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Research and application of a new jet stream arc extinguishing gap lightning protection device

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ABSTRACT

After a lightning flashover, the resulted power frequency arc may cause the damages of insulators and the overhead line tripping. To solve this problem, a new kind of jet stream arc extinguishing gap lightning protection device (JSIGLPD) installed on the overhead transmission lines was developed. The proposed scheme can provide better distributed lightning protection to the overhead transmission lines. The JSIGLPD can limit the extreme over-voltage on insulators and avoid frequent tripping of circuit breakers. In arc extinguished test, the waveforms of voltage and current were observed with the high-speed camera and oscilloscope. In this paper, the characteristics of electric arc under jet streams are studied based on the chain arc model and shock wave theory, and the arc quenching process is discussed. The results of the arc-extinguishing experiment show that the JSIGLPD is a new type of efficient lightning protection method for overhead transmission lines.

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1. Introduction

Lightning frequently causes faults on overhead lines, and it is one of the major risks to the safe operation of power systems. The transmission lines often must span over long large distance, so line lightning accident in power system occupied large proportion of the total trip-out accidents and accidents caused by lightning account for a large portion of the total trip-out accidents of power systems [1].

In high-voltage systems where insulations are often reduced to minimum for economic reasons, lighting overvoltage can occasionally cause arcs. Lightning overvoltage often cause insulator breakdown and reduce the reliability of power systems. The traditional methods of line lightning protection include: reducing the tower ground resistance, unbalanced insulation method, automatically reclosing, non-effectively neutral point grounding, increasing insulation level and using line arrester, etc.

Since the 1960s, Japan, Germany, France and other countries have begun to study parallel discharge gap which used on overhead transmission lines and has accumulated rich experience in technical data and operation [2,3]. In 2002, Japan's Tsukima and others through the experiment proves that the airflow can drive arc movement [4]. In recent years, China was studied with respect to the parallel gap lightning protection research [5,6]. Due to its durability, insulator parallel gap lightning protection is an effective complement to traditional lightning protection methods. However in the situation that the power frequency arc is not cut out in time, even a durable plate will be damaged [7,8].

The proposed JSIGLPD is developed from based on the principle of parallel gap lightning protection. It can effectively to protect the 35–500 kV overhead transmission lines power system when the faults caused by lightning strokes. The proposed device is installed at the upper end of the parallel gap. When the gap is broken by the lightening, the sensor will trigger the air-blast equipment to generate the jet stream. At the same time, the transient arc is built up at the gap, so the two processes are happening simultaneously, and the power frequency arc is effectively suppressed at the early stage. This ensures that the arc extinguish time is shorter than the relay action time, thus the tripping rate is greatly reduced.

The arc model under the action of the jet stream was built, and the gas flow field and temperature field were simulated using finite element software ANSYS 14.0. A JSIGLPD was built [7,8], and large number of arc extinguishing tests was conducted on the jet stream arc extinguishing test platform. The arc extinguishing tests proved that the JSIGLPD can effectively extinguish alternating current arc less or equal to 15 kA. The JSIGLPD's structural parameters were optimized and the numbers of gas shells, jet-point location,

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and spray angle of gas devices were determined based on the test [9–14].

2. Simulation of gas flow field and temperature field

2.1. Arc model under the action of the jet stream

The mathematical model of interactions between jet flow and arc was built based on the internal particle motion, energy conversion and macro-statistical methods, assuming local thermodynamic equilibrium, macro-neutral and continuous media [15–17]. The basic equations in of the mathematical model are:

Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r)+\frac{\partial}{\partial z}(\rho v_z)=S_m \quad (1)$$

$$\rho v_r\frac{\partial v_z}{\partial r}+\rho v_z\frac{\partial v_z}{\partial r}=-\frac{\partial \rho}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\mu+\mu_t)\frac{\partial v_z}{\partial r}\right]-S_m \quad (2)$$

Mass conservation equation:

$$\frac{\partial \rho}{\partial r}=\rho\frac{v_\theta^2}{r} \quad (3)$$

$$\rho v_r\frac{\partial (rv_\theta)}{\partial r}+\rho v_z\frac{\partial (rv_\theta)}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}\left[r(\mu+\mu_t)\frac{\partial (rv_\theta)}{\partial r}\right]-\frac{2}{r}\frac{\partial}{\partial r}[(\mu+\mu_t)(rv_\theta)]-S_\theta \quad (4)$$

Energy conservation equation:

$$\rho v_r\frac{\partial h}{\partial r}+\rho v_z\frac{\partial h}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\frac{k}{C_p}+\frac{\mu_t}{\sigma_h}\right)\frac{\partial h}{\partial r}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho D+\frac{\mu_t}{\sigma_f}\right)(h_1-h_2)\frac{\partial f}{\partial r}\right]-S_h-U_r \quad (5)$$

$$\rho v_r\frac{\partial f}{\partial r}+\rho v_z\frac{\partial f}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(D\rho+\frac{\mu_t}{\sigma_f}\right)\frac{\partial f}{\partial r}\right] \quad (6)$$

Gas state equation:

$$\rho v_r\frac{\partial K}{\partial r}+\rho v_z\frac{\partial K}{\partial Z}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial K}{\partial r}\right]+\mu_t\left(\frac{\partial v_z}{\partial r}\right)^2-\rho\varepsilon \quad (7)$$

$$\rho v_r\frac{\partial \varepsilon}{\partial r}+\rho v_z\frac{\partial \varepsilon}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial r}\right]+C_1\frac{\varepsilon}{K}\mu_t\left(\frac{\partial v_z}{\partial r}\right)^2-C_2\rho\frac{\varepsilon^2}{K} \quad (8)$$

where

$C_1=1.44$; $C_2=1.92$; $C_\mu=0.09$; $\sigma_f=0.9$; $\sigma_h=0.9$;

$\sigma_\varepsilon=1.0$; $\sigma_k=1.3$;

$$\mu_t=\frac{C_\mu\rho K^2}{\varepsilon};$$

S_m, S_θ and S_h are source terms in the continuity equation, mass conservation equation and energy conservation equation, respectively; ρ is the gas density; ε is the dielectric constant; V_r and V_z is the axial and radial velocity of the gas, respectively; and K denotes the gas temperature.

2.2. Simulation of jet stream

On the basis of the above models, the arc model of high speed air flow field coupling was established, and the process of the arc was truncated by the finite element analysis software ANSYS14.0. In the calculation of flow field by ANSYS, sub-regional division was used to analysis the distribution of pressure intensity. Because the jet flow field in the vent area changes rapidly, the meshes within this region were densified in order to improve the accuracy of calculation.

Simulation model consists of 4 elements: arc, arc extinguishing tube, air and TNT explosive. In the simulation, the TNT flash weak energy material was used to simulate the arc. The simulation of the arc was the grid of the explosive and the air area was set to the Euler grid, the ceramic cylinder and the electrode were set to the Lagrange grid, and the process of the explosion was a

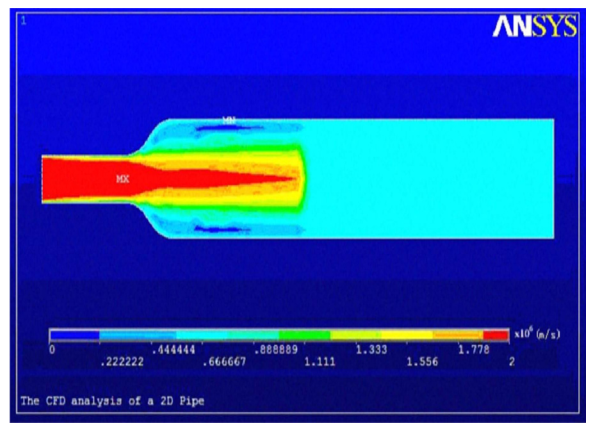

Fig. 1. Jet flow field's distribution at 1 ms after the gas generator started.

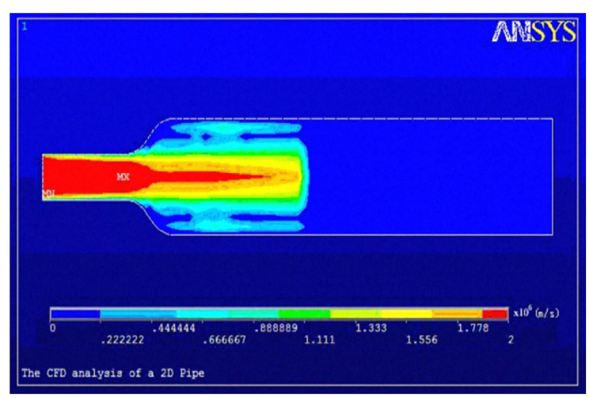

Fig. 2. Jet flow field's distribution at 4 ms after the gas generator started.

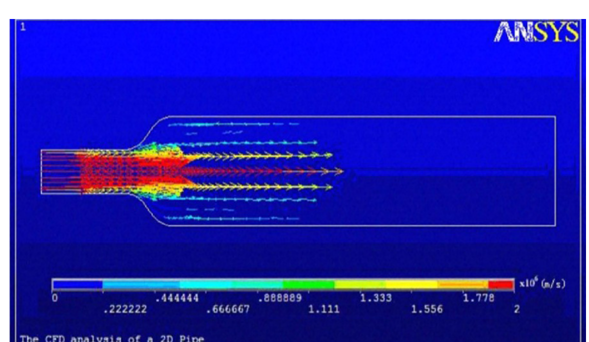

Fig. 3. Velocity vector of jet stream at $t = 1$ ms.

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