Thermal-electrical Coupled Simulation Analysis of Sealed Electromagnetic Relays

Min Tian
Department of Mechanical and Electronic Engineering
Xi'an Technological University
Xi'an, 710021, China
E-mail: 18829238804@163.com

Feng Ding
Department of Mechanical and Electronic Engineering
Xi'an Technological University
Xi'an, 710021, China
E-mail: dd_feng@sina.com

***Abstract*—The heat generated during the working process of the relay directly affects the mechanical strength of the metal material and the dielectric strength of the insulating material. Sealed electromagnetic relays tend to be miniaturized. The effect of temperature on its working life is getting stronger. Therefore, it is very important to analyze the thermal characteristics of the main components inside the relay. The mathematical model of the thermal field is established by analyzing the heat transfer mode of the sealed electromagnetic relay and the boundary conditions of each component. The finite element model of the relay is established by the ideal equivalent method. This model has higher computational efficiency and accuracy than traditional computational models when performing thermal analysis. The temperature field of this model is studied by thermoelectric coupling method. The effects of ambient temperature and current intensity on the steady-state temperature field and transient temperature field of the sealed electromagnetic relay are discuss separately. The simulation results show that the ambient temperature is independent of the temperature distribution inside the relay and the current intensity will affect the main heat source type inside the relay. The research method of this paper can provide technical support for thermal characteristic analysis in the design stage of sealed electromagnetic relay.**

Keywords-Sealed Electromagnetic Relay; Thermal Analysis, Temperature Field; Heat Source

I. INTRODUCTION

The inside of the sealed electromagnetic relay is filled with nitrogen[1]. It has strong anti-interference ability, high reliability and long service life under harsh working conditions. Therefore, its application fields are extensive and the demand is extremely large[2]. With the improvement of the capacity and integration of power systems, the volume of sealed electromagnetic relays tends to be small[3] and manufacturing techniques are generally improved. The increase of heat productivity per unit volume can result in inner parts overheating thereby affecting the physical properties of the material. Therefore, the steady state and transient heating characteristics of sealed electromagnetic relays become important aspects of research[4].

The thermal analysis methods of switchgear mainly include Newton's heat calculation formula, thermal network method and finite element method[5]. The Newtonian heat calculation formula is used in the project to calculate the stable temperature rise of the electrical surface. The heat transfer process of electrical appliances is very complicated, it is difficult to establish a mathematical formula that considers various factors[6]. Therefore, its practical value of engineering is limited. Then the thermal network method is proposed based on the principle of thermal path and circuit similarity[7]. The thermal path model is established by analyzing the heat transfer path of the research object[8] and the heat field problem is simplified in the process. It has the advantages of clear concept and easy understanding. however, the complexity of model makes it difficult to determine the heat transfer path and the lumped thermal resistance parameter division scale. The resulting error will directly affect the final analysis results[9], and sometimes it is difficult to meet the needs of actual engineering. Finite element method is an efficient numerical method. It can simplify some definite solutions problem with complicated structure and boundary conditions. Widely used in various engineering fields. In recent years, Simulation software and computer simulation technology continue to improve. Realized the simulation of the temperature field of electronic components. The calculation results are relatively accurate, so it has great practical value in engineering.

In the later stages of electrothermal analysis, finite element thermal analysis of electrical appliances was performed using finite element analysis software and visualization techniques. In 1999, Kawase analyzed the temperature distribution of the thermal relay by using the three-dimensional finite element method, and verified the calculation results in the single-phase loop experiment[10]. In 2000, M. Lindmayer established a simplified model for thermal analysis of low-voltage circuit breakers. The temperature field of this model is obtained by thermoelectric coupling simulation analysis[11]. In recent years, Rockwell Labs has done a lot of research work on the thermal analysis of low-voltage switchgear, mainly include on mechanical, electrical and thermal coupling analysis. Rockwell's Frei and Weichert have done a lot of work on the heat calculation of motor breakers. They not only build a complete thermal calculation model, but also do a lot of work on the contact resistance and thermal resistance of contact and contact connections[12]. Many universities, research institutes and enterprises in China have carried out research on visual simulation technology in the field of electrical apparatus design. The research results they have obtained have been applied to the design of low-voltage electrical products.

In this paper, the heat conduction path of the sealed electromagnetic relay is determined, and a finite element model of the relay is established by the ideal equivalent method. The finite element model of the relay is established in ANSYS. The effects of ambient temperature and voltage intensity on the steady state and transient temperature field of the relay were analyzed by thermoelectric coupling method. The conclusions obtained will be of great significance for the optimal design of the relay.

II. Key Methods of Thermal-Electrical Coupled Analysis

A. Establishment of thermal-electrical coupling mathematical model

The heat transfer inside the sealed electromagnetic relay mainly includes heat conduction, heat convection and heat radiation. There are two or three heat transfer modes coexisting during the work, mainly heat conduction. There are two main heat sources inside the sealed electromagnetic relay. It is the Joule heat caused by the coil resistance when the current flows and the Joule heat caused by the contact resistance between the static and dynamic contacts. The heat is conducted from the two heat source elements to the other elements in the form of heat conduction. Then transmitted to the outer casing through the air gap in the form of heat convection. Finally transmitted to the atmospheric space by radiation and convection. The mathematical model of the thermal field is established by analyzing the heat transfer mode of the sealed electromagnetic relay and the boundary conditions of each component. The thermal-electrical coupling mathematical model of the relay is shown in Equation (1):

$$\begin{cases} \dfrac{\partial\left[K_x \dfrac{\partial T}{\partial x}\right]}{\partial x}+\dfrac{\partial\left[K_y \dfrac{\partial T}{\partial y}\right]}{\partial y}+\dfrac{\partial\left[K_z \dfrac{\partial T}{\partial z}\right]}{\partial z}+q_1+q_2=0 \\ \dfrac{\partial\left[K_x \dfrac{\partial T}{\partial x}\right]}{\partial x}+\dfrac{\partial\left[K_y \dfrac{\partial T}{\partial y}\right]}{\partial y}+\dfrac{\partial\left[K_z \dfrac{\partial T}{\partial z}\right]}{\partial z}+q_1+q_2=pc\left[\dfrac{\partial T}{\partial t}\right] \\ \alpha\left(T-T_0\right)=-K\dfrac{\partial T}{\partial n} \\ T\big|_{t=0}=T_0 \end{cases} \quad (1)$$

Where K is the thermal conductivity, q_1 and q_2 are the internal heat source, n is the normal vector on the boundary surface, ∂ is the surface heat dissipation coefficient, T is the object temperature, T_0 is the medium temperature.

B. Establishment of three-dimensional finite element model of the whole device

1) Establishment of an ideal equivalent model

The traditional method of analyzing the temperature field of a sealed electromagnetic relay is to establish two solid models. The contact system of one model is in the disconnected state, and the contact system of the other model is in the closed state. The calculation result of the closed model is specified as the initial condition for disconnecting the model, and vice versa. There are two drawbacks to this method. One is that the finite element meshes of the two models are different. It is difficult to make all the temperature points correspond to each other in the process of mutual allocation, resulting in data errors. Other is manual operation makes the assignment process error-prone and extremely inefficient. The two working states of the relay are simulated with one model, and the data of the two working states can be automatically assigned. Which is important for improving the accuracy and computational efficiency of calculation results. This article can achieve this by using the ideal equivalent method to build the model.

There is a difference between the ideal equivalent model and the traditional mode. It simulates the contact resistance between contacts by creating a small cylinder between the contacts. At the same time, the magnetic gap is filled with a certain volume of material. The relay changes the working mode by changing the material properties of the cylinder and the filler. When the contact system of the relay is in the disconnected state, the properties of the material are the same as those of the internal gas. when the contact system of the relay is in the closed working state, the material properties of the cylinder and filler correspond to the material properties of the contacts and Iron core.

2) Meshing of the model

Meshing is a crucial step in the finite element simulation analysis. The number and quality of the mesh will directly affect the accuracy of the simulation results. In this paper, the unit types SOLID87 and SOLID227 for thermal-electrical coupling field analysis are selected. The components of the solid model are assigned corresponding element properties. ANSYS software includes three methods of meshing: free meshing, scanning meshing and mapping meshing. The structure of the analysis object in this paper is very complicated, so the free mesh method is adopted. The three-dimensional finite element model of the sealed electromagnetic relay is shown in Figure 1:

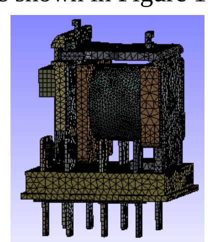


Figure 1. Finite Element Model of Sealed Electromagnetic Relay

C. Set the load and boundary conditions of the relay

1) Calculation method of thermal load

There are two main heat sources inside the sealed electromagnetic relay. It is the Joule heat caused by the coil resistance when the current flows and the Joule heat caused by the contact resistance between the static and dynamic contacts.

The control coil generates Joule heat when the current is passed, and is regarded as the internal heat source of the relay when calculating. The heating power of the coil is shown in Equation (2):

$$P_1=\frac{U^2}{R_1} \quad (2)$$

Where U is the Coil voltage, R_1 is the Coil resistance.

The coil heat generation rate is shown in Equation (3):

$$q_1 = \frac{P_1}{V_1} \tag{3}$$

Where V1 is the Coil volume.

The conductive loop of the contact system is analyzed by direct thermal electrical coupling method. Select all nodes of the static contact, the voltage value is set to 0. The coupled moving contact guides the node voltage of all nodes on the foot end, acquires the concentrated node and applies different current sizes.

The heating power of the conductive loop of the contact system is shown in Equation (4):

$$P_2 = I^2 R_2 \tag{4}$$

Where I is the contact system current, R_2 is the contact system resistance.

2) Determination of surface heat dissipation coefficient

There are two cases of the natural convection heat transfer of components of the sealed electromagnetic relay. The first is to seal the internal components of the electromagnetic relay, its surface belongs to small space natural convection. The second is to seal the external terminals of the electromagnetic relay and the relay housing exposed to the air, the surface of which is a large space natural convection.

In actual engineering applications, the heat transfer with convection and radiation is called composite heat transfer. The composite heat transfer coefficient α_τ is the sum of the convective heat transfer coefficient α_{conv} and the radiation heat dissipation coefficient α_{rad}. The calculation method of the comprehensive heat dissipation coefficient is shown in Equation (5):

$$\alpha_t = \alpha_{conv} + \alpha_{rad} \tag{5}$$

According to formula (5), the comprehensive heat dissipation coefficient at different ambient temperatures is calculated as shown in Figure 2.

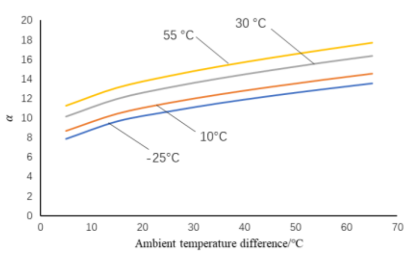
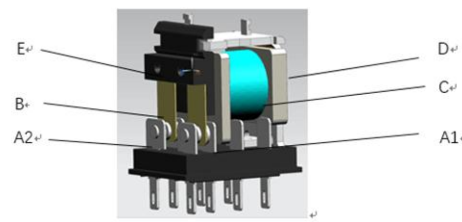


Figure 2. Comprehensive heat dissipation coefficient at different ambient temperatures

III. Results of Thermal-Electrical Coupled Analysis

A. Simulation analysis of steady-state temperature field

The reliability of the sealed electromagnetic relay directly affects the performance of the automatic control system. The sealed electromagnetic relay studied in this paper must be able to function normally in the range of large ambient temperature range of -25 °C to +55 °C. Therefore, it is of great theoretical and practical significance to conduct thermal analysis of sealed electromagnetic relays. This chapter mainly uses ANSYS software to calculate the steady-state temperature field of sealed electromagnetic relays under long-term working systems. At the same time, Study the effect of ambient temperature and current on the temperature field of the relay. The key points of the thermal analysis are shown in Figure 3.



A1—Static contact A2—Moving contact B—Reed
C—Coil D—Coil bobbin E—Yoke

Figure 3. Key points selected inside the sealed electromagnetic relay

Sealed electromagnetic relay performs steady-state thermal analysis in ANSYS software including pre-processing, solving and post-processing. Pre-processing work has been completed in Sections 2 and 3. The geometric model of the sealed electromagnetic relay was established by using UG software. The material properties were defined and mesh in ANSYS software to obtain the finite element model. Next, we need to solve based on the existing finite element model. A heat generation rate load is applied to the control coil, and a thermal-electrical coupling analysis is performed on the main circuit. Convective heat dissipation constraints are applied to the surface of each component, and then solved. After the solution is completed, the calculation results are viewed by the general post processor and analyzed.

1) Influence of Ambient Temperature on Steady-State Temperature Field of Sealed Electromagnetic Relay

The working area of the sealed electromagnetic relay is different, and there is a big difference in the ambient temperature. It must ensure that the system works stably in a variety of complex environments. Therefore, the relay must ensure its reliability over a wide range of ambient temperature variations. Considering the above reasons, this paper selects the temperature range of -30 ℃, -10 ℃, 20 ℃, 40 ℃ and 60 ℃ to study the effect of ambient temperature on the steady temperature field of sealed electromagnetic relay. Temperature distribution at different ambient temperatures during long-term work is shown in Figure 4.

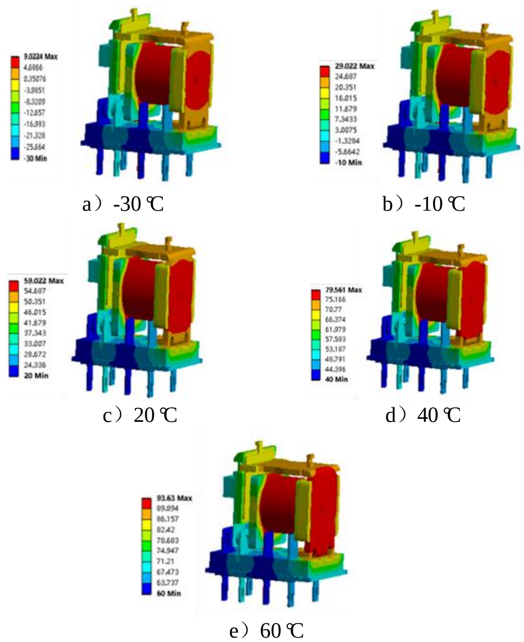


Figure 4. Temperature distribution at different ambient temperatures during long-term work

The simulation results show that the highest temperature point does not shift with the change of ambient temperature. The temperature change trend of each key point under different ambient temperatures is shown in Figure 5.

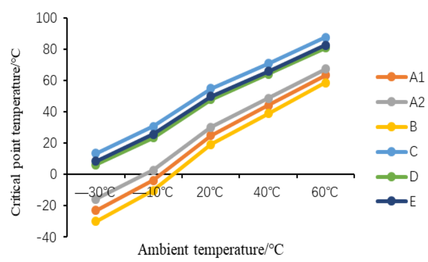


Figure 5. The temperature of each key point as a function of ambient temperature

It can be seen from the above Figure 5 that the temperature of the relay rises as the ambient temperature increases. The highest temperature point is at the coil. The temperature distribution of each part of the relay is relatively uniform.

2) Effect of Current Intensity on Steady-State Temperature Field of Sealed Electromagnetic Relay

The ambient temperature is set to 20℃. The temperature field distribution of the sealed electromagnetic relay when the load current is 10A, 20A, 30A and 40A respectively is shown in Figure 6.

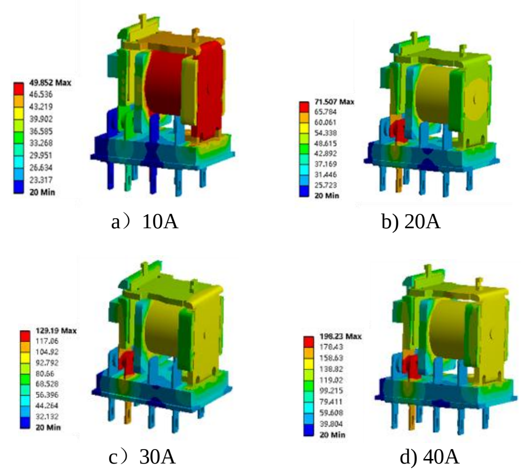


Figure 6. The internal temperature distribution of the relay under different current intensities

As can be seen from the above Figure 6, when the load current of the relay is 10A, the highest temperature point inside is located at the coil part. When the current increases by 10A，30A and 40A, the highest temperature point of the relay appears in the contact and its surrounding parts. The position of the highest temperature point changes with the change of current. The heat generated by the coil resistance is the main heat source of the relay when the load current is 10A. The heat generated by the contact resistance is the main heat source when the load current is greater than 10A. Therefore, the contact resistance of the sealed electromagnetic relay should be strictly controlled when a large load current is applied. This is critical to ensure the work reliability of the relay.

B. Simulation analysis of transient-state temperature field

The ambient temperature is set to 20 °C. This paper investigates the distribution of transient temperature fields of sealed electromagnetic relays when 10A, 20A, 30A and 40A load currents are applied. The limit stable temperature values of the key components inside the relay at different current intensities are shown in Figure 7.

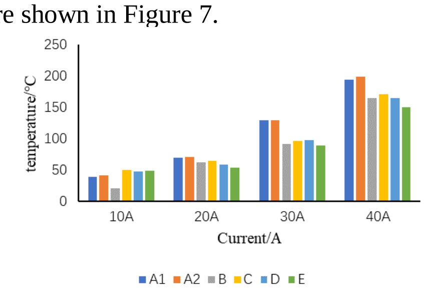
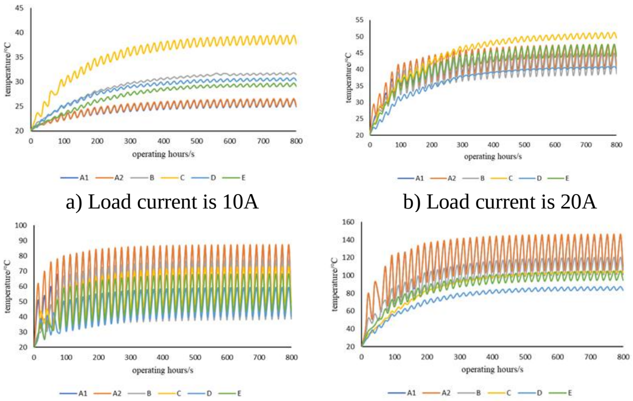


Figure 7. Stable temperature of each key component at different current intensities

The working period of the relay is 20s. Its contact system has a closing time of 12s and a disconnection time of 8s. It is set to work for 40 cycles. The temperature values of the key components at the end of the contact closure and contact breakaway are selected once every five working cycles. The temperature change trend of key parts are shown in Figure 8.



a) Load current is 10A b) Load current is 20A

c) Load current is 30A d) Load current is 40A

Figure 8. Temperature change of each key point with time under different load currents in short-time working

It can be seen from the Figure 8 that in the early stages of relay work, the temperature of its internal key components rises rapidly with time. When the number of operations reaches a certain value, the temperature value of the key component fluctuates with a similar amplitude.

The time required for each key component of the relay to reach the ultimate stable temperature at different current grade is approximately constant. Although the relays have different stable temperature values under different load currents, the time required to reach a stable temperature is constant.

The limit stability temperature of each key component increases as the current grade increases. When the load current is set to 10A and 20A, the temperature distribution of the relay is relatively uniform, and the coil element has the highest temperature. Contacting element has the highest temperature when the load current is 30A and 40A. According to the simulation results, the maximum temperature point of the relay will shift with the increase of the current grade.

IV. CONCLUSIONS

In this paper, the finite element model of sealed electromagnetic relay is established by ideal equivalent method. This model can be used to simulate two working states of a relay. The effects of ambient temperature and current intensity on the steady-state temperature field and transient temperature field of the sealed electromagnetic relay were obtained by thermal-electrical coupling method. The following conclusions are gotten:

- When the sealed electromagnetic relay works under the same current grade, its temperature distribution law is not affected by the ambient temperature change. The temperature of each part increases as the ambient temperature increases.
- When the sealed electromagnetic relay works in the same ambient temperature, its main heat source is not affected by the working mode. The main heat source of the relay in the case of small load current is the heating power of the coil, and its temperature distribution uniformity. When the relay is applied with a large load current, its main heat source is the contact heating power, and the temperature distribution inside the relay is not even.

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