

# Research on burnout fault of moulded case circuit breaker based on finite element simulation

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**Abstract.** In the failure event of molded case circuit breaker, overheating of the molded case near the wiring terminal has a very important proportion. The burnout fault has become an important factor restricting the development of molded case circuit breaker. This paper uses the finite element simulation software to establish the model of molded case circuit breaker by coupling multi-physics field. This model can simulate the operation and study the law of the temperature distribution. The simulation results show that the temperature near the wiring terminal, especially the incoming side of the live wire, of the molded case circuit breaker is much higher than that of the other areas. The steady-state and transient simulation results show that the temperature at the wiring terminals is abnormally increased by increasing the contact resistance of the wiring terminals. This is consistent with the frequent occurrence of burnout of the molded case in this area. Therefore, this paper holds that the burnout failure of the molded case circuit breaker is mainly caused by the abnormal increase of the contact resistance of the wiring terminal.

## 1 Introduction

In the failure event of low-voltage circuit breaker, the molded case burn failures near the wiring terminal occupy the majority of the proportion. When low voltage electrical apparatus work, under the effect of electric current, the conductor will produce heat. Coupled with the trend of miniaturization of low voltage electrical apparatus led to increased heat is more obvious, so the heat analysis has become an important factor affecting its development <sup>[1]</sup>. People can use many simulation software to achieve temperature field analysis of low voltage electrical apparatus with high accuracy. People can establish foundation to prevent burning malfunction by simulation of wiring terminal failure and analysis of temperature distribution law.

In this paper, through increasing the terminal resistance to simulate the terminal failure caused by various factors, the steady-state and transient temperature distribution models under the action of multi-physics are established. Steady-state and transient simulation results show that the position near the wiring terminal, especially the incoming side of live wire has the highest temperature in the entire model area. This is consistent with the burning phenomenon of the molded case circuit breaker at the project site, and it is verified that the burn failure is caused by the failure of the wiring terminal.

## 2 The burnout failure and wiring terminals failure of molded case circuit breaker



### 2.1 Overheat burn failure of molded case circuit breaker

After the temperature beyond a certain range, the mechanical strength and dielectric strength of metal materials and insulation materials used in molded case circuit breaker will be significantly lower. Electrical work temperature is too high, its service life will be reduced, or even damage. According to the fault statistics, the burns because of switch overheat occupy a large proportion. The low-voltage circuit breaker failure statistics of a Chinese province in January-May 2014 are shown in Table 1 below.

Table 1: Statistics of low voltage circuit breakers in a province for 5 months.

Total amount of failure	Overheating burnout		Other reasons	
	Amount	Proportion	Amount	Proportion
67396	44532	66.1%	22864	33.9%

According to field experience, molded case circuit breaker burned in the location mainly near wiring terminal, shown in Figure 1 below<sup>[2]</sup>.



Figure 1: Burnout failure of molded case circuit breaker

The main causes of overheating burnout may be wiring terminal failure caused by oxidation and poor contact. After the transmission operation, the large contact resistance leads to its abnormal heat causing the decrease of dielectric strength, and then the circuit breaker may burn out.

### 2.2 The failure mechanism of the wiring terminals

The wiring terminals are the terminals themselves and the conductors connected to them. The active area is "contact interface", with contact resistance, and then generate heat due to the Joule effect. When a piece of metal is applied to the other metal, contact occurs at a certain number of points of the so-called "unit contact". Dust, oxide layer on the contact surface can increase the contact resistance. The main factors that affect the contact resistance are the properties of the conductor material, temperature, corrosion, and so on.

## 3 Mathematical model

The Joule heat field, the heat transfer field and the air flow field need to be coupled to establish the mathematical model of the molded case circuit breaker.

### 3.1 Joule heat field

In the molded case circuit breaker, wiring terminals and other electrical institutions in the voltage source generate current and heat, known as Joule heat. The Joule thermal equations represent the coupling between the electric field and the temperature field. Steady state with the following equation:

$$\nabla \cdot (-\sigma \nabla V + J_e) = Q_j \quad (1)$$

$$Q = J \cdot E = (\sigma E + J_e) \cdot E \quad (2)$$

$$E = -\nabla V \quad (3)$$

where  $V$  is potential;  $E$  is electric field intensity;  $J_e$  is current density generated by external current source;  $Q_j$  is the current source applied to the conductor, i.e., the bulk current density;  $\sigma$  is electrical conductivity;  $Q$  is the total heat generated by the Joule heat field.

For the transient Joule heat field, the formula (1) is rewritten as:

$$\nabla \cdot \left( -\sigma \nabla V + \frac{\partial D}{\partial t} + J_e \right) = Q_j \quad (4)$$

$$J_D = \frac{\partial D}{\partial t} \quad (5)$$

Among that,  $D$  is electric displacement;  $J_D$  is displacement current density.

### 3.2 Heat transfer field

Heat transfer is the process of transferring heat from high temperature to low temperature. There are three ways of heat transfer: heat conduction, thermal convection, heat radiation. In this model, the heat generated by the Joule heat field is  $Q$ , and the temperature  $T$  is obtained by solving the mathematical constraints of these three kinds of transfer modes, including the steady temperature field and the transient temperature field. The temperature field on the inner surface between the molded case circuit breaker and the ambient air is continuous.

#### (1) Thermal conduction

The heat  $Q$  generated by the Joule heat field is calculated by coupling to the heat transfer field for the next step. In this model, there is no material with a thermal conductivity of zero, so it is considered that there is a heat conduction phenomenon in the whole solution domain. The spatial distribution of temperature and changes over time are studied in the heat conduction problem, denoted by  $T(x, y, z, t)$ .

The heat transfer law is used to describe the transient heat transfer field as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) + \rho C_p u \cdot \nabla T = Q \quad (6)$$

where  $\rho$  is material density;  $C_p$  is heat capacity;  $Q$  is heat source, that is, the heat absorbed by the study object from the Joule heat field;  $k$  is thermal conductivity (related to material);  $u$  is the field variable in the convective term, and is set to velocity in this model.

The steady-state heat conduction equation is rewritten as:

$$\rho C_p u \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q \quad (7)$$

#### (2) Thermal convection

Thermal convection is a phenomenon that can not be neglected during heat transfer. For convective phenomena, the corresponding convective boundary conditions are used to describe the heat transfer between the system and the surrounding fluid. In this model, there is a convective heat flux between the boundary of the air fluid and the air fluid, and the steady-state equation and the transient equation are consistent:

$$-\mathbf{n} \cdot (-k \nabla T) = h \cdot (T_{\text{ext}} - T) \quad (8)$$

where  $\mathbf{n}$  is the vector of the boundary;  $h$  is heat transfer coefficient;  $T_{\text{ext}}$  is environment temperature.

#### (3) Thermal radiation

Thermal radiation is the radiation electromagnetic wave phenomenon caused by the temperature, and all object that the temperature is greater than the absolute zero can produce heat radiation. In general, thermal radiation can be converted to boundary conditions for mathematical definition. The steady-state equation is consistent with the transient equation:

$$-\mathbf{n} \cdot (-k \nabla T) = \varepsilon \sigma (T_{\text{amb}}^4 - T^4) \quad (9)$$

where  $\mathbf{n}$  is the vector of the boundary;  $\varepsilon$  is surface emissivity;  $\sigma$  is the boltzmann constant,  $\sigma=5.6696 \times 10^{-8} \text{W}/(\text{m}^2 \cdot \text{K}^4)$ ;  $T_{\text{amb}}$  is environment temperature.

### 3.3 Flow field

The flow field in this model is to solve the air flowing through the enclosed rectangular space around the molded case circuit breaker. The flow field is obtained by solving the momentum balance and the mass balance of each spatial coordinate  $(x, y, z)$ . The inlet speed is defined by the parabolic velocity profile of the fully developed laminar flow. In the exit position, the normal stress is equal to the outlet pressure and the tangential stress is zero. On all solid surfaces, the speed of the three spatial directions are set to zero.

The air flow field is set to incompressible laminar flow to solve the flow rate  $\mathbf{u}$ . The steady state flow field is described by the incompressible Navier-Stokes equation (N-S equation):

$$\rho(\mu \cdot \nabla) \mathbf{u} = \nabla \cdot \left[ -p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \right] + \mathbf{F} \quad (10)$$

$$\rho \nabla \cdot \mathbf{u} = 0 \quad (11)$$

Transient incompressible laminar flow is described as:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mu \cdot \nabla) \mathbf{u} = \nabla \cdot \left[ -p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \right] + \mathbf{F} \quad (12)$$

$$\rho \nabla \cdot \mathbf{u} = 0 \quad (13)$$

where  $\mathbf{u}$  is velocity vector distribution of flow field;  $\rho$  is fluid density;  $\mu$  is fluid viscosity;  $p$  is pressure;  $\mathbf{F}$  is volume force.

## 4 Finite element simulation

Finite element method (FEM) is a popular temperature field analysis method<sup>[3]</sup>. Finite element method is a numerical analysis method. The working principle is to separate the solution domain into a finite number of non-overlapping units. Select the appropriate nodes as the interpolation points in each unit, and then rewrite the dependent variables in the partial differential equations to be calculated as stiffness matrices and solve them by appropriate numerical methods. The 3D model of molded case circuit breaker is established by finite element simulation software, and the real working condition of molded case circuit breaker is simulated according to the model construction, material property definition and ambient air environment setting.

### 4.1 Finite element simulation model of molded case circuit breaker

The finite element method is used to model the material and mechanical structure of molded case circuit breaker. Then, the multi - physics field of electric field, heat transfer field and air flow field are coupled through each interface, and the complete finite element simulation model is established by applying the boundary conditions of each field. The finite element model is scientifically meshed before solving it, and the whole solution domain is divided into many interconnected sub-regions. Select the appropriate solver to get a convergent approximation and perform the appropriate post-processing as needed. The simulation of molded case circuit breaker model is shown in Figure 2.

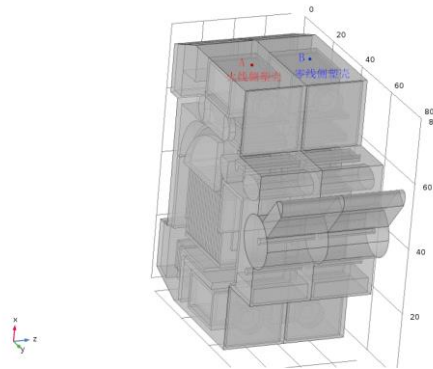


Figure 2: Molded case circuit breaker finite element model

#### (1) Material setting

The material of arc chamber is copper, wiring terminals for the iron material, and molded case is of flame retardant nylon 66. In addition, according to the foregoing analysis, in the molded case circuit breaker, the contact resistance at the wiring terminals increase due to various reasons. Therefore, in the simulation of the defect state, the conductivity of the wiring terminal and other related parameters must be corrected.

#### (2) Boundary conditions

According to IEC60898-2 provisions, the air temperature in the circuit breaker ambient does not exceed  $+40\text{ }^{\circ}\text{C}$ , and within 24 hours the average temperature does not exceed  $+35\text{ }^{\circ}\text{C}$ , with a temperature over  $-5\text{ }^{\circ}\text{C}$ <sup>[4]</sup>. The default ambient temperature is 293.15K. The current boundary value of the internal mechanism of the circuit breaker is set to  $1.5 \times 10^4\text{ A/m}^3$ , and the average velocity of the air flow field is  $5 \times 10^{-4}\text{ m/s}$ , which is set to incompressible laminar flow.

### 4.2 Steady state and transient simulation results

The steady state and transient model is established to calculate the temperature distribution of the molded case circuit breaker. According to the failure mechanism of the wiring terminal described in section 1.2 above, the increase of contact resistance of the wiring terminal is simulated by reducing the conductivity of wiring terminal.

#### (1) Steady-state analysis

The temperature distribution of molded case circuit breaker is analysed by the finite element simulation, and the reasonableness of failure mode is verified.

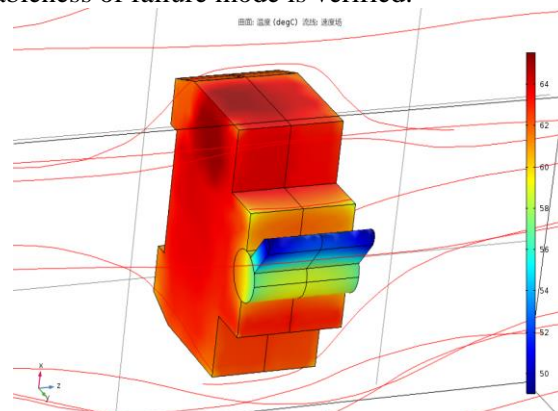


Figure 3: Steady temperature distribution under normal condition of wiring terminal

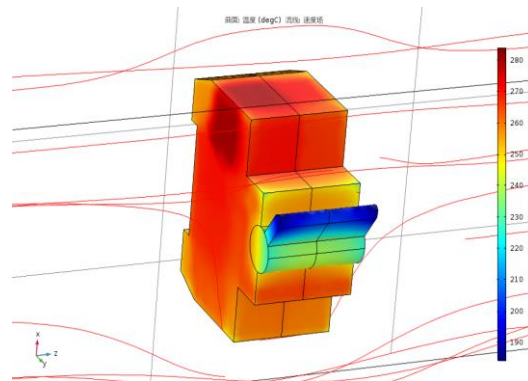


Figure 4: Steady-state temperature distribution interminals with increased contact resistance

From the steady-state simulation results in Figure 3 and Figure 4, the temperature near the wiring terminal, especially the incoming side of live wire, of the molded case circuit breaker is significantly higher than that of other areas. When the contact resistance of the wiring terminal is increased, the circuit breaker is abnormally heated, especially at the wiring terminal. The insulation properties and heat resistance of molded case is limited, so it is easy to occur near the wiring terminal of the molded case overheating burning phenomenon. The area with the highest temperature on the molded case of the circuit breaker conforms to the position of the molded case burned in the case of the actual fault shown in Figure 1.

## (2) Transient analysis

The transient temperature field of molded case circuit breaker is simulated by finite element simulation software, obtaining the temperature development process. Figure 5 shows the simulation results of the molded case circuit breaker transient temperature field at four time nodes.

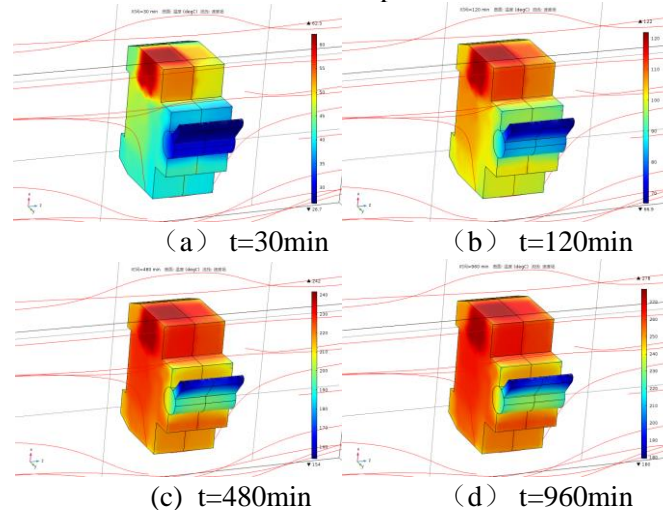


Figure 5: Transient temperature distribution at different time nodes

The above simulation results show that, over time, the temperature of molded case circuit breaker gradually increase, and eventually tend to steady temperature. Through transient analysis, the temperature distribution similar to the steady-state results can be obtained. As the current action the increase of the contact resistance, the temperature of the wiring terminal area rise the fastest with the maximum temperature.

The temperature data of the two points A and B, showed in Figure 1, on the side of the live wire and the zero line, and the lowest temperature of each time point are taken out to draw the scatter plot showed in Figure 6

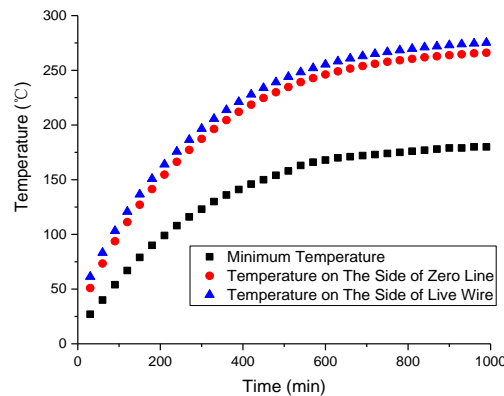


Figure 6: Three regions of the temperature development trend

As shown in Figure 6, the temperature rise of the molded case circuit breaker tends to be gentle over time. The temperature at the wiring terminal is much higher than the lowest, and the temperature at the side of live wire is higher than that of the zero line with constant temperature difference.

## 5 Conclusion

In the steady state and development process of temperature, the wiring terminal area, especially the incoming side of live wire, is the region with the highest temperature of the whole molded case circuit breaker. In addition, the increase of contact resistance caused by oxidation and other reasons for the wiring terminal will make the temperature increases abnormally, so it is prone to overheating failure for the molded case near the wiring terminal. The burnout failure of the molded case circuit breaker can be attributed to the increase in the contact resistance caused by the failure of the wiring terminal.

## Acknowledgements

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