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ABSTRACT

In order to reduce the lightning trip-out rate of grid power lines, a kind of impulse quenching based multichamber arc quenching structure (IQBMAS) is developed by the authors. This kind of MAS can attract the lightning impulse arc into its arc quenching channel and truncate the impulse arc into multiple parts rapidly. In this case, the impulse arc will not develop into steady power frequency current, so the lightning trip-out can be avoided. In this paper, simulations and experiments are conducted to verify the arc-quenching effect of IQBMAS on the basis of expounding the operating principle of IQBMAS, establishing the arc model in the channel as well as deriving the relevant numerical equations. The test result shows that IQBMAS can extinguish the power frequency arc of 10 kV lines within 1.5 ms with no reignition.

I. INTRODUCTION

Lightning overvoltage poses serious threats to the safe operation of grid lines. In some areas where lightning is strong and frequent, approximately 70% of trip-out accidents are caused by lightning strikes.1–3 When lightning strikes occur, the short circuit arc at the insulator is a primary cause of line trips, thus, research on arc quenching of the insulator has been conducted by groups worldwide.1

In the past few years, some arc quenching devices were invented for lightning protection of grid lines, including the arcing horn5 and the JSALPG which can generate high speed air flow to quench arc,6,7 the nonlinear resistance arresters that can suppress arc development,8 and the magnetic-type lightning arrester using magnetic force to elongate and truncate arc.9 But these lightning protection devices have some drawbacks such as short service life, complicated structure and high cost. To solve these problems, some scholars try to apply multichamber structure to arc quenching of lightning protection of grid lines. As we know, multichamber structure is mostly used in the field of circuit breakers and switches.10 Liu et al.11 pointed out that multichamber structure can balance electric field distribution and ensure the breakdown stability of the gap. And as mentioned in Ref. 12, changing the long arc into series of short arcs is conducive to extinguishing the arc. Taken into consideration the above advantages, the multichamber structure based lightning protection device may provide a new method in reducing the lightning trip-out rate of grid lines.

G. V. Podporkin et al.13,14 developed the first type of MAS based arrester which can lengthen and cut off the arc within 10ms. The mechanism of which is that the arc extinguishing time is shorter than the action time of relay protection, so no trip will occur. They also found that there are two modes of arc quenching in MAS. The first mode is called “Zero Quenching”. In this case, the arc current will stop flow at the zero-crossing. The second mode is named “Impulse Quenching”. In this manner, where the arc will be suppressed in the initial stage of impulse arc. In contrast, the “Impulse Quenching” has obvious advantages such as shorter extinguishing time and higher current interrupting threshold.

Unfortunately, since “Zero quenching” plays a leading role in the arc quenching process of the currently used MAS based arresters, the arcing time of such devices are designed to be less than 10 ms, so they cannot avoid the erosion of chambers and electrodes.
For the purpose of improving the performance of MAS based arrester, the impulse quenching based multichamber arc quenching structure (IQBMAS), with shorter arc extinguishing time, higher current interrupting threshold and longer service life, is investigated in this paper.

II. OPERATING PRINCIPLE AND NUMERICAL MODEL

A. Operating principle of IQBMAS

Fig. 1 shows the installation diagram of IQBMAS. The IQBMAS is installed beside the insulator and there is a series gap between it and the high voltage side. To satisfy the insulation coordination with the insulator, the distance of the series gap should be controlled in a certain range. By this way, the flashover will occur at the side of the IQBMAS and the insulator can be protected effectively. In this paper, we mainly discuss the arc development in IQBMAS, so the influence of series gap and the skirt border of the device are ignored. A two-dimensional internal geometric model of the two kinds of MAS is shown in Fig. 2. In IQBMAS, the impulse quenching mode plays a more important role in the arc quenching process. Compared with general MAS, the arc is elongated to a greater extent in IQBMAS, and the contact area between the arc and the external space is increased, which strengthens the convective heat dissipation performance, thereby, accelerates arc cooling.

The principle of impulse quenching is introduced in detail in the next section.

B. Numerical model of impulse arc quenching in IQBMAS

When lightning overvoltage happens, the trajectory of impulse arc will be constrained in the spiral arc channel of IQBMAS. The physical radius of the arc will decrease dramatically through three types of compression listed below:15

1) Mechanical compression: The arc is compressed by the limited structure and the size of the channel.
2) Cooling compression: When the high temperature arc has a very close contact with the cold wall, the cooling compression is triggered under the huge difference in temperature. The arc gradually cools from the outside to the inside, the electric particles in cooling zone become dissociate and dielectric, so the cross section of arc column has been narrowed.
3) Electromagnetic compression: The magnetic field of arc current compresses arc itself.

The model of arc in the channel is shown in Fig. 3. Analyzing the arc motion in the arc channel by using the finite element method, dividing the arc cylinder into multiple linear infinitesimal current, ignoring the inductive magnetic field generated by the outer conductor, we can divide the arc cylinder into parts of linear infinitesimal current; thus, the force analysis of each infinitesimal can be described as follows:

$$\frac{dP}{dr} + j_r \cdot B_\phi = 0$$ (1)

Where $P$ is the barometric pressure, $j_r$ is the density current of arc column in axial direction, and the magnetic field produced by arc column is indicated as $B_\phi$.

The relation of magnetic field and current can be solved by using the ampere circuital theorem (The arc is axial symmetry),

$$\oint B \cdot dl = \mu_0 \sum I$$ (2)

Where $\mu_0$ is the magnetic permeability of vacuum, $\sum I$ is the sum of current in the closed circuit $l$. When $l$ is defined as a circle of radius $r$, then equation (2) can be simplified as follow:

$$B_\phi = \frac{\mu_0}{r} \int_0^r j_r \cdot rdr$$ (3)
By substitution of (3) into (1),
\[ \frac{dP}{dr} + \mu_0 \frac{j_x}{r} \int_0^r j_x \cdot r \, dr = 0 \] (4)

Transforming (4) into
\[ dP = -\mu_0 \left( \frac{j_x}{r} \int_0^r j_x \cdot r \, dr \right) \, dr \] (5)

Integrating \( P \) over the edge to the center of the arc column, \( P_0 \) is the environmental pressure at the edge of the arc column, \( \Delta P(r) \) is the pressure difference,
\[ \Delta P(r) = P(r) - P_0 = \mu_0 \int_0^r \frac{j_x}{r} \int_0^r j_x \cdot r \, dr \] (6)

With \( j_x = I / \pi r^2 \), \( \Delta P(r) \) can be expressed as follows:
\[ \Delta P(r) = \frac{\mu_0}{4\pi} \frac{I^2}{\pi^2} \left( 1 - \frac{r^2}{r^2} \right) \] (7)

With \( r = 0 \), we can see a maximum pressure difference in the arc axis,
\[ \Delta P_{\text{max}} = \Delta P(0) = \frac{\mu_0}{4\pi} \frac{I^2}{\pi^2} \] (8)

We can observe from the above equations that the pressure produced by electromagnetic compression is directly proportional to the square of the arc current and is inversely proportional to the square of the arc radius. While mechanical compression and cooling compression reduces arc radius, the effect of electromagnetic compression becomes more significant. The arc will be compressed dramatically via the three compressing effects.

Fig. 4 shows the development process of arc in adjacent channel. While the arc is compressed, a mass of gas will be sucked into the channel to fill up the space; thus, “gas aggregation” will occur in each channel. Baked by the compressed arc with high temperature, the radial pressure of gas will turn into axial pressure and form expanding airflow blowing outward of the channel. At the same time, arcs in each channel would gush out with the high speed expanding airflow from both ends, forming the phenomenon of “arc spray” which makes the movement distance of arc to the next channel increase; thus, the arc energy will dissipate drastically at each inflexion of adjacent channel, forming energy breakpoint. Finally, without the energy supply from the power frequency, the arc will soon be extinguished.

III. SIMULATION ANALYSIS

The general law for arc extinguishing in the channel is given above. To better analyze the arc quenching process, we simulate the coupling process of expanding airflow and arc plasma in the channel.

A. Simulation conditions

The microstructure change of arc is not required in this simulation and the development process of arc in each chamber is similar, so only a section of IQBMAS between two electrodes is selected for observation. The geometry model of the simulation is shown in Fig. 5.

The k-\( \varepsilon \) model is chosen as turbulence model. The Navier-Stokes equation and the Maxwell equation are chosen as fluid
and electromagnetic field coupling control equation respectively. The 10/350 μs lightning impulse of 1.2 kA coupled with the power frequency current of 500 A is applied to the electrode. The solution is obtained by using unsteady time step iteration.

B. Simulation result and analysis

The interval step of this simulation is set to 10 μs. The distribution cloud charts of the velocity field, temperature field and conductivity field in the channel are obtained as shown in Fig. 6, Fig. 7 and Fig. 8 respectively.

To highlight the actual effect of the blowing process between adjacent channel, the inflexion is designed to connect exterior space in the simulation. Thus, the expanding airflow in adjacent channel will finally spurt outside the inflexion. The development process is shown in Fig. 6(a)–(d). As we can see at 100 μs, the velocity mainly distributes around the electrodes and has a tendency to diffuse all around. Under the effect of arc heating, the gas sucked into the channel rapidly expands, the velocity reaches the maximum radial velocity of 500 m/s in the inner wall of the channel. During the period of 100 μs to 500 μs, the charts display an obvious velocity transformation from channel to outside space. The expanding airflow forms a huge impact load, crushing arc into the inflexion. Meanwhile, the velocity drops gradually. At 1000 μs, the velocity decreases to about 25 m/s, arc plasma in the expansion flow becomes fragmentary and extinguished under the impact of accelerating diffusion and electron recombination. At approximately 1500 μs, the velocity of air flow outside the channel drops to a low level.

The development process of the self-expanding airflow has been clearly obtained in the velocity diagram. To better reveal the arc energy changing process and show the determining condition of arc quenching, the internal temperature field diagram is used for further analysis.

Fig. 7(a) shows that at about 100 μs, the internal temperature of arc-quenching channel was concentrated near the electrode and the temperature reaches 9×10³ K at this time. The “arc spray” occurs around 500 μs, by this time, the mixture of arc and expanding airflow sprays out of the channel. With the effect of convection, conduction and radiation, the energy of the compressed arc is attenuated rapidly at about 1000 μs. Simultaneously, the internal energy in the channel becomes evenly distributed. At 1500 μs, we can see the temperature goes down even further, at this time, the maximum temperature is approximately 2500 K, which is far below the maintaining temperature required for arc combustion (approximately 3500 K). Soon afterwards, the arc is annihilated in the exterior space.

The conductivity field shown in Fig. 8 gives a clearer criterion of arc quenching. We can observe that the conductivity in the channel decays rapidly from 100μs to 1000μs and was finally extinguished at about 1500μs.

IV. TEST

This experiment is designed to verify the arc-quenching result of IQBMAS under the dual effect of impulse arc and power frequency arc. The experiment principle diagram is shown in Fig. 9. The AC power supply capacity is 120 kVA. The power frequency...
generating circuit is set to generate power frequency between IQB-MAS to simulate the situation in 10 kV line. The lightning impulse generating circuit is set to generate 10/350 μs lightning impulse of 2 kA.

The experimental steps are as follows:
1) Complete the main circuit connection, connect the power supply, adjust the voltage regulator and transformer, and ensure the whole circuit functions properly.
2) Start the impulse current generator and adjust it to generate the impulse current required to simulate the impulse arc. Simultaneously, record the development progress and the physical change of the arc in the IQBMAS by using a high-speed camera. 

3) Record the voltage and current between IQBMAS. 

The arc-quenching process of IQBMAS was captured by a high-speed camera. Current and voltage waveforms of IQBMAS were recorded by digital oscilloscope. The data can be used to analyze the arc quenching process in IQBMAS.

CH 1 and CH 2 in Fig. 10 are the voltage and current waveforms of IQBMAS in the test respectively. When the impulse current generator started, IQBMAS was broken down by impulse arc and the oscilloscope started to record. We could observe that the voltage of IQBMAS declined sharply due to the generation of arc. But the arc was quickly extinguished, so the voltage bounced back at the bottom and recovered to the normal state in a very short time. The current waveform also showed that after hitting the peak current of about 2kA, the arc was finally quenched with no reignition. To sum up, the arc quenching process was started at impulse arc stage, the impulse arc was truncated so the arc was not able to obtain energy from power frequency supply. So the arc quenching time was considerably shortened.

The arc-quenching process is shown in Fig. 11. As we can see, the arc entered the arc-quenching channel within 50 μs, coupled with the expanding airflow produced in IQBMAS. Due to the utmost compression of the impulse arc, the energy density of the compressed arc in the arc quenching channel reached a relative peak; therefore, a large cluster of light surrounded the device, and the arc was greatly bent. It could be seen that the response time of IQBMAS was extremely short.

At approximately 150 μs, a high longitudinal pressure gradient was produced in every channel. Under the effect of the high speed expanding airflow, the “arc spray” phenomenon occurred. At this time, the arc was fully suppressed, with multiple breakpoints appearing.

We could see that a distinct energy segment appeared at about 300 μs. Because of the combination of arc plasma and the electric charge in exterior space, the energy of impulse arc dissipated sharply. At this moment, the arc at the inflexion was blown out by the accumulated expanding airflow in every arc quenching channel.

Within 300 μs to 500 μs, the coupling and decoupling processes were observed. During this time, the power frequency arc was deeply suppressed by the expanding airflow, segmented arc columns appeared clearly and there was no sign of any energy increase of the arc.

Between 500 μs to 1000 μs, the power frequency arc coupled completely with the expanding airflow and the arc was attenuated.
gradually. We can see that the quantity of segmented arc column and the density of energy decreased obviously, thus substantially lowering the possibility of arc reignition. The arc was quenched at about 1500 $\mu$s.

V. CONCLUSION

The thin arc quenching channels arranged in a specific space structure can accurately locate the arc development trajectory, generating expanding airflow under the compressing effect, which will expedite the movement of the arc at the adjacent inflexion, thereby forming energy multibreak points and enhancing the energy dissipation of the arc.

The simulation results show that IQBMAS can effectively restrain the physical size of the arc, and the expanding airflow can considerably dissipate the arc energy in each inflexion of IQBMAS. The arc quenching time is about 1.5 ms.

In the test, IQBMAS could break the entire arc into multiple dissected arc columns, and the impulse arcs were almost quenched at their inception phase. In the simulation, the arc of 2 kA impulse current coupled with 10kV power frequency was also quenched at approximately 1.5 ms, with no sign of reignition. The experimented and simulated results were in good agreement.

Further research will focus on the application in lines of higher voltage.

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