frequency power supply; K - ac circuit breaker; TM - voltage regulating transformer; T - test transformer; $R_0$ - current limiting resistance; QX - protecting the clearance; V - ac high voltage meter; $R_2$ - fuse resistance; D - CMALPGD; JY - high speed iron insulator; $R_1$ - sampling resistance; DOS - digital oscilloscope

Figure 12. Equivalent test circuit

3.2. Analysis of test results

Fig.13 shows the quenching process of the arc caused by the high-speed air flow recorded by the high-speed camera with time variation. When $t=0.01$ms, the fuse has been fused and arcs begin to occur.
t=0.1ms-0.5ms, arc gradually brightens and arc is basically formed. From t=0.5ms-2.0ms, the arc light is obviously weakened at this stage, indicating that the arc-extinguishing device has acted during this period to generate high-speed airflow and be used for arc. At t=3.0ms, the arc was completely cut off and gradually disappeared without reignition. Therefore, it took 3ms from the generation of the arc to the extinction of the arc.

Through the above analysis, the arc extinction time of the CMALPGD test is 3.0ms, and there is an error of about 0.5ms from the simulation result (2.5ms). Since the simulation conditions are that the ideal gas is different from the laboratory environment, the error is within the acceptable range. To sum up, simulation results and test results can fully explain the arc-extinguishing and arc reignition suppression ability of CMALPGD, providing scientific basis for the future application of arc-extinguishing device in high-speed railway catenary.

![Figure 13 Arc development process shot by high speed camera](image)

4. Conclusion
1) The CMALPGD developed by the author's team, through theoretical modeling, simulation and experimental analysis, shows that it can effectively extinguish the arc and suppress the reignitions of the arc, which provides a strong basis for the feasibility of CMALPGD's future application in the high-speed rail contact network.

2) The author simulated and analyzed the changes of arc temperature, conductivity and velocity of high-speed air flow at the fracture A of the arc-extinguishing chamber during CMALPGD action, combined with theoretical analysis of the gas generation principle of CMALPGD, verified that the generated high-speed air flow can act on the arc, and proved that CMALPGD belongs to self-energy arc-extinguishing, and the whole arc-extinguishing time is about 2.5ms.

3) The arc-extinguishing test was conducted in the laboratory environment, and the total arc-extinguishing time of CMALPGD was 3ms. Because the simulation environment is in an ideal environment, there are some reasonable errors between them.

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References
[1] J Zheng, Key technologies for high speed railway bridge construction, Engineering Sciences. 7(2008)18-27.
[2] Y C Cui, Key Construction Technologies of Bridge Crossing over the Existing High Speed railway, railway Engineering. 4(2017)34-36.
[3] Z H Yang, Key technologies for high speed railway bridge construction, Engineering Technology and Application. 1(2018)64-67.

[4] H J Fan, J Luo, Research on the Lightning Protection of OCS in Passenger Dedicated Lines, Journal of railway Engineering Society. 8(2008)80-83.

[5] W Y Wei, Study on Lightning Characteristics and Arrester Protective Effect of Traction Power Supply Catenary of High-Speed railway, Insulators and Surge Arresters. 6(2014)54-58.

[6] F Peng, W J Chen, C R Li, 110 kV and 220 kV composite gap of transformer neutral point protection, High voltage engineering. 34(2008)243-246.

[7] Y M He, G Song, R J Cao, Test research of secondary arc in 1 000 kV UHV double-circuit transmission lines, Proceedings of the CSEE. 31(2011)138-143.

[8] D Ge, Y Mao, Z M He, et al, Calculation of powe frequency voltage and electric field distribution on 110kV composite insulators with parallel gap, Insulators and Surge Arresters. 5(2011)26-30.

[9] J F Wang, W X Feng, Y L Wang, Research on the influence of the arc-extinguishing time of arc extinguishing lightning protection gap(AELPG) for lightning trip-out rate, 2012 Second International Conference on Digital Intelligent System Design and Engineering Application (ISDEA), Sanya, Hainan, 2012.

[10] Schavemaker P H, Van Der Slui L, An improved Mayr-type arc model based on current-zero measurements, IEEE Transactions on Power Delivery. 15(2000)580-584.

[11] W Z Zhao, G Z Zhu, Y Y Zhou, et al. New approach to calculating methods of black-box arc model[J]. Proceedings of the CSEE. 8(1988)1-11.

[12] J F Wang, G D Li, D Wu, et al, Mechanism and application of lightning protection gap extinguishing power frequency are assisted by explosion shock wave, High Voltage Engineering. 41(2015)3036-3041.

[13] J F Wang, Z D Huang, Z P Chen, et al, The Mechanism Study of Jet Stream Interrupter Gap Lightning Protection Device, Asia-Pacific International Symposiumon Electromagnetic Compatibility, Beijing, China, 2010.