Study on the Arc Motion Characteristics of Multi-Chamber Arrester Based on 3D Model

YICEN LIU, GUANGNING WU, (Fellow, IEEE), KAI LIU, YUJUN GUO, (Member, IEEE), XUEQIN ZHANG, (Member, IEEE), AND CHAOQUN SHI
School of Electrical Engineering, Southwest Jiaotong University, Chengdu 610031, China
Corresponding author: Kai Liu (liukai@swjtu.edu.cn)
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ABSTRACT In ultra HVDC transmission system, arcing horn gap breakdown makes the arc hard to extinguish, threatening transmission safety. Multi-chamber arrester (MCA) is applied in extinguishing the arc to ensure safety. Here, we investigated the arc motion characteristics of the MCA to analyze its arc extinguishing ability. First, a three-dimensional model of the arc plasma in a single chamber was established based on magneto-hydrodynamic (MHD) theory, and the arc motion inside and outside the chamber were analyzed. Next, changes of temperature, velocity and pressure field were simulated. The results showed that the time required for arc totally exiting the chamber is approximately $96 \mu s$, the airflow maximum velocity is about $865 \text{ m/s}$, and the highest pressure is more than $4 \text{ atm}$. Particularly, there is a flow reflux at the outlet, as the air flows inward from the outside and form an “oscillation”. Moreover, the arc motion characteristics of different discharge currents within different chamber structure were analyzed. It was found that the spacing between anode and cathode, the radius of electrodes and the outlet radius are the key factors regulating the airflow velocity, and the outlet radius of the chamber has the greatest influence. At last, the accuracy of our model was validated with experimental data.

INDEX TERMS Arcing horn, multi-chamber arrester, MHD, 3D model, arc motion characteristics.

I. INTRODUCTION
An arcing horn is used to protect insulators of ultra HVDC transmission line from being burned by the arc [1]. As shown in Fig. 1a, the arcing horn is installed in parallel at the both ends of the insulator string. When the overhead transmission line is struck by lightning, a high lightning overvoltage is generated on the insulator string. The arcing horn gap is first discharged to form an arc, under the action of electrodynamic force and thermal buoyancy, the arc moves to the end of the arc angle, therefore protecting the insulator from arc burning.

The arc-extinguishing process is directly related to the protection effect of the arcing horn [2]. As the voltage level of HVDC transmission systems continues to increase, the risk of grounding line faults is increasing, the difficulty of extinguishing the arc has seriously threatened the safety of transmission lines: on the one hand, the switching overvoltage level on the grounding line is increased, so that the probability of insulation breakdown increases; on the other hand, when the mono-pole ground return operation mode is operated, the current flowing through the grounding line increases, from a few hundred amperes in the past to thousands of amperes. Therefore, when insulation breakdown occurs at the arcing horn, the DC continuous current will also increase, and the arc will be more difficult to extinguish. Fig. 1b shows an arcing horn that has suffered severe ablation. There is an urgent need to study the arc-extinguishing measures which

FIGURE 1. (a) A picture of an arcing horn. (b) A picture of an arcing horn after severe burning.
has important applications in the design and manufacture of arcing horn of HVDC transmission line.

There have been many studies on arc extinguishing measures of arcing horn: using non-linear resistance characteristics of Zinc oxide resistors (MOA) to extinguish arcs [3]; using magnetic field to force the arc to elongate rapidly or to rotate the arc at high speed [4]; making polyvinyl chloride produce gas to blow the arc at high temperature [5], etc. However, these measures have some limitations, such as complex structure, processing difficult, cost expensively, poor reliability, and heavy maintenance workload in the later stage. Therefore, it is necessary to develop arc extinguishing device which is facile and meets the requirements of arc extinguishing performance.

In recent years, insulator protection device for transmission line called multi-chamber arrester (MCA) have been developed, which is illustrated in Fig. 2. The device is a multi-segment micro-porous structure, which is similar to a self-blasting circuit breaker, which divides the arc into sections, and heats the air in the micro-chamber by the arc’s own energy, so that the temperature and the pressure in the micro-chamber is increased, and then the arc is ejected out of the chamber, cooled by the cold air outside the chamber and extinguished. Researchers analyzed temperature, speed and the arc motion process in the multi-chamber [6]–[9]. The effects of electrical conductivity, temperature, airflow velocity, current amplitude and structural parameters on arc motion in multi-chamber are analyzed [10], but the process in the simulation results is in the order of milliseconds, which is quite different from the experiment results, which is in the order of microseconds. The temperature field and velocity field of multi-chamber under different currents are analyzed and the results show that due to the Lorentz force reverse (toward the inside of the outlet), the arc is pushed into the chamber, causing the outlet to have both positive and negative airflows [11]. It has been showed that the instantaneous increase of temperature is the cause of the change of airflow velocity, and the chamber structure has a significant impact on the arc extinguishing effect [12]. The above mentioned studies mainly analyzed two-dimensional arc model for the arc motion characteristics in MCA; the arc motion time is quite different from the experiment; the state after the arc ejected from the chamber is not considered; the influence of different structural parameters of the chamber on the arc motion characteristics was not evaluated; and the analysis of the change in airflow at the outlet of the chamber need further research.

In this study, a three-dimensional model of arc in a single-chamber of MCA was established based on the theory of magnetohydrodynamic. The temperature field and pressure field in the arc combustion process were studied respectively. The motion of the arc inside and outside the chamber were further analyzed, and the influence of structural parameters on the arc motion was determined. Our study provides support for studying the arc extinguishing performance of MCA and its design or improvement.

II. MHD MATHEMATICAL MODEL OF ARC IN SINGLE CHAMBER OF MCA

A. ASSUMPTIONS

A magnetohydrodynamic model for arc in single chamber of MCA was established, assuming that the arc plasma meets the following conditions:

1) The arc plasma is a thermal plasma that satisfies the local thermodynamic equilibrium conditions.
2) The arc fluid is assumed to be laminar flow and has compressibility.
3) Ignore the melting of the metal electrode.
4) The initial generation process of the arc plasma is not considered.

B. MAGNETOHYDRODYNAMIC (MHD)

According to the above assumptions, the arc plasma satisfies mass conservation, momentum conservation, energy conservation, and current conservation, as follows:

1) Mass conservation equation

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

where \( \rho \) means fluid density, \( t \) means time, \( \vec{v} \) means speed vector and \( p \) means pressure.

2) Momentum conservation equation

\[ \frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \mu \Delta \vec{v} + J \times B \]  

where \( \mu \) means viscosity, \( J \) means current density, \( B \) means magnetic induction. Since the effect of electromagnetic fields is not considered, \( J \times B \) is 0.

3) Energy conservation equation

\[ \frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} H) = \frac{\partial p}{\partial t} + \nabla \cdot \lambda \nabla T + \vec{v} \cdot \nabla p + Q \]  

where \( H \) means specific enthalpy, \( \lambda \) means thermal diffusion coefficient, \( Q \) means Joule heat.

4) Gas state equation

\[ p = \rho RT \]

where \( R \) means gas constant.
5) Current conservation equation

\[
\begin{align*}
J &= \sigma (E + \vec{v} \times B) \\
\nabla \cdot E &= \frac{\rho_q}{\varepsilon_0}
\end{align*}
\]  

(5)

where \( \vec{v} \times B \) is 0, \( \sigma \) means conductivity, \( E \) means electric field intensity, \( \rho_q \) means charge density, \( \varepsilon_0 \) means dielectric constant.

C. PHYSICAL MODEL

Fig. 3 shows a 3D geometric model of MCA. As can be seen from the figure, MCA consists of three components: electrodes (A, B, C, D, E, F), silicone rubber (H) and arc-extinguishing chamber (G), "I" is the outlet of the chamber. One individual chamber and its external space was selected as the calculation domain with its axial section shown in Fig 4, and the detailed dimensions are listed in Tab. 1. The electrode radius is 6 mm, the distance of anode and cathode is 2 mm, the chamber depth is 14 mm, and the outer space is a cylinder with a radius of 6 mm and a height of 10mm centered on the axis of the chamber.

D. BOUNDARY CONDITION

The material of the electrode (a-b-a, i-j-i) is Cu. Arc-extinguishing chamber and external space is filled with air. The initial solid and fluid temperatures are both 293 K and the pressure is 1 atm. The detailed boundary conditions of the calculation domain are shown in Tab. 2.

At the initial moment, a lightning current is applied to the anode (a-b-a), and the lightning current is a current pulse waveform of 8/20 \( \mu \)s, which can be expressed as a power function:

\[
i(t) = AI_{m}t^3 e^{-t/\tau}
\]

(6)

where \( A \) is 0.01243(\( \mu \)s)\(^{-3} \), \( \tau \) is 3.911\( \mu \)s, \( I_m \) means lightning current amplitude, which is 2 kA.

III. RESULTS AND DISCUSSION

A. ARC MOTION PROCESS

The temperature field and velocity field of the calculation domain are obtained through simulation, and the motion of the arc inside and outside the chamber were analyzed. Fig. 6 and Fig. 7 show the movement of the arc plasma in the chamber.

As can be seen from the figure:

1) 0-9 \( \mu \)s: the air gap between the electrodes breaks down to form arc plasma. With the increase of discharge current, the radius of arc column increases and develops to...
both sides of the chamber. The maximum temperature of arc column exceeds 280,000K, and the air around the arc is heated sharply.

2) 9-46 µs: the current continues to increase. Due to the poor thermal conductivity of the material at the edge of the chamber, heat cannot be conducted to the external region, causing the temperature in the chamber to rise sharply and the air to expand to form a high-speed airflow toward the exit. As the airflow moves, the arc column leaves the area between the electrodes and enters the channel, and the arc root moves toward the edge of the electrodes. At the same time, the arc temperature gradually decreases as the current decreases. At 46 µs, the arc column moves to the outlet of the chamber and the temperature drops to 6900 K.

3) 46-96 µs: the arc column moves outside the chamber, the arc temperature continues to decrease and cooling outside the chamber. At 80 µs, the arc column is pushed out to the outside of the chamber, and the temperature of the arc column is reduced to 4500 K which was cooled by the air outside the chamber.

4) 96-430 µs: almost all the arc plasma moves integrally to the outside of the chamber and spreads to the periphery. The temperature and the airflow speed gradually decrease. The arc is completely extinguished at 430 µs. But the air in the chamber is not completely cooled, reaching 600 K.

It can be concluded from the simulation that the MCA chamber is broken down by lightning current, and an arc plasma is formed between the electrodes. The arc is burning intensely so that the air in the chamber is in the state of high-temperature and high-pressure, and then a high-speed airflow is formed towards the exit. The whole process occurs rapidly and takes only about 80 µs for the arc from generation to move from outside the chamber.

The magnitude of the current is the decisive factor affecting the arc temperature, the trend of change between current and temperature is basically the same. The airflow velocity also changes with temperature, but it happens later than the temperature due to heat conduction. It can be seen from Fig. 8 and Fig. 9 that the trend of temperature and pressure is basically the same. However, the pressure drops from 9 µs due to the rapid expansion of the air forming a high-speed airflow toward the outlet releasing some of the pressure. Although the initial stage airflow velocity fluctuates with pressure, the maximum air pressure in the chamber exceeds 4 atm, which is much higher than the pressure out of the chamber (1 atm). Therefore, the airflow velocity increases under pressure, reaching the maximum of 865 m/s.

**B. REVERSE FLOW AT THE OUTLET**

It can be seen from Fig. 10 that from 70 µs, the airflow at the outlet of the chamber is reversed with external air entering the chamber. The reason is that the air in the chamber expands rapidly when heated and sprays out, which results in the decrease of density and pressure in the chamber, and a reverse pressure difference between the inside and the outside of the cavity to cause air to flow from the outside (Fig. 11).

As can be seen from Fig. 12, air enters from the edge of the arc column. With the increase of pressure difference between inside and outside, the air entering area gradually enlarges. The cool air enters the chamber mixes with the hot air in the chamber and gets heated, then forms a pressure difference.
with the chamber outside again, and ejects out of the chamber. So reciprocating, the air flow “oscillates” at the outlet, which promotes the temperature reduction and enhances the decoupling effect of the chamber, which contributes to the arc extinguishing.

C. ARC CHARACTERISTICS UNDER DIFFERENT CURRENTS

As can be seen from Fig. 13, temperature and current are positively correlated. The larger the current, the larger the discharge energy, and the more intense the arc burns, and the higher the velocity of the airflow is required to extinguish the arc quickly. Therefore, it is necessary to improve the chamber structure under the same current to increase the energy density per unit volume in the chamber, rapidly heat the air, and form a high-speed airflow, thereby improving the arc extinguishing performance.

D. ARC CHARACTERISTICS UNDER DIFFERENT STRUCTURES

In order to enhance the arc extinguishing ability of the MCA by changing the structure, the airflow velocity of the chamber under different structures were analyzed respectively (Tab. 3). The velocity decreases with the increase of electrode spacing, which is due to the greater compression of air by the smaller electrode spacing. The velocity decreases as the radius of the electrode increases, as the radius of the electrode becomes smaller, the space is smaller, and the compression of the gas is greater. The velocity has little effect with the depth of the chamber, but the smaller the depth the faster the velocity reaches its maximum. The velocity decreases with the increase of the radius of the outlet. This is because the larger the radius is, the smaller the compression effect on air.

IV. EXPERIMENTAL VERIFICATION

In order to validate the accuracy of this 3D model, the data in the published literature is used for comparison.

Jia et al. performed an MCA experiment and the results are shown in Fig. 14 [10]. The arc plasma moves outside the
chamber after 39.6 $\mu$s, during this process the temperature and brightness of the arc are constantly decreasing, as shown in Fig. 14 (7)–(11). After 92.4 $\mu$s, almost all the arc plasma moves out of the chamber, and the arc cannot be observed at 422.4 $\mu$s, as shown in Fig. 14 (12)–(24).

It can be seen that the simulation results of our 3D model are in accordance with the experimental results. It takes only about 46 $\mu$s for the arc plasma to spray from the inside to the outside of the chamber, and takes about 96 $\mu$s to totally exit the chamber. Then the arc plasma temperature decreases gradually, and the arc plasma is completely extinguished at 430 $\mu$s. The key process of arc motion in the simulation is very close to the experiment, and the changes in temperature and radius of the arc plasma are consistent with the experimental observations.

V. CONCLUSION

In this study, a three-dimensional magnetohydrodynamic model (MHD) of MCA was established and the motion characteristics of the arc plasma inside and outside the MCA chamber were analyzed. The temperature, velocity, pressure and the arc plasma motion characteristics of MCA chamber under different structures were simulated. The conclusions obtained are as follows:

1) The mechanism of MCA arc extinguishing is that the arc burns in the chamber, so that the air is in a high temperature and high pressure state, and a high speed airflow (supersonic flow) is formed to spray the arc out of the chamber. In this process, the arc is suppressed by being elongated and cooled. In addition, our simulation found that in the initial stage of the arc motion, the airflow velocity will decrease temporarily. The reason is that the arc in the initial stage of the increase in current moves toward the outlet, releasing part of the pressure, causing a temporary drop in pressure.

2) When the current is gradually reduced, there is a reverse phenomenon in the airflow velocity at the outlet of the chamber. The external gas enters the chamber, mixes with the hot air in the chamber and is heated and ejected out of the chamber again. Repeatedly, the airflow “oscillates” at the outlet. The “oscillation” is beneficial to the temperature reduction, and enhances the decoupling effect of the chamber, and facilitates arc extinguishing.

3) Arc temperature and airflow velocity are positively correlated. The arc extinguishing performance of MCA can be improved by improving the chamber structure to increase the gas flow velocity. The electrode spacing, electrode radius and outlet radius have an effect on the gas flow velocity, wherein the outlet radius has the greatest influence and the chamber depth has less influence. Therefore, improvements should be made to the outlet radius, electrode spacing and electrode radius.

4) It takes about 96 $\mu$s for the arc to move outside the chamber, and the highest instantaneous airflow speed is about 865m/s. After the arc is ejected from the chamber, it appears as a “mushroom cloud”. The results from our simulation agrees well with the existing simulation and experimental results.

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GUANGNING WU (Fellow, IEEE) was born in Nanjing, China, in 1969. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering, from Xi’an Jiaotong University, Xi’an, China, in 1991, 1994, and 1997, respectively. He is currently a Professor with the School of Electrical Engineering, Southwest Jiaotong University, Chengdu, China. His research interests include condition monitoring, fault diagnosis, and insulation life-span evaluation for electrical equipment.

KAI LIU was born in Guiyang, China, in 1990. He received the B.E. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2013, and the Ph.D. degree in electrical engineering from Chongqing University, Chongqing, China, in 2018. His current research interests include the fault diagnosis of grounding grid and the multi-physics coupling field calculation for power system device.

YUJUN GUO (Member, IEEE) was born in Wuhan, China, in 1989. He received the B.Sc. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, in 2011, and the Ph.D. degree in electrical engineering from Chongqing University, Chongqing, China, in 2017. He is currently a Lecturer with the School of Electrical Engineering, Southwest Jiaotong University. His research interests include outdoor insulation and protection of transmission lines.

XUEQIN ZHANG (Member, IEEE) was born in Chengdu, China, in 1979. She received the B.Sc. and Ph.D. degrees in electrical engineering from Southwest Jiaotong University, Chengdu, in 2002 and 2008, respectively. She is currently an Associate Professor with the School of Electrical Engineering, Southwest Jiaotong University. Her research interests include high voltage and insulation technology.

CHAOQUN SHI was born in Zhoukou, China, in 1989. He received the M.S. degree in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 2014, where he is currently pursuing the Ph.D. degree in electrical engineering with the School of Electrical Engineering. His major research interests include outdoor insulation for high-speed railway and electrical discharge.

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