Heat dissipation characteristics of anode saturable reactors with high thermal conductivity epoxy resin used for ultra-high-voltage direct current converter valves

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Abstract: A saturable reactor is one of the important components of converter valves in high-voltage direct current transmission systems. With the ever-increasing capacities of converter valves, the heat losses generated by saturable reactors are also increasing. Thus, a thermal–fluid mechanics coupled heat dissipation model for saturable reactors is proposed. In order to study the factors affecting the thermal dissipation in the saturable reactor, the epoxy resin insulating layers with different thermal conductivity were considered in this work. The simulation results showed that the hot spots in the saturable reactor are on the iron core and close to the pipe inlet that most of the generated heat can be extracted by a cooling pipe and that the effect of heat dissipation can be improved by raising the thermal conductivity of the epoxy resin. The thermal conductivities of the epoxy resin used in the two reactors were 0.8 and 1.2 W/mK, respectively. The time dependence of the iron core temperature was in accordance with the simulation results and the maximum temperatures of the saturable reactor were also consistent with the simulation results. By increasing the thermal conductivity of the epoxy insulation layer, the temperature of the iron core could be significantly reduced.

1 Introduction

As a crucial component of converter valves, a saturable reactor is employed to inhibit excessive growth of the current during the opening of a thyristor. With the increase in power capacity or voltage level of ultra-high-voltage direct current (UHVDC) converter valves, the losses of saturable reactors are also on the increase, especially those of their iron cores. Excess heat and increased temperatures generated by running saturable reactors will lead to local overheating [1–3]. Overheating will accelerate the thermal ageing of the epoxy insulating layer, and thus reduces its service life, and will also cause the terminal failure of the iron core.

To reduce the temperature that the saturable reactor reaches, an air cooling system was used in the first few generations of converter valves. In the 1970s, two main alternative solutions based on water cooling and freon cooling were developed [4]. As a result of the adverse environmental effects of freons, the water cooling system has been more frequently used since, due to its high thermal capacity, simple system design, and the absence of permissions required with regard to environmental laws and restrictions. The coil winding of the saturable reactor in the epoxy encapsulation layer is part of the water cooling system. Epoxy resin serves as the main insulating material for the encapsulation of the coil winding [5–10] and the thickness of the epoxy encapsulation layer between the iron core and the winding is typically 10 mm. The thermal conductivity of the epoxy encapsulation layer is the key factor affecting the heat dissipation efficiency of the iron core [11–15]. The thermal conductivity of a conventional epoxy encapsulation layer is about 0.5–0.6 W/mK, which is relatively low, and cannot meet the actual operating conditions of a saturable reactor. Prediction and analysis based on heat conduction theory show that the high thermal conductivity of the epoxy encapsulation layer will increase the heat dissipation of the iron core and thus reduce its temperature, or that of the running saturable reactor, and vice versa. When the thermal conductivity of the epoxy encapsulation layer is greater than 1.0 W/mK, the iron core temperature can meet the current operating conditions [16, 17].

Most of the studies on saturable reactors thus far, however, have focused mainly on operation control analysis and optimal design [18–25]. Little research has been carried out involving thermal calculations for saturable reactors, which have important practical significance nowadays. Since there is only direct contact with the coil winding and no contact with the iron core, the water cooling system cannot directly dissipate the heat of the latter. In addition, it is unrealistic to try to improve the heat dissipation capability by increasing the distance between the cores due to the compact structure of the converter valve, as well as space and size restrictions. Therefore, the use of an epoxy encapsulation layer with high thermal conductivity is still the most effective way to change the temperature distribution and heat dissipation capacity of saturable reactors and ensure their safe and reliable operation.

In this paper, a high thermal conductivity epoxy resin was applied to the encapsulated technology of the coil winding of a saturable reactor for UHVDC converter valves, and a heat dissipation coupled thermal–fluid mechanics model was proposed and used to calculate the temperature distribution in the saturable reactor. The time-domain simulation method was used to simulate the temperature distribution characteristics of the reactor and the factors that can affect the thermal dissipation were analysed. Two real saturable reactors were built and tested under equivalent working conditions and the temperatures at different locations were measured. The temperature data from the simulation were compared with those of the experimental results. The method of...
calculation was shown to support the future engineering design and optimisation of saturable reactors.

2 Theoretical analysis

2.1 Equivalent circuit model of a saturable reactor

Fig. 1 shows the equivalent circuit model of a saturable reactor, in which $L_{\text{air}}$ and $R_{\text{cw}}$ are the air inductance of the coil and the DC resistance of the coil, respectively. These two parameters have fixed values and can be easily obtained from the experimental measurement. The nonlinear inductance $L_{\text{core}}$ is related to the degree of saturation of the core. The core resistance $R_{\text{c}}$ of the saturable reactor is equivalent to the eddy current loss and hysteresis loss in the transient electromagnetic process.

2.2 Thermal heating source

A saturable reactor involves winding and iron cores. The total heat of such a reactor comprises the winding loss and the iron core loss [16, 17]. The winding loss depends on the DC resistance of the winding and the winding current, which can be expressed as [16]

$$P_{\text{winding}} = \frac{1}{T} \int_{0}^{T} I(t) \text{d}t$$

(1)

in which $T$ is the period, $I$ is the current, and $R$ is the resistance of the aluminium winding.

The heat generated by the winding loss can be swiftly removed by the cooling pipe and can be easily calculated, resulting in this kind of loss receiving little attention from researchers. Due to the complex nonlinear characteristics of saturable reactors and the influence of connected power thyristors, the simulation calculations and experimental studies are usually carried out from the impact of iron losses on the operation of converter valves. The size of the iron losses can be affected by multiple factors, such as the rates of change of the valve commutation current, the reverse recovery current of the thyristors and the valve firing, and the extinction voltage [22–25]. Numerous papers have provided methods for evaluating the iron loss, and the average loss can be calculated by means of the following expression:

$$P_{\text{iron}} = \frac{1}{T} \int_{0}^{T} P_{\text{iron}}(t) \text{d}t$$

(2)

in which $P_{\text{iron}}(t)$ is the iron core loss at time $t$. The calculation of the iron core loss has been widely reported in previous studies [21–25]. The method of calculation is introduced here and the results of the calculation are confirmed in this paper.

2.3 Thermal dissipation

Except for the cooling water, all transfer of heat is between solid materials. The time dependence of heat transfer in solid layers is described as

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q$$

(3)

in which $\rho$ is the density, $C$ is the heat capacity, $T$ is the absolute temperature, $k$ is the thermal conductivity, and $Q$ represents one or more heat sources. Similarly, the heat transfer between the pipe wall and the cooling liquid can be described as

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

(4)

in which $u$ is the velocity of the cooling liquid. The heat flux at the boundary can be expressed as

$$Q_{\text{flux}} = h(T_{\text{ext}} - T_{\text{wall}})$$

(5)

in which $h$ is the heat transfer coefficient, $T_{\text{ext}}$ is the ambient temperature, and $T_{\text{wall}}$ is the temperature of the boundary wall.

Fluid mechanics includes both momentum conservation and mass conservation. The mass continuity can be given as

$$\frac{\partial \rho}{\partial t} = - \nabla \cdot (\rho \mathbf{u})$$

(6)

Assuming that the water flow is incompressible, the momentum conservation can be expressed by the Navier–Stokes momentum equation:

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

(7)

in which $p$ is the pressure, $\mu$ is the dynamic viscosity, and $\mathbf{F}$ is the volume force vector.

2.4 Thermal resistance model of the iron core

The thermal resistance analysis model of the iron core is shown in Fig. 2, in which $Q_1$ is the heat lost from the iron core to the cooling water, $Q_2$ is the heat lost from the iron core to the air, $T_e$ is the temperature of the core, $T_a$ is the temperature of the air, $T_w$ is the temperature of the cooling water, $T_{\text{ext}}$ is the temperature of the surface of the saturable reactor, $h$ is the air convection coefficient on the surface of the reactor, $R_{\text{ca}}$ is the thermal resistance of the iron core to air, and $R_{\text{cw}}$ is the thermal resistance of the iron core to the cooling water [26].

The heat generated by the core can be expressed as

$$Q = Q_1 + Q_2 = \frac{T_e - T_a}{R_{\text{ca}}} + \frac{T_e - T_w}{R_{\text{cw}}}$$

(8)

According to (8), the temperature of the iron core can be given by
conduction paths as seen in Fig. 3. The first type is the heat
obvious defects; (ii) all properties were independent of
To simplify the simulation, the following assumptions were made:
3.2 Assumption and boundary conditions
4௑Simulation settings
3.1 Geometric scheme
Two model saturable reactors were built for the simulation of the
temperature distribution characteristics and their dimensions were
580 mm × 210 mm × 340 mm in length, width, and height,
respectively. Each saturable reactor contained ten pairs of U-type
iron cores, one elliptical hollow coil, a plastic shell made of
polyurethane elastomer, and epoxy resin insulation. Epoxy resin
insulated both the iron cores and the coil. Polyurethane elastomer
was poured outside the iron core to reduce its vibration and fix the
position of the core. A schematic diagram of the saturable reactors
built for the simulation is shown in Fig. 4.

The major properties of the materials used in the simulation,
including heat capacity, density, and thermal conductivity, are
given in Table 1 [27–35].

3.2 Assumption and boundary conditions
To simplify the simulation, the following assumptions were made:
(i) all materials were isotropic, with uniform distributions without
obvious defects; (ii) all properties were independent of
temperature; and (iii) the temperature of the surroundings was
constant.

The temperature of the inlet water was 323 K and the ambient
temperature was set to 303 K. The heat transfer coefficient of the
heat flux on the saturable reactor surface was set to 5 W/m²K.
The pipe wall was set to the no-slip condition, the inlet water flow
rate was set to 9 l/min, and the outlet boundary pressure was set to
atmospheric pressure. The heat power of the iron core was set to
670 W. The time step was 20 s and the total simulation time was
15,000 s.

4 Simulation results

\[
T_c = \frac{R_{ca}Q + R_{cw}T_a + R_{ca}T_w}{R_{ca} + R_{cw}}
\]  

(9)

The main heating source of the saturable reactor is the heating of
the core and the winding. The heating of the winding is mainly
carried away by the cooling water flowing through the winding.
The heating of the core mainly includes two forms of thermal
conduction paths as seen in Fig. 3. The first type is the heat
carried to the coil winding and then carried away by the cooling
water in the coil winding passing through the epoxy insulation
layer. Thus, the thermal conductivity of the epoxy insulating layer
is the key parameter determining the efficiency of this thermal
conduction path. The second path is that the heat of the core is
conducted to the saturable reactor casing through the polyurethane
elastomer encapsulation layer, and then the saturable reactor casing
exchanges heat with the air through the heat radiation.

In summary, most of the heat of the electric reactor core is
mainly heat conduction through the path and the thermal
conductivity of the epoxy insulating layer is one of the key factors
affecting the temperature of the core of the saturable reactor.

Table 1 Properties of materials used in the simulation

| Material     | Heat capacity, J/kg K | Density, kg/m³ | Thermal conductivity, W/mK |
|--------------|-----------------------|----------------|---------------------------|
| iron core    | 440                   | 7870           | 76.2                      |
| epoxy resin  | 1370                  | 2000           | 1.20                      |
| polyurethane | 2370                  | 1200           | 0.78                      |
| elastomer    |                       | 4800           |                           |

The simulation results for the temperature distribution of the
saturable reactor are given in Fig. 5. The rise in temperature of the
cooling water was ∼1.5 K. The average and highest temperatures
of the different components are given in Table 2. The main heat
source in this simulation was the iron core, whose temperature was
much higher than that of other components.

It seems that the heat generated in the iron core could be
partially extracted by the cooling pipe. A schematic cross-section of
the iron core is given in Fig. 6. The temperature distribution
inside the core was nearly even. A high-temperature gradient can be
observed in the epoxy resin layer in the figure. The heat transfer
in the epoxy resin can determine where hot spots occur as well as
the maximum temperature of the saturable reactor. Epoxy resin
with high thermal conductivity may effectively improve the heat
dissipation of the saturable reactor. If the thermal conductivity of
the epoxy layer is low, the layer can become an obstacle between
the iron core and the cooling pipe, resulting in overheating of the
iron cores. The maximum temperature of the epoxy resin layer was
356 K, while the lowest temperature was around 320 K. The thermal
stress caused by the uneven temperature distribution in the epoxy
resin layer would reduce its service life. Local insulation
damage due to thermal stress would ultimately result in the failure
of the entire insulation layer.

To better understand the effect of the thermal conductivity of
epoxy resin on the maximum temperature of the saturable reactor,
Simulations were carried out with epoxy resins of different thermal conductivities. As the model saturable reactors were manufactured from epoxy resins with thermal conductivities of 0.8 and 1.2 W/mK, this parameter was set to 0.4, 0.8, 1.2, or 1.6 W/mK. The effect of the thermal conductivity of the epoxy resin on the steady-state temperature distribution of a saturable reactor is shown in Fig. 7. It can be seen that the maximum temperature of the saturable reactor was lowered by 30 K for high thermal conductivity epoxy resin when the latter increased from 0.4 to 1.6 W/mK. Therefore, increasing the thermal conductivity of the epoxy resin layer in a saturable reactor can increase the heat dissipation.

The time dependences of the maximum equilibrium temperature of the epoxy resin layer and the iron core are shown in Figs. 8 and 9, respectively. As can be seen from the figures, the thermal dissipation of the saturable reactor takes more than 3 h to reach the quasi-equilibrium state, and a low thermal conductivity will extend the transient period. The maximum temperature increases quickly at the beginning, and then gradually becomes stable. By raising the thermal conductivity of the epoxy resin layer, the maximum temperatures of the iron core and the epoxy resin layer can be reduced and the thermal dissipation improved. The time dependences of the maximum temperature of the iron core and the epoxy resin layer are quite similar. The maximum temperature of the iron core is slightly higher than that of the epoxy resin layer after 15,000 s.

### Table 2  Calculation data for the temperature field

| Component      | Average temperature, K | Maximum temperature, K |
|----------------|-------------------------|-------------------------|
| iron core      | 355.8                   | 359.0                   |
| epoxy resin    | 328.9                   | 356.8                   |
| polyurethane   | 352.8                   | 358.6                   |
| elastomer      | 324.3                   | 325.2                   |
| aluminium pipe | 324.3                   | 325.2                   |

**Fig. 5** Steady-state temperature distribution of a saturable reactor

**Fig. 6** Steady-state temperature distribution of the cross-section of an iron core

**Fig. 7** Effect of thermal conductivity of epoxy resin insulation on the steady-state temperature distribution of a saturable reactor

**Fig. 8** Time dependence of the maximum temperature of the epoxy resin layer

**Fig. 9** Time dependence of the maximum temperature of the iron core
The improvement in heat dissipation was significant when the thermal conductivity increased from 0.4 to 0.8 W/mK. However, a further increase in thermal conductivity brought no further improvement, which means that, for high thermal conductivity epoxy resins, other factors, such as thermal blockage of the polyurethane cover, the velocity and temperature of the inlet water, and the ambient temperature, become essential for efficient thermal dissipation in a saturable reactor. By integrating particles of high thermal conductivity, thermal conduction channels are formed that increase the thermal conductivity. Mechanical and electrical properties, however, may be compromised as the thermal conductivity is raised to a very high level. With the addition of high thermal conductivity filler, the epoxy vacuum casting process of the saturable reactor of the coil winding will become more and more difficult. Therefore, it is impractical to increase the thermal conductivity of the epoxy resin layer as high as possible.

5 Verification test and analysis

Two saturable reactor prototypes with different thermal conductivities have been developed. The thermal conductivity of the epoxy resins used in the two reactors was 0.8 and 1.2 W/mK. The prototype of the saturable reactor for a UHVDC converter valve has a similar geometric structure to the simulation model and is illustrated in Fig. 10. Temperature sensors have been added to the tops of the iron cores, and each iron core is fastened with a thin stainless steel belt. During the test, the ambient temperature was \( \sim 30°C \), and the temperature of the inlet water, flowing at \( \sim 9 \text{ l/min} \), was maintained at \( 50°C \). In fact, it was difficult to install the saturable reactor, with an iron loss of around 600 W, on a real converter valve to test its thermal properties. In this test, a 20 kHz square wave with a peak-to-peak value of 680 V was used as the voltage source to generate losses similar to those in real-world working conditions. The temperature of the core was measured by an embedded optical fibre sensor and the time dependence of the temperature of the core was recorded. The thermal test system adopted for the saturable reactor is shown in Fig. 11. Data for the output voltage and the current were recorded for the loss calculation and are shown in Figs. 12 and 13. The voltages and currents measured for the two saturable reactors were quite similar. Based on the experimental results, the average iron loss was close to 670 W and the average winding loss was <1 W. Therefore, the loss due to joule heating on the aluminium winding could be ignored, which is in accordance with our previous simulation settings.

The temperature dependence of the maximum temperature of the iron core is shown in Fig. 14, where the simulation results are also given for comparison. As can be seen from the figure, the total trend of the time dependence of the measured maximum
temperature is in good agreement with the calculated results. The measured maximum temperature increased slightly faster than the simulation case and the steady-state maximum temperature was also slightly higher than the simulated value. This was probably due to the uneven division of the ambient temperature. The temperature of the gap between the two parallel iron core arrays should have been higher than that of other regions. However, the heat flux coefficients at the boundary of the saturable reactor and the ambient temperature were set to constant values. Therefore, the heat dissipation effect in the above simulation should have been slightly better than the actual situation. To sum up, increasing the thermal conductivity of the epoxy resin layer can reduce the thermal stress in a saturable reactor effectively and improve its heat dissipation. As the thermal stress on the epoxy resin layer is reduced, its service life can be prolonged.

6 Conclusion

In this paper, a thermal–fluid mechanics coupled heat dissipation model for a saturable reactor is proposed, and the temperature distribution of the flow field has been calculated. As heat can be removed by a cooling pipe, the temperature of the winding and the inner side of the epoxy resin layer is close to the temperature of the cooling water. The maximum temperature is always located in the iron core. Furthermore, the effect on the thermal dissipation of the saturable reactor conducted by high thermal conductivity epoxy encapsulation has been studied. A layer of the latter can improve the heat dissipation process and reduce the thermal stress on the epoxy resin insulation. Two saturable reactors using 0.8 and 1.2 W/mK thermal conductivity epoxy resin have been manufactured and thermal tests have been carried out on them. There was shown to be good consistency between the simulation and test results, namely, that the temperature of the saturable reactor core can be significantly reduced by increasing the thermal conductivity of the epoxy insulation layer. The application of high thermal conductivity epoxy resin in the manufacture of saturable reactors can reduce the cost of cooling devices and has great practical significance in engineering applications.

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8 References

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