Development of Fault Detection Device for Dry-Type Reactor Based on Infrared Remote Sensing

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Abstract: First of all, the heat transfer and heat dissipation process of the dry-type reactor are studied. Combining with the theory of inverse heat transfer problem and the actual operation of the dry-type reactor, a calculation model of the hot-spot temperature for dry-type reactor windings is obtained by using the conjugate gradient method. Finally, a set of on-line monitoring system for winding temperature of dry-type reactor is built.

Keywords: dry-type reactor; hot-spot temperature of windings; inverse heat transfer problem on-line monitoring.

1. INTRODUCTION

Dry-type reactor is the main auxiliary equipment in the long-distance AC transmission system, which is mainly used to limit the short circuit current of the system and compensate the reactive capacity of the system. Under the normal current and voltage, the reactor in operation will cause internal loss and heat generation, which will increase the temperature of the reactor, but the temperature rise will be within the allowable range, and the phenomenon of local overheating will not occur. When there is a defect in the reactor, the temperature of the reactor, especially the defect part, will increase significantly. When the reactor fails, 90% of the reactor will also experience local temperature overheating. The external insulation of dry-type reactor adopts the epoxy resin solidification molding process. It is easy to cause partial discharge during operation, resulting in overheating of insulation materials. Class B insulation materials used in reactors have a maximum operating temperature of 130 °C and a maximum temperature of 80 °C. When the temperature exceeds the maximum permitted operating temperature, the service life of insulating materials will be reduced by half by 10 degrees per increment [1].

At present, non-contact live detection methods mainly include infrared imaging and ultraviolet imaging technology. The instruments used are expensive, bulky and inconvenient for testing. In addition, the existing detection methods lack a method for evaluating the internal temperature of the device and cannot evaluate the internal defects of the device.
Therefore, it is of great significance and practical value to use the theoretical model to calculate the temperature field distribution of the reactor and apply the appropriate infrared temperature measurement method. The purpose of this paper is to use infrared remote sensing technology to judge the fault of the power system. It can not only detect the fault of the power equipment at a long distance to improve the detection efficiency but reduce the volume of the detection device as well.

2. ANALYSIS OF HEAT TRANSFER AND HEAT DISSIPATION OF DRY-TYPE REACTOR

2.1 Analysis and calculation of the heat generation of the dry-type reactor

The various losses in the power equipment are the excitation sources that cause the temperature to rise. Therefore, the accurate calculation of the loss distribution is a necessary condition for the study of the temperature field [2-3]. The heat source of the reactor is mainly the resistance loss of the winding and the eddy current loss in the winding.

The thermal analysis of the reactor loss is equivalent to a homogeneous heating body, which assumes that the heat generated on the windings is a constant value when the heat balance is reached, and the heat generation rate per unit volume of the winding is used as the heat source to be applied as a load, as shown in formula (1).

\[
q = \frac{P}{V}
\]  

(1)

In the formula: \(q\)——the unit volume heat generation rate of the winding;  
\(V\)——the total volume of the winding;  
\(P\)——the loss of the winding.

2.2 Analysis and calculation of the heat dissipation of the dry-type reactor

As with other objects, the heat dissipation of a dry reactor is also mainly achieved by heat conduction, thermal convection, and heat radiation. The interior of the reactor is thermally conducted by heat conduction, and the surface is dissipated by natural convection and radiation.

According to the principle of heat transfer, the heat transferred by heat conduction per unit time is proportional to the area and temperature gradient perpendicular to the heat flow cross section, and the expression is (2).

\[
q = -\lambda S \frac{dT}{dx}
\]  

(2)

In the formula:  
\(q\)——thermally conductive heat flow, the amount of heat passing through a constant cross section per unit of;  
\(S\)——cross-sectional area perpendicular to heat flow;  
\(\frac{dT}{dx}\)——the temperature increase along the heat flow in this section;  
\(\lambda\)——thermal conductivity.
Heat radiation is the energy emitted by a substance at a certain temperature, and the actual heat emission from the surface of the object can be expressed in the modified form of the Stefan-Boltzmann law, as shown in formula (3).

\[ q_{12} = \varepsilon_1 \sigma S_1 F_{12} (T_1^4 - T_2^4) \]  

\[ (3) \]

In the formula: \( q_{12} \) —— the heat transferred from the surface of the object 1 to the surface of the object 2 through radiation;
\( \varepsilon_1 \) —— surface emissivity of object 1;
\( \sigma \) —— Stefan-Boltzmann constant;
\( S_1 \) —— radiation area of object 1;
\( F_{12} \) —— angle coefficient from radiating surface 1 to radiating surface 2;
\( T_1, T_2 \) —— absolute temperature of surface of object 1, object 2.

Convection cooling is the process of heat exchange between a solid surface and a moving fluid. The heat of convection can be expressed in Newton's law of cooling as shown in equation (4).

\[ q = \alpha S (T_f - T_w) \]  

\[ (4) \]

In the formula: \( q \) —— convection heat transfer;
\( \alpha \) —— convective heat transfer coefficient;
\( S \) —— convective heat transfer area on solid surface;
\( T_f \) —— fluid temperature;
\( T_w \) —— the temperature of the solid surface.

### 2.3 An overview of the inverse heat transfer problem

The positive solution to the heat transfer problem is the consistent geometry, thermophysical parameters, initial conditions, and boundary conditions of the object, and the temperature distribution variations within the object (including the boundary) are solved. There is also a class of inverse solutions to the heat transfer problem, namely the inverse problem of heat transfer. The inverse problem of heat transfer theory is characterized by: using experimental means to measure the temperature of some point or some points of the object, by solving the differential equations of heat conduction, to obtain the boundary conditions of the surface of the object, the convection heat transfer coefficient of the surface, the internal heat source term or Initial conditions and so on [4]. Based on the theory of inverse heat transfer and the theory of heat generation and heat dissipation of reactors, the inverse problem of heat transfer in reactors is established.

### 3. DRY-TYPE REACTOR HEAT TRANSFER MODEL

#### 3.1 Radiation heat transfer model between inner and outer encapsulating windings

First, a physical model of three-dimensional radiation heat transfer between inner encapsulating winding and outer encapsulating winding is established. The heat transfer between the inner encapsulating winding and the outer encapsulating winding is mainly through the heat radiation, that is, the inner surface of the outer encapsulating winding (G
surface in Fig. 1 and will be represented by G surface in the following) and the outer surface of the inner encapsulating winding (F surface in Fig. 1 and will be represented by F surface in the following) transfer heat through the heat radiation, which affects the distribution of the temperature field of the outer wrapping winding. The G surface is decomposed into a number of equal-area small heating elements, and the inner surface of the outer envelope winding is decomposed into a number of small surface elements each of which receives the heat radiation of the inner envelope-wrapping winding. Each heat-generating facet element and each accepting facet element constitute a Lambertian radiator whose characteristics are consistent with Lambert's radiation theorem [5].

Fig 1. Inner and outer encapsulating winding radiation heat transfer model

The G surface is decomposed into $M \times N$ heat emission small facets, the F face is decomposed into $M \times N$ heat receiving small facets, and the E face is also decomposed into $M \times N$ small facets. The coordinates of the facet $\Delta S_y$ of the i-th row and the j-th column on the G surface are $(x_i, y_i, z_i)$, the area of the fact is $\Delta S_y$, the center temperature is $T_y$, and the radiant intensity is $I_q$. The area of $\Delta A_{mn}$ in the m-th row and n-th column on the F surface is $\Delta A_{mn}$, and the coordinates are $(x_m, y_n, z_m)$. The radiation flux density $q_{\Delta A_y \rightarrow \Delta A_{mn}}$ that $\Delta S_y$ project onto the face element $\Delta A_{mn}$ is shown in formula (5). The density of the radiative flow generated by the facet $\Delta A_{mn}$ of the $M \times N$ facets $\Delta S_y (i = 1,2,...M; j = 1,2,...N)$ is accumulated, and the total radiative density $q_{\Delta A_{mn}}$ of the facet $\Delta A_{mn}$ is obtained as a formula (6).

$$q_{\Delta S_y \rightarrow \Delta A_{mn}} = \frac{\sigma T_y}{\pi} \Delta S_y \times \frac{y_g^2}{(x-x_y)^2 + y_g^2 + (z-z_y)^2}$$  \quad (5)$$

$$q_{\Delta A_{mn}} = \sum_{i=1}^{M} \sum_{j=1}^{N} q_{\Delta S_y \rightarrow \Delta A_{mn}}$$  \quad (6)$$
3.2 Three-dimensional heat conduction mathematical model of outer encapsulating winding

In the solving of the flow and heat transfer problems, the required governing equation for the main variables (velocity, temperature, etc.) can be expressed in a general form [6], that is, formula (7) represents.

\[
\frac{\partial \rho \phi}{\partial t} + \text{div}(\rho \mathbf{U} \phi) = \text{div}(\Gamma \phi \text{grad} \phi) + S \phi
\]  

(7)

Specifically, for the thermal conduction inside the outer envelope winding, the governing equation is formula (8).

\[
k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + \frac{P}{V} = 0
\]  

(8)

Where \( P \) is the loss of the outer envelope winding and \( V \) is the outer envelope volume of the winding, \( k_x, k_y, \) and \( k_z \) are the thermal conductivity in the \( x, y, \) and \( z \) directions, respectively. In order to make the solution of the governing equation (8) uniquely determined, the boundary conditions corresponding to the specific heat transfer problem must also be given. The two sections of the encapsulating windings are treated by the adiabatic surface when the equation of boundary conditions is written out [7]. The boundary condition of heat transfer equation for outer wrapping winding is given.

\[
\begin{align*}
-k_x \frac{\partial T}{\partial x} &= 0, x = 0, x = x_g \\
-k_z \frac{\partial T}{\partial z} &= \alpha(T - T_s), z = 0 \\
-k_z \frac{\partial T}{\partial z} &= \alpha(T - T_s), z = z_g \\
-k_y \frac{\partial T}{\partial y} &= \alpha(T - T_s), y = 0 \\
-k_y \frac{\partial T}{\partial y} &= q_{\Delta m}, 1 \leq m \leq M, 1 \leq n \leq N, y = y_f
\end{align*}
\]  

(9)

Where \( \alpha \) is the convection heat transfer coefficient after the folding of each boundary, \( k_x, k_y, \) and \( k_z \) are the thermal conductivity of \( x, y, \) and \( z \) direction in the outer encapsulating winding, \( T \) is the temperature of the outer surface of the outer encapsulating winding, \( \rho \) is the density of the outer enveloping winding material, that is, the density of the copper material, \( c \) is the specific heat capacity of the outer layer encapsulated winding, that is, the specific heat capacity of the copper material, and \( T_s \) represents the ambient temperature.

3.3 An inverse heat transfer model for internal and external encapsulating windings

The conjugate gradient method to solve the inverse problem of heat transfer can be simply described as estimating the heat flux density of the inner surface of the outer encapsulating winding by monitoring the temperature of the outer surface of the outer encapsulating winding, and accurately identify the heat spot temperature of the inner encapsulating winding and spatial location.
First of all, it is necessary to initialize the space vector $M$ of the parameters required to determine the temperature and position of different heat surface elements on the outer surface of the inner encapsulating winding. $M = (T_{ij}, x_{ij}, z_{ij})(i = 1, 2, ..., M, j = 1, 2, ..., N)$. Initialize vector $M$ based on simulation data or actual experience, the initial $M$ is substituted into equation (5) and (6), and the heat flux distribution $q_M(x, y, z)$ of the outer encapsulating winding is solved. The resulting heat flux distribution is substituted into equation (8) and (9) to solve the temperature distribution $T_{mn}$ of the outer surface of the outer encapsulating winding. At the same time, the temperature distribution $Y_{mn}$ of the outer surface of the outer encapsulating winding is measured with a portable infrared sensor. The obtained $T_{mn}$ and $Y_{mn}$ are substituted into (10) to determine whether it is established. If it is true, $M$ is considered as the current optimal solution. If it is false, the above steps are repeated after the correction is made.

$$f(M) = \sum_{m=1}^{M} \sum_{n=1}^{N} (T_{mn} - Y_{mn})^2 < \varepsilon$$  \hspace{1cm} (10)

If the formula (2-11) is not established, the following corrections are made to the phasors: Let $M^{k+1} = M^k + \lambda^k P^k$, $\lambda^k$ is the iteration step size of $k$, $P^k$ is the optimal search direction from $k$-th to $k+1$-th, $\lambda^k$ and $P^k$ satisfy the formulas (11) and (12), respectively. The calculation flow chart is shown in (2).

Fig 2. The flow chart of the 3D inversed-heat transfer model
4. RESEARCH ON ON-LINE MONITORING SYSTEM FOR WINDING TEMPERATURE OF DRY-TYPE REACTOR

4.1 Hardware structure of on-line monitoring system for winding temperature of dry-type reactor

This article has designed a set of on-line temperature monitoring system of infrared remote dry-type reactor windings, which mainly consists of the following parts: The main task of the infrared detection device hardware circuit is the real-time surface temperature, ambient temperature and other conditions of long-distance detection. The data transmission system is responsible for transferring the collected equipment temperature and other data to the analysis platform. The comprehensive data analysis platform manages the entire temperature monitoring system, completes the recording and analysis of temperature parameters, and estimates the temperature distribution of the equipment based on the detection results and the ambient temperature to determine the degree of defect.

Taking into account the measurement needs and costs, select the S101 infrared temperature sensor, and select the corresponding accessories power supply, laser sighting device and the range finder needed to correct the error, and package them in the PCB box. The physical map is shown in Figure 3.

![Infrared temperature sensor with accessories](image)

The data acquisition uses the PCI-9812 data acquisition card with high-efficiency and reliable data acquisition capabilities produced by Taiwan's ADLINK Technology Corporation.

In high-frequency analog signal acquisition applications, to ensure that the signal transmission process does not reflect to the measured signal source, we must ensure that the source impedance and the target impedance match, that is, in the data acquisition before adding impedance matching and impedance conversion signal Conditioning circuit. The minimum load impedance of the S101 infrared temperature sensor is 10k Ω, while the input impedance of
the PCI-9812 data acquisition card can be adjusted to 50 Ω, 1.25k Ω, or 15M Ω, but at the same time in order to prevent signal reflection on the line, the signal conditioning circuit is designed to convert the impedance to 50 Ω, while setting the corresponding solder joints on the PCI-9812 solder plate to adjust the input impedance to 50 Ω, and the input voltage is ±5V.

![Fig 4. The design of signal conditioning circuit](image)

**4.2 Correction of Temperature Online Monitoring System Based on Influence Factors of Measurement Accuracy**

The factors influencing the measurement accuracy of the infrared temperature sensor mainly include the target emissivity, the ambient temperature, and the measurement distance [8]. The charged device requires a certain safety distance when measuring, so the measuring distance must not be too small, and the effect of the measuring distance on the measurement accuracy needs to be taken into account when correcting. The method of error correction produced by the distance adopts the method of error proportional factor fitting proposed in [9].

**4.3 On-line monitoring system for winding temperature of dry-type reactor**

This paper uses the Labview software to compile the data display interface, including three aspects:

(1) Data acquisition card parameter settings. Data is collected through the 0 channel; a relatively high sampling frequency can ensure the accuracy of the temperature signal acquisition; the sampling frequency of this experiment is set to 1 MHz; the sampling clock selects the internal clock.

(2) The interface shows the change curve of the outer encapsulating winding temperature collected by the temperature sensor in real time, the temperature-distance compensation of the measured temperature curve is made, and a correction curve of the outer encapsulating winding temperature is obtained, so that the operator can grasp the trend of the temperature change of the outer envelope winding in real time.

(3) Status Display. The interface displays the temperature value of the monitoring point in real time. The dry-type reactor temperature warning threshold is set. When the warning threshold is exceeded, the operator is prompted.
5. CONCLUSION

The research on the hot spot temperature of the windings of dry-type reactors is not only conducive to the reasonable selection of insulation materials in the design phase of the reactors to reduce the cost of reactors, but also can take corresponding measures to improve the reactor in the reactor operating phase according to the changes of the hot spot temperature of the windings. The safety, reliability, economic efficiency of the operation stage, and the research of the reactor winding hot spot temperature have important significance for ensuring the safe and stable operation of the system. In this paper, based on the results of heat transfer and heat dissipation of dry reactors and on-line temperature measurement system of dry-type reactor windings, the main conclusions are:

(1) The encapsulating windings of the dry-type reactor vary little in the circumferential temperature range, that is, are evenly distributed in the circumferential direction. The temperature of the encapsulated windings is unevenly distributed in the axial direction. (2) The temperature distribution along the axial direction is as follows: the temperature gradually increases from the lower layer to the upper layer along the axial direction. The temperature rises quickly at the beginning, and the temperature increases as the height increases. Slowly, to the upper middle, the temperature dropped slightly.

REFERENCES


