Simulation of Arc Erosion on the Main Contact of On-Load Tap Changer

Yuanxiang Zhou, Yasong Dai, Jianning Chen, Yuhang Li, Xuzhao Hou, and Zhen Zhang

Abstract Long-term operation and switching of transformer on-load tap-changers can cause degradation and deterioration of the main contact material, even leading to contact arcing damage in severe cases. However, the arcing mechanism of the main contact during the switching has not been clarified yet. A magneto-hydrodynamic simulation method of main contact arcing has been proposed. The geometry of the main contact in transformer oil is simplified, and the simulation model of the arc temperature field of the main contact in transformer oil coupled with electric, magnetic, thermal and fluid fields is proposed. The dynamic evolution of the arc temperature has been investigated at peak currents of 2100 A, 1500 A, 600 A and 300 A, respectively. The results show that with the increase of the spacing between contacts, the temperature at arc core rises rapidly and then decreases slowly, and the temperature can reach 50177 K at 2100A. Due to the electron bombardment at the anode surface, the temperature at anode surface is higher than that at cathode surface under different chopped currents. The highest temperatures at anode and cathode surface can reach 4142.5 K and 4081.7 K respectively.

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1 Introduction

On-load tap-changer is a key component of the converter transformer, which adjusts the valve-side voltage and valve-side trigger angle in high-voltage DC transmission systems [1–4]. Long-term switching of the on-load tap-changer causes deterioration of the material and component properties of the current-carrying system, fatigue fracture of the connections, damage to the main contacts, and arcing erosion of the vacuum tube contacts. The result is a contact that is difficult to open reliably [5–8].

Wu [9] used magneto-hydrodynamic (MHD) to establish a numerical model simulation of steady-state heat transfer in a DC fault arc. The results show that the arc conduction to both sides of the electrode will occur a sudden drop in temperature, and the electrode spacing on the arc conduction temperature effect is not significant. Zhong [10] introduced copper vapor for the simulation and testing of small-current DC arcs, and it was found that the simulation of arcs containing copper vapor medium was closer to the experimental data than that of pure air medium. Cressault [11] established the arc erosion model of air and metal vapor by adopting the two-temperature model. Jolly [12] simulated the current value of anode contact point at melting. Wang [13] established an arc melt pool model to obtain electrode erosion The current studies on arc fault characteristics and simulation modeling are mainly on isolating switches, relays, circuit breakers, vacuum tubes, but less on the main contact arc of on-load tap-changers. Unlike gas discharges, the main contact is immersed in transformer oil for switching, and the mechanism of arc erosion in the oil of the on-load tap-changer main contact is not yet clear. So the study of its physical mechanism has important scientific significance and engineering value.

In order to analyze the erosion of the on-load tap-changer main contacts in transformer oil, a finite element simulation model of arc erosion of the on-load tap-changer main contacts based on magneto-hydrodynamics was established. The dynamic evolution of the temperature at the main contact with varied chopped currents was studied and analyzed.

2 Numerical Simulation

This paper has carried out a simulation study on the arc characteristics during the contacts disconnection process, and analyzed the dynamic evolution of the arc temperature at different moments of the contact and the temperature rise law of the arc area under the conditions of the peak chopped currents of 2100 A, 1500 A, 600 A and 300 A, respectively.

2.1 Geometric Modeling

The on-load tap-changer main contacts are mostly made of copper and are immersed in transformer oil. In order to save computation, the simulation model simplifies the material shape and uses the two-dimensional model shown in Fig. 1 as the geometric model for the arcing process of the on-load tap-changer main contacts. The overall calculation area is 45 mm long and 30 mm wide. The copper electrode is 5 mm long and 5 mm wide with a radius of 1 mm at the chamfer. The other area is the transformer oil and the initial spacing between the two electrodes is 0.2 mm. A triangular mesh is used for unstructured meshing of the simulation area. The number of triangular cells is 24,099, the number of nodes is 84,524, and the mesh is partially shown in Fig. 2. The arc region occurs in the spacing part between the two electrodes and involves multi-physical fields coupling, where the parameters of each physical property of the material in the simulation model are shown in Table 1.

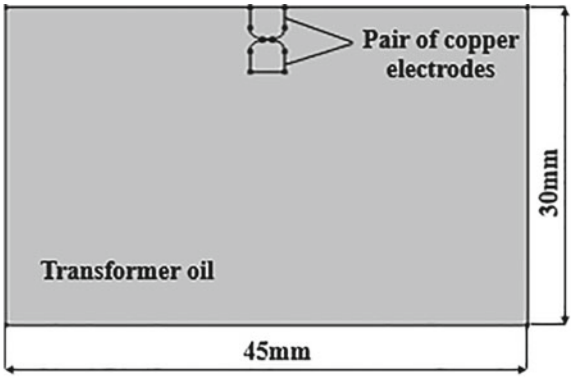


Fig. 1 Simulation of geometric models

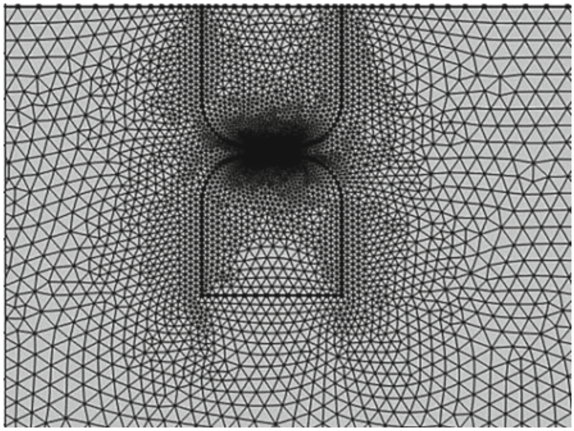


Fig. 2 Partial grid subdivision

Table 1 Parameters of physical properties of materials in numerical model

Parameter	Value
Copper density /(kg/m^3)	8960
Copper thermal conductivity /[W/(m· K)]	400
Copper specific constant pressure heat capacity /[J/(kg· K)]	385
Copper conductivity /(S/m)	5.998×10^7
Relative dielectric constant of transformer oil	2.125
Conductivity of transformer oil (S/m)	0.0714

2.2 Magneto-Hydrodynamic Control Model

This paper simulates contact arc erosion based magneto-hydrodynamic equations, which includes hydrodynamic equations and Maxwell's equations [5, 6].The simulation of arc plasma is a multi-physical field coupled electric–magnetic-thermal-fluid interaction process. The arc equations include the mass conservation equations, momentum conservation equations, energy conservation equations in fluid dynamics, and also Maxwell's equations in electromagnetism. The control equations are as follows:

Conservation of mass equations:

$$\rho \nabla \cdot \mathbf{u} = 0 \tag{1}$$

Conservation of momentum equations:

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot \left[-p\mathbf{I} + \mu\left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\mathrm{T}}\right)\right] + \boldsymbol{F} \tag{2}$$

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} \tag{3}$$

Conservation of energy equations:

$$\rho C_\rho \left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T\right) - \nabla \cdot (k \nabla T) = Q \tag{4}$$

$$Q = \frac{\partial}{\partial t}\left(\frac{5 k_{\mathrm{B}} T}{2\mathrm{e}}\right)(\nabla T \cdot \boldsymbol{J}) + \boldsymbol{E} \cdot \boldsymbol{J} - Q_{\mathrm{vd}} \tag{5}$$

where: ρ is the fluid density; $\boldsymbol{u}$ is the fluid velocity vector; p is the pressure; $\boldsymbol{I}$ is the unit matrix; μ is the kinetic viscosity; and $\boldsymbol{F}$ is the force source term (Lorentz force); $\boldsymbol{J}$ is the current density vector; $\boldsymbol{B}$ is the magnetic induction intensity vector; C_ρ is the constant pressure heat capacity; T is the temperature; k is the thermal conductivity; Q is the heat source term, mainly including enthalpy transfer, Joule heat and viscous dissipation, corresponding to the three terms in Eq. (5); k_{B} is the Boltzmann constant;

e is the unit charge; Q_{vd} is the viscous dissipation loss, which is an inherent physical parameter of transformer oil.

Electric field equations:

$$\nabla \cdot \boldsymbol{J} = 0 \tag{6}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} \tag{7}$$

$$\boldsymbol{E} = -\nabla \varphi \tag{8}$$

Magnetic field equations:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{9}$$

$$\boldsymbol{B} = \mu_{\mathrm{r}} \mu_0 \boldsymbol{H} \tag{10}$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{11}$$

where: $\boldsymbol{J}$ is the current density; $\boldsymbol{E}$ is the electric field strength vector; φ is the potential; $\boldsymbol{H}$ is the magnetic field strength; $\boldsymbol{B}$ is the magnetic induction strength; μ_{r} is the relative magnetic permeability, which takes the value of 1 here; μ_0 is the magnetic permeability of the vacuum; and σ is the electrical conductivity.

2.3 Boundary Conditions

In the geometric model shown in Fig. 1, the copper contact electrode pairs are divided into dynamic contact and static contact, where the top contact is fixed as static contact and the bottom contact is dynamic contact whose movement speed is 0.2 m/s. In the current field setting, the current of the dynamic contact is set to the starting amplitude of 2100 A, 1500 A, 600 A, 300 A oscillating decay chopped current, and the waveform is shown in Fig. 3. The initial value of temperature in the calculation domain is set to 293.15 K, the initial value of transformer oil domain pressure is 101 kPa, and the wall condition is set to no slip.

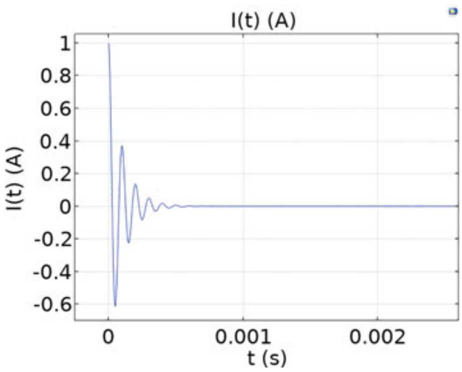


Fig. 3 Chopped current unit initial waveform

3 Research Results

Based on the established model, this paper explores the dynamic evolution characteristics of the arc and copper contact electrode surface temperature in transformer oil with the opening process, and investigates the influence of different peak chopped currents on the temperature distribution characteristics of the arc region.

3.1 Dynamic Process Arc Temperature Distribution Characteristics of Contacts Under 1500A Chopped Current

The contact erosion process was simulated for a peak interruption current of 1500 A and the temperature distribution in the arc region at different moments was obtained, as shown in Fig. 4.

As can be seen from Fig. 4, with the simulation time progressing, the contact spacing gradually increases and the arc temperature first increases sharply, up to 2.59×10^4 K. Then until the final moment of simulation 0.012 s, the arc temperature slowly decreases to 1.02×10^4 K. During the opening process, the shape of the arc gradually evolves from the initial arc column to arc wire shape, and the highest temperature is mainly concentrated in the arc center near the electrode area of the two contacts.

The changes of upper and lower electrode surface temperatures over time are shown in Fig. 5. As can be seen from Fig. 5, the arc generated in the breaking process has different influences on the surface temperature of the lower electrode on the contact. The surface temperature of the upper electrode is higher than that of the lower electrode, which is mainly caused by electron bombardment on the anode surface.

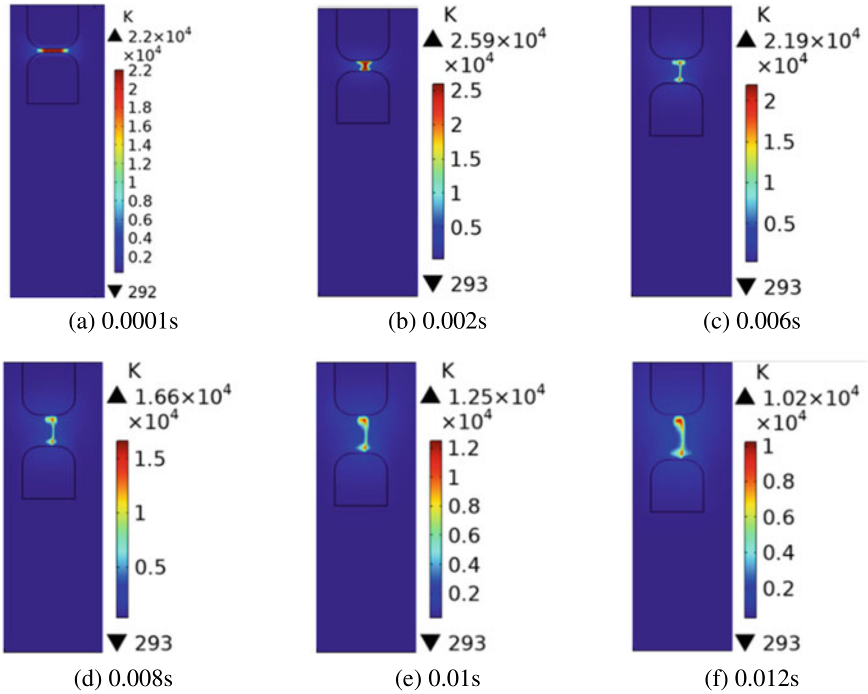
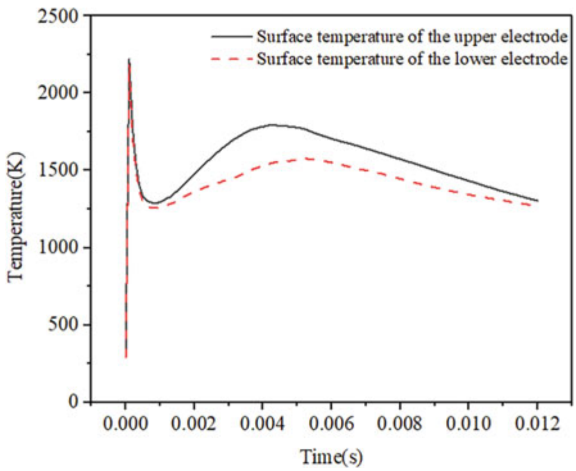


Fig. 4 Arc temperature distribution in transformer oil at different time of 1500 A chopped current amplitude

Fig. 5 Temperature distribution of upper and lower electrodes with a chopped current amplitude of 1500 A

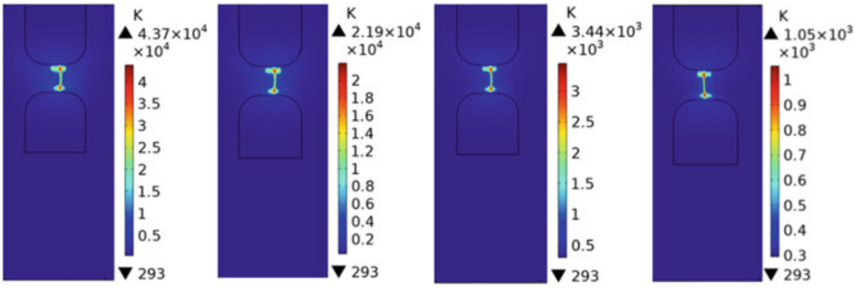


3.2 Characteristics of Peak Chopped Current on Arc Temperature Distribution in Oil

To investigate the effect of peak chopped current on the temperature distribution characteristics of the arc in oil, the temperature plots with the currents of 2100, 1500, 600 and 300A were selected for analysis at 0.012 s, as shown in Fig. 6.

When the chopped current reaches the maximum of 2100A at 0.012 s, the maximum temperature of the arc at the end of simulation can reach 4.37×104 K. With the decrease of the peak current, the arc temperature gradually attenuates to 2.19×10^4 K, 3.44×10^3 K and 1.05×10^3 K, respectively. The variation curve of the maximum temperature in the arc region over time under different current is shown in Fig. 7.

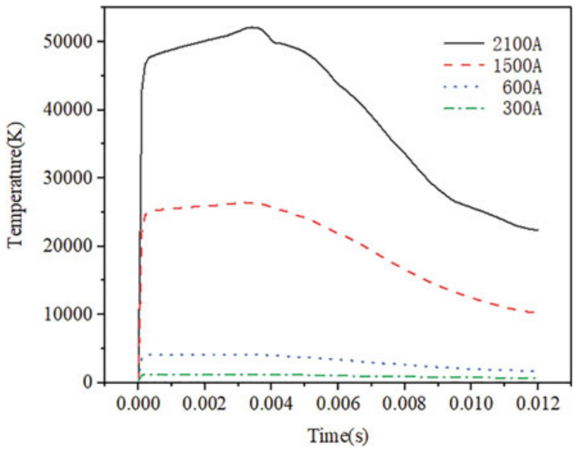
In the whole process of discharge, under different peak chopped currents, the arc temperature increases sharply first and then rises slowly. Gradually, it shows a decreasing trend after reaching the peak value. With the increase in peak chopped



(a) 2100A (b)1500A (c) 600A (d) 300A

Fig. 6 Arc temperature distribution in oil with different chopped current amplitudes at 0.012 s

Fig. 7 Curve of maximum arc temperature with time under different chopped current amplitudes



current, the peak arc temperature also increases. When the peak current is 2100 A, the arc temperature reaches a maximum of 52116 K.

3.3 *Effect of Arc on Temperature Field Distribution of Contact Electrode Surface*

Figures 8 and 9 respectively show the temperature distribution laws of the arc on the upper and lower electrode surfaces for different chopped current amplitudes

Similar to the law in Fig. 5, the surface temperature of the upper electrode is higher than that of the lower electrode due to the effect of the electron bombardment on the

Fig. 8 Temperature distribution curves of upper electrode surface with different chopped currents

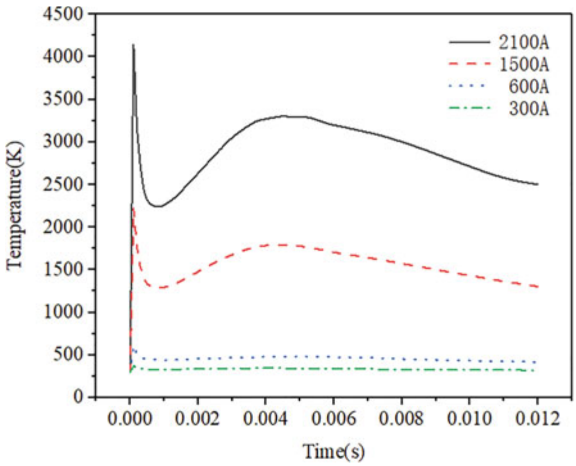
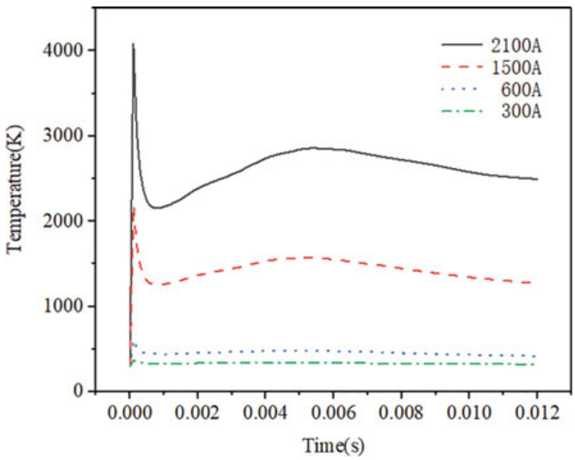


Fig. 9 Temperature distribution curves of lower electrode surface with different chopped currents



anode surface. The electrode surface temperature is closely related to the peak size of chopped current. When the maximum chopped current is 1500 A, the maximum electrode surface temperature is 747.02 K. When the minimum chopped current is 250 A, the maximum surface temperature of the upper electrode is just 306.6 K.

4 Conclusion

In this paper, a coupled multi-physical field simulation model of arc erosion on the main contact of an on-load tap-changer is established and the influence of arc erosion on the temperature change of the main contact is calculated for different chopped currents.

(1) During the current breaking process, the temperature of arc core rises rapidly first and then decreases slowly with the increase of breaking distance. The main reason is that the arc plasma channel is formed under the action of the initial moment of chopped current. After the arc is formed, the temperature rises rapidly. Later, with the increase of the opening distance, transformer oil convection occurs, which takes away part of the arc heat, making the arc temperature show a slow decline trend.
(2) At different chopped currents, the anode surface temperature is higher than the cathode surface temperature due to the electron bombardment of the anode surface. During the formation of an electric arc, there is a continuous thermal movement of electrons and ions. However, the electrons are moving much faster than the ions. The number of electrons impinging on the anode is much greater than that of the cations impinging on the cathode. As a result, the temperature of the anode is higher than the surface of the cathode in the arc process.

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