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Study on Loss and Temperature Increases in Hollow Oil-immersed Reactors

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Abstract. Oil-immersed hollow reactors have been applied to high-voltage frequency-modulated resonant power supplies due to their favorable linearity and high insulation strength. A high-quality reactor is the key component of a high-voltage test system. The characteristics of loss and temperature-rise characteristics are the core factors affecting the quality factor of the reactor. In this paper, a finite-element numerical simulation model was established based on a large capacity series resonance test system for a 500-kV submarine cable in China. The eddy current loss, AC resistance loss, and circulating current loss of the oil-immersed air-core reactor were calculated. With these as a foundation, the flow and temperature field distribution characteristics were obtained for an oil-immersed hollow reactor through the coupling of magnetic heat and flow field. Finally, the temperature distribution characteristics of the reactor were compared with the dates obtained from the release testing, and the reliability of the calculation model was verified.

Index terms: hollow resonant reactor, losses, multiphysics coupling, temperature rise

1. Introduction

Hollow reactors are key inductive components of frequency-modulated resonant power supplies, used to resonate with the experimental sample and provide the high voltage required for experimentation [1], [2]. Hollow reactors are mainly used to conduct partial insulation testing on various parts of high and ultra-high voltage electrical equipment, complete assembling experiment, and evaluate the insulation values during final acceptance tests. Reactor quality is crucial to measuring the voltage increase in resonant testing power supplies; high-quality reactors contribute to the overall performance of the system [3], [4]. To conduct experiments that require substantial electrical capacity for sample testing (e.g., on-site final acceptance test for a long-distance 500-kV submarine cable project), the power supply must have low resonant frequencies, which is only capable through high-quality power sources.

Properties related to circuit loss and temperature increases are crucial factors in power supply quality. This study analyzed properties related to current loss and temperature increases in high-voltage oil-immersed resonant reactors, which provides invaluable information for industrial applications.

Few studies have examined the temperature increase and current loss of oil-immersed hollow reactors. However, recent studies on temperature increases and current loss in other high-voltage



equipment have yielded valuable results. Because oil-immersed hollow reactors and oil-immersed voltage transformers both use transformer oil for insulation and heat dissipation, studies on oil-immersed hollow reactors and transformer oil velocity can reference those on oil-immersed voltage transformers [5]-[7]. Swift *et al.* used numerical simulations of heat transfer to calculate the temperature inside voltage transformers and compared them with actual transformer results on temperature increases to verify simulation accuracy [5], [6]. Chen *et al.* used the finite volume method (adapted from the semi-implicit method for pressure-linked equations) and other variables, such heat capacity and thermal conductivity, to calculate the temperature distribution in oil-immersed coil-winding voltage transformers. The calculation results of Chen *et al.* had only a 5.8% error compared with the actual test results [7]. Because the coupling flow field and thermal field inside an enclosed space are similar to the structure of an SF₆ high-voltage circuit breaker, calculations regarding the coupling of flow and thermal fields of oil-immersed voltage transformers can use the SF₆ high-voltage circuit breaker as a reference [8]-[10]. Regarding the influence of heat in different materials, Pawar *et al.* used finite element analysis to calculate the electromagnetic field of an SF₆ high-voltage circuit breaker, and then applied the obtained ohm loss to the ANSYS software program to further calculate the thermal field and obtain more accurate thermal field results [8, 9]. As the physical properties of SF₆ gases change under different temperature and pressure, Xu analyzed the relationship between the internal electric field, temperature field, and flow field of an SF₆ high-voltage circuit breaker, thereby obtaining the coupling temperature-rise and current-loss model [10]. The structure of a dry-type hollow reactor can be studied to improve the loss model and equivalent circuit model of the oil-immersed reactor's special flat coil winding structure [11]-[13]. Based on electromagnetic and heat transfer theories, Jiang *et al.* established a 3D temperature field calculation model for a dry-type hollow reactor and revealed the distribution properties of reactor temperature fields [11].

Accordingly, this study established circuit-loss and temperature-rise models for an oil-immersed reactor using the high-capacity series-connected resonant test system for the 500kV submarine cable in China. The eddy current loss, AC resistance loss, and circulation current loss of the reactor were calculated and served as fundamental information to obtain the flow- and temperature-field distribution properties of an oil-immersed hollow reactor. Finally, the reactor's temperature increase was measured using an infrared thermometer and compared with the calculations of this study to evaluate the study's effectiveness.

2. Loss Calculation of the Reactor

Numerous studies on oil-immersed reactors have used electromagnetic field loss calculations to determine fluid dynamics and heat transfer. Calculations regarding eddy current loss, resistance loss, and circulation current loss were used to conduct further analysis of heat source loading conditions.

2.1. Current Loss Calculations

A cross-sectional analysis of the eddy current distribution and the related calculations for the conductive wire (A-A') are displayed in Figure 1 [12].

First, j_x is established as the eddy current density of area x ; $j_x + dj_x$ is the eddy current density of $x + dx$. Therefore, the induced voltage between x and $x + dx$ is as follows:

$$e = -\frac{\partial \phi_x}{\partial t} = -\frac{\partial B_x}{\partial t} l dx \quad (1)$$

where ϕ_x represents the magnetic flux of the area with a breadth of dx , and l is the length of the eddy current path.

Because the eddy current is developed in a closed circuit, the induced voltage of the eddy current equals the voltage drop of the circuit. Therefore, the eddy current density value can be calculated using (2); the eddy current loss of a single unit in area x is shown in (3). Equation (4) shows the eddy current loss of a single conductive wire, and by integrating (4), the total eddy current loss of a single conductive wire can be obtained using (5). As the reactor coils are composed of multiple flat coil

layers that are series-connected (with each flat coil layer featuring numerous parallel-connected coiled conductive wires), the total eddy current loss of the reactor coils can be derived using (6).

$$J_x = \frac{\gamma B_m \omega}{\sqrt{2}} x \quad (2)$$

$$P_0 = \frac{J_x^2}{\gamma} = \frac{\gamma B_m^2 \omega^2}{2} x^2 \quad (3)$$

$$P_1 = \pi D \int_{-R}^R dy \int_{-\sqrt{R^2-y^2}}^{\sqrt{R^2-y^2}} \frac{\gamma B_m^2 \omega^2}{2} x^2 dx \quad (4)$$

$$P_1 = \frac{\pi^2 D \gamma B^2 \omega^2 d^4}{64} \quad (5)$$

$$P_E = \sum_{i=1}^n \sum_{j=1}^m \frac{\pi^2 \gamma \omega^2 D_i d_i^4 B^2}{64} \quad (6)$$

where B_m and B respectively represent the maximum and effective magnetic flux densities of the wire (measured in T). The conductivity is represented as γ (S/m) and the angular frequency is ω (rad/s). D is the flat coil diameter (m) and d is the conductive wire diameter (m). Finally, m is the parallel-connected conductive wire radical of a single unit of flat coil; n is the number of series-connected flat coils.

2.2. Ohm Loss Calculation

2.2.1. AC resistance loss. A cross-section of a round conductive wire is shown in Figure 2. R represents the conductive wire radius, and the wire width is evenly divided into N layers. Excluding the central layer, these layers can be viewed as rings of even thickness. Therefore, the thickness of layer i is represented as $r_i = R/N$ and its circumference is denoted as $c_i = 2\pi R (i - 0.5)/N$. In large-scale settings (when N is a sufficiently larger value), the skin effect of each layer can be ignored [13].

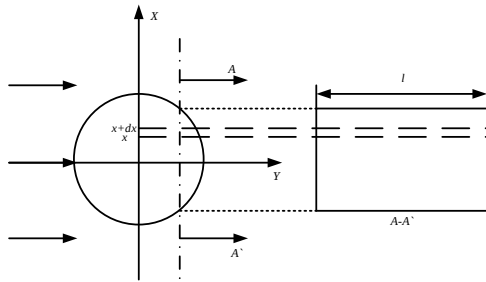


Figure 1. Eddy current loss calculation

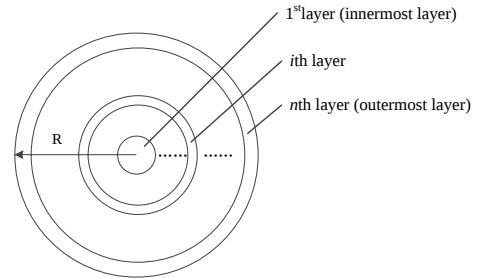


Figure 2. Round wire cross-section

Set R_i as the AC resistance of layer i , thus:

$$R_i = \frac{l}{\gamma c_i r_i} \quad (7)$$

where γ represents the conductivity of the conductive wire.

To calculate the effective value of the total electric current of the conductive wire (I), the following equation was established:

$$I = \sum_{k=1}^N I_k \quad (8)$$

The total ohm loss of a single conductive wire equals the cumulative resistance loss of each layer, which can be expressed as

$$P = \sum_{k=1}^N \frac{I_k^2 \pi D}{\gamma c_k r_k} \quad (9)$$

The AC resistance loss of the reactor coils is displayed in (10):

$$P_n = n \sum_{j=1}^c \sum_{k=1}^N \frac{I_k^2 \pi e D_j}{\gamma c_k r_k} \quad (10)$$

where n is the number of flat coils, c is the number of radial layers, e is the average number of coils in each flat coil layer; N is the number of layers of the conductive wire; and D_j is the diameter of the jth layer.

2.2.2. Circulation current loss calculations. Circulation current loss occurs in compound coil winding in addition to winding resistance loss. As each coil layer of the reactor is located in different positions of the AC field and exhibits different resistance values, circulating currents between each layer are produced when the reactor is operating.

Assume that R_a is the total resistance of a single flat coil passed through by the circulating current; R_a can then be obtained from (11) and the circulating current loss can be calculated using (12).

$$R_a = \frac{P_a}{I_b^2} \quad (11)$$

$$P_h = a \sum_{m=1}^b \left[I_m^2 - \left(\frac{I_b}{b} \right)^2 \right] R_a \quad (12)$$

I_b is the total electric current that passes through a single coil, I_m represents the electric current that passes through the mth conductive wire, and b is the number of parallel-connected wires that the flat coil is connected to.

Finally, P, P_E, P_n, and P_h are designated as the total loss, eddy current loss, AC resistance loss, and the circulation current loss, respectively, and established the following equation:

$$P = P_E + P_n + P_h \quad (13)$$

Analyzing (6) and (12) showed that eddy loss P_E and conductive wire diameter d₄ were directly proportional; thicker conductive wires exhibited greater corresponding eddy current losses.

3. Reactor Simulation Model

3.1. Reactor Structure and Variables

The present study is based on the oil-immersed reactor of a high-capacity series resonance test system for a 500-kV submarine cable in China. The rated inductance value was 26 H, the rated current was 80 A, and the resonant frequency was 30 Hz; the system employed oil cooling and natural convection as cooling methods.

The internal structure of the reactor is shown in Figure 3, and mainly consists of flat coils (coil winding), an oxygen circulation lid and tank, a base, insulation paper board, and duct strip. The coil winding is composed of 12 series-connected flat coils; each flat coil is composed of 16 parallel-connected enameled wires with a diameter of 1.6 mm (QZ2-130)]. Each flat coil is separated with a paper board, and paper boards and flat coils are both fixed to the duct strips. Transformer oil is used to fill in the remaining space.

The reactor was 2.53 m in height and had a base radius of 1.2 m. The flat coil height was 0.11 m, with an internal diameter of 0.35 m and external diameter of 0.85 m. The distance between each flat coil was 0.05 m. Because the fluid and temperature fields both require large numbers of computational grids, the calculation model was reasonably simplified. As the flat coils served as the main heat source, heat transfer occurred between the coils and the transformer oil. Through heat transfer, the transformer oil transferred heat to the oxygen circulation lid and tank, which then transferred the heat to the external environment. Duct strips were used as insulation materials in the reactor. As the duct strips were relatively small, their influence on heat transfer and transformer oil flow was negligible. Therefore, based on the model construction and solution process, the following assumptions are made [14],[15]:

- 1) The flange and related components have axial symmetry.
- 2) The coils connecting each flat coil together and the duct strip support are ignored.
- 3) The flat coils are regarded as a uniform medium.
- 4) The nonlinear relationship between the material variables and temperature is ignored.

Figure 4 displays the simplified calculation model, featuring flat coils, an oxygen circulation lid, transformer oil, and duct strip supports.

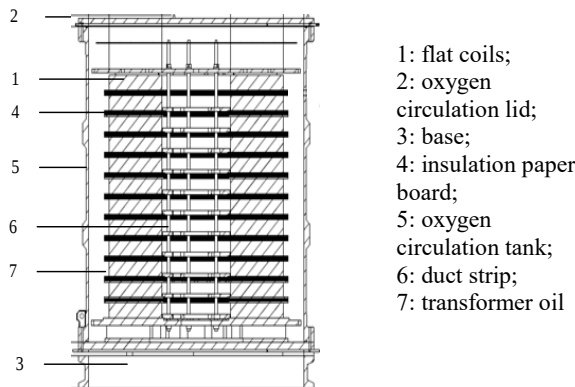


Figure 3. Internal structure of the hollow oil-immersed reactor

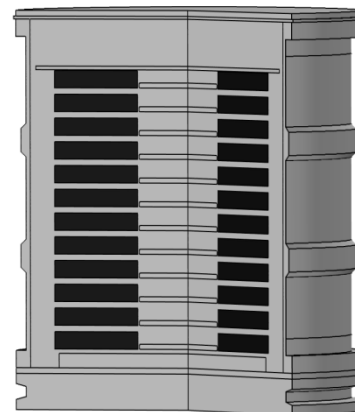


Figure 4. Calculation model of reactor temperature increase

3.2. Reactor Structure and Variables

3.2.1. Border condition calculation. (1) Initial value: The initial temperature of the reactor was set to 20 °C (293 K), similar to the experiment environment.

(2) Heat source: The reactor operated under AC (30 Hz, 80 A), similar to the power source conditions of the field experiment. By analyzing the reactor structure variables, the eddy current loss, AC resistance loss, and circulation current loss of the flat coil winding was obtained, which was then used with the heat source to conduct temperature increase calculations.

(3) Heat flux: Because low heat transfer occurred between the reactor and the ground surface, its base was determined to be insulated. The outer casing of the reactor conducted natural convection with the outside air; thus, the heat transfer equation for natural convection in cylinder models was used [16]:

$$\begin{cases} G_r = \frac{g \alpha_v \Delta T L^3}{\nu^2} \\ N_u = C (G_r \cdot Pr)^n \\ h = N_u \frac{\lambda}{L_o} \end{cases} \quad (14)$$

where Gr is the Grashof number, Nu is the Nusselt number, and Pr is the Prandtl number. The constant (C) and the exponent number (n) are decided by Gr . In addition, g represents the gravitational acceleration (m/s^2), α_v is the expansion coefficient ($1/K$), ν is the kinematic viscosity of air (m^2/s), ΔT is the temperature difference between the outer case and air (K), λ is the thermal conduction coefficient of air (W/mK), L is the length and size of the rain cover or packaging (m), and h is the natural convection heat transfer coefficient (W/m^2K).

The oxygen circulation lid was the main component involved in heat transfer; its heat conductivity coefficient was set as $0.5 W/(m^2K)$.

3.2.2. Governing equations The Navier–Stokes and Maxwell equations were used to determine the coupling of magnetic and flow fields. The governing equations are as follows [17]:

Law of conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \quad (15)$$

Law of conservation of energy:

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \cdot \nabla T \right) - \nabla \cdot (k \nabla T) = Q \quad (16)$$

Law of conservation of momentum:

$$\rho \left(\frac{\partial v}{\partial t} + v \cdot \nabla v \right) = \nabla \cdot [-pI + \mu(\nabla v + (\nabla v)^T)] - \frac{2}{3} \mu(\nabla \cdot v)I + J \times B \quad (17)$$

Governing equation for electromagnetism:

$$\nabla \times A = B \quad (18)$$

Governing equation for heat transfer:

$$q = -\lambda \nabla T = -\lambda \left(\frac{\partial T}{\partial x} i + \frac{\partial T}{\partial y} j + \frac{\partial T}{\partial z} k \right) \quad (19)$$

where ρ is the density, v is the flow velocity, T is the temperature, Q is the heat source, I is the unit matrix, J is the electric current density, μ is the kinetic viscosity, B is the magnetic density, A is the magnetic velocity, λ is the heat conductivity coefficient, and q is the heat flow density.

3.3. Calculation Variables

The main components examined in the calculation of reactor temperature increases were the transformer oil, flat coil winding, and oxygen circulating tank. Related variables include density (ρ), heat conductivity coefficient (λ), specific heat capacity (c), kinetic viscosity, and specific heat ratio (g). The material parameters are listed in Table 1.

Table 1. Material parameters of temperature increase calculation[18]

Material	Transformer oil	Coil winding (copper)	Oxygen circulation tank
$\rho/(kg/m^3)$	890	8930	1950
$\lambda/(W/(m \cdot K))$	0.112	398	0.21
$c/(J/(kg \cdot ^\circ C))$	1960	386	1511
$\eta/1Pa \cdot s$	0.02	/	/
g	1.05	/	/

4. Simulation Results and Experimental Verification

4.1. Loss Calculation Results

Reactor-related variables and load conditions were applied to (6), (10), and (12). The eddy current loss, AC resistance loss, and circulation current loss of the reactor's flat coil winding component were separately calculated; the results are shown in Table 2.

From the aforementioned results, it was revealed that the eddy current loss, circulation loss, and AC resistance loss contributed to 0.73%, 15%, and 84.25% of the total loss, respectively. The eddy current loss was 0.89 kW, which is a relatively small overall proportion; however, if the conductive wire diameter were to be increased, the eddy current loss would drastically increase.

Table 2. Calculation results of loss

Loss type	P_E	P_n	P_h	P
Results (kW)	0.89	101.95	18.15	121

4.2. Flow and Temperature Field Simulation Results

4.2.1 Temperature field simulation results. The temperature distribution obtained using the coupling calculation of heat transfer and flow field is shown in Figure 5, and the flow speed distribution is displayed in Figure 7.

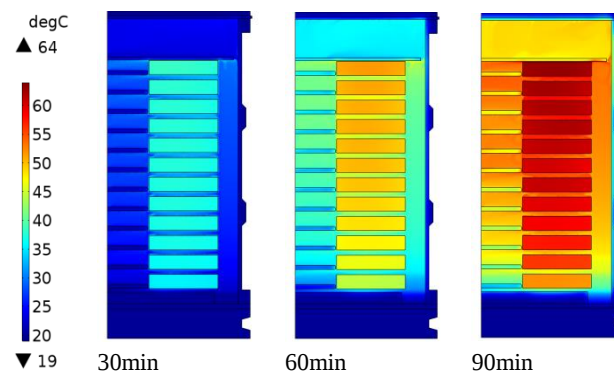


Figure 5. Distribution of temperature in the reactor

Figure. 5 displays the temperature distribution of the reactor at 30, 60, and 90 min of operation. Comparing the distributions revealed that the oil temperature of the upper section of the reactor was higher than that of the lower section. The top area was blocked off by the duct strip, resulting in the oil in the top layer heating up slower than the top flat coil. As the operation time increased, the overall temperature increased. At 90 min, the heat in the reactor was still not evenly distributed; the heat spot temperature reached 64 °C and was located at the uppermost flat coil area (the temperature had increased by 44 °C, which was in the acceptable range [19]).

To further analyze the temperature increase of the reactor, three points were separately chosen and recorded from the upper, middle, and lower sections of the reactor's transformer oil tank. The temperature changes at the three points are displayed in Figure 6.

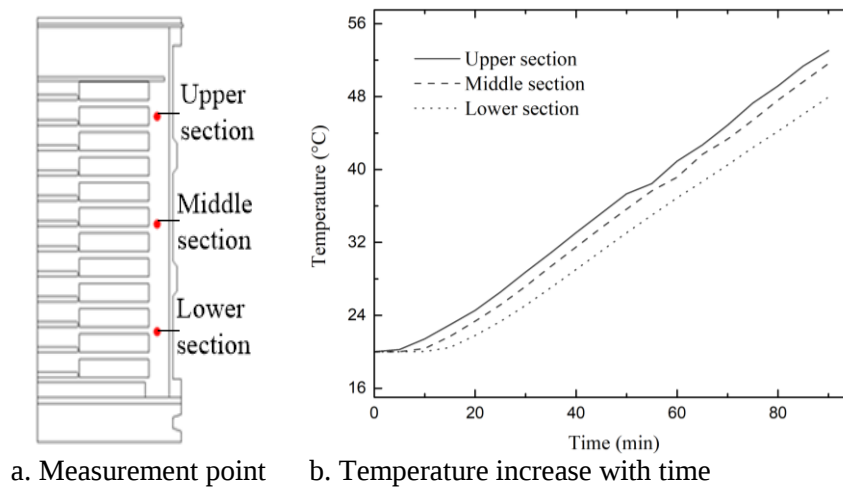


Figure 6. Temperature increases at different areas of the reactor

At the start of the experiment, the temperature of the three observation points was 20 °C. As the reactor operation continued, the transformer oil in the upper section of the reactor was the first to exhibit a temperature increase after 5 min. After 10 min of operation, the lower and middle observation points showed evident temperature increases. Figure 6(b) reveals that the upper and middle observation points exhibited similar temperature increase rates; the lower observation point showed a slower temperature increase in comparison. At 90 min, the temperatures of the upper, middle, and lower observation points were 53.04 °C, 51.62 °C, and 47.95 °C, respectively.

4.2.2 Flow field simulation results. As presented in Figure 6, the heat spots of the reactor were mainly located in the upper flat coil winding area. This was due to the transformer oil flow in the reactor, which was further analyzed.

Figure 7 displays the reactor transformer oil velocity at 30, 60, and 90 min.

A comparison revealed that the velocity of the reactor transformer oil was mainly axially distributed. The radial velocity of the reactor's transformer oil was greatest between the upper area and the top area (near the oxygen circulation lid). The oil's velocity was lower at the middle and lower area, but greater at the upper area (near the flat coil winding component and the oxygen circulation tank). After 90 min of operation, the maximum velocity of the transformer oil was 0.1 m/s.

Combining the heat and flow velocity distribution data showed that the area with a high flow velocity had the highest temperature increase, namely, the upper area near the flat coil winding component. Figure 8 displays an enlarged image of the reactor's transformer oil flow in the upper area and the top area.

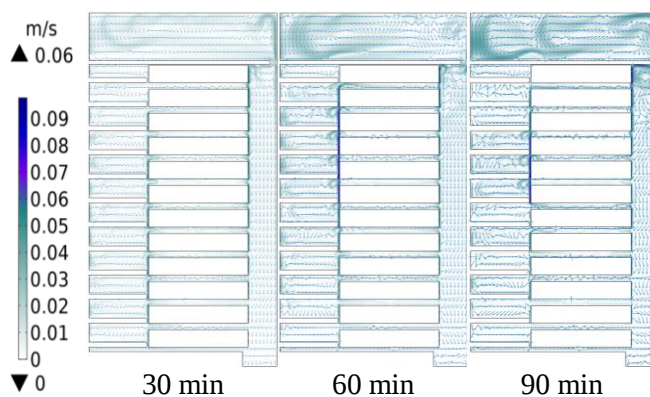


Figure 7. Distribution of reactor oil velocity

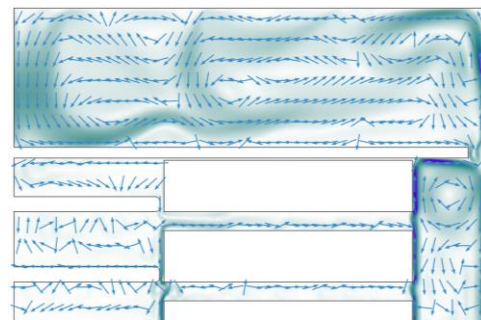


Figure 8. Local oil flow distribution at 90 min

The duct strip support was the main cause of greater transformer oil flow in the top and upper section. Beneath the duct strip support, the transformer oil formed a looped circulation, which exhibited a higher velocity around the flow line. The oil velocity near the flat coil winding was 0.06 m/s and flowed upwards. The transformer oil near the oxygen circulation tank flowed in two directions: one part of the oil flowed towards the lower area, and the other flowed towards the top area at 0.04 m/s.

4.3. Reactor Temperature Increase Test

Serially connected resonant devices are the most tested high-voltage power sources in on-site voltage tests. Figure 9 shows the circuit principle of the serial-connected resonant devices during the voltage test.

The experiment conditions were identical to the test conditions; to simulate the submarine cable capacity load, eight sets of capacitors were parallel-connected into a group, and 10 groups were serial-connected to achieve a capacity load of 1.6 μF . The voltage divider variable was 500 kV/1500 pF. Five serially connected frequency transformer power supply devices were employed to generate excitation voltage. An infrared thermometer was used to measure the reactor surface temperature change (error of $\pm 2\%$). Figure 10 displays the layout of the test site, and Figure 11 shows the constant position of the infrared thermometer and the reactor.

During the experiment, the voltage divider and the current clamp meter were respectively used to measure the voltage and current. The input of the reactor current was maintained at 30 Hz and 80 A; the surface temperature of the reactor was recorded every 5 minutes, and the recording time lasted for a total of 90 minutes.

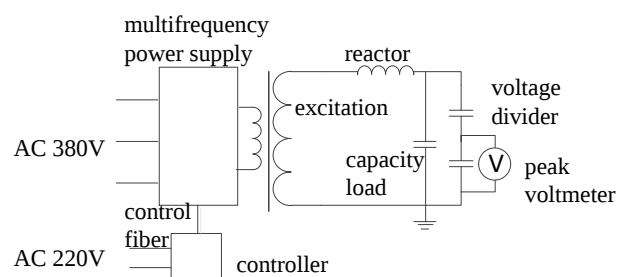


Figure 9. Circuit of test

Figure 12 compares the middle area temperature increase data from both test and simulation results. Figure 12 presents a comparison between simulation results and test results. The largest error occurred at 65 min, with the 1.5 $^{\circ}\text{C}$ difference presenting a percentage error of approximately 5%.



Figure 10. Layout of test site



Figure 11. Infrared Thermometer

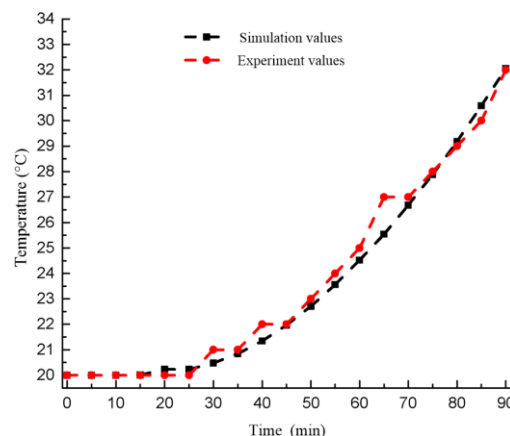


Figure 12. Comparison of simulation results of temperature and test results

5. Conclusion

(1) This study used the voltage test of the reactor for a 500-kV submarine cable to calculate and analyze the eddy current loss, AC resistance loss, and circulation current loss of the oil-immersed hollow reactor. The results proved that AC resistance loss had the highest proportion in terms of total current loss. Under a similar cross-sectional area of conductive wire, greater numbers of serially connected conductive wires exhibited higher circulation flow loss, and thicker conductive wires resulted in greater eddy current loss.

(2) The total current loss of the flat coil winding component of the reactor was the main heat source in the experiment. Multiple physical principles were used to calculate the distribution of temperature increases and flow velocity in the reactor. The temperature increase results are listed from highest to lowest as follows: upper area, middle area, and lower area. After 90 min of operation, the temperature increased in the heat spot by 44 °C, and the heat spot was located at the uppermost flat coil area.

(3) After 90 min of operation, the flow velocity was mainly radially distributed. The velocity distribution between the top area and flat coils was mainly axially distributed. The flow velocity was higher in the top area and lower at the middle and lower areas. The highest flow velocity occurred at the top area (near the uppermost layer of the flat coils), exhibiting a speed of 0.1 m/s.

Acknowledgments

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