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Research on Losses and Heat Dissipation of Saturable Reactor Used in Converter Valve

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ABSTRACT Based on the analysis of the principle and structure of a saturable reactor used in a converter valve of HVDC transmission, this paper analyzes its power loss composition and summarizes and derives the power loss equations. According to finite element analysis, the saturable reactor is modeled, its transient electromagnetic characteristics are simulated, and the core loss density distribution is studied. The influence of the cooling circuit and air on the heat dissipation of the saturable reactor is studied. The power loss density obtained by the electromagnetic field finite element analysis is mapped as the heat source to the finite fluid element for thermal simulation in order to obtain the spatial temperature distribution of the saturable reactor. The maximum temperature of the case is about 68.5°C, while the maximum temperature of the iron core is about 87.9°C. The converter valve operation test validates the accuracy of the heat dissipation analysis and temperature field simulation. The research results can serve as a reference for the design of saturable reactors used in converter valves.

INDEX TERMS HVDC transmission, converter valve, saturable reactor, core loss, temperature field.

I. INTRODUCTION

The converter valve is an essential part of HVDC transmission project to achieve AC/DC and DC/AC power conversion [1]. The saturable reactor plays an important role in the thyristor-based line-commutated converter (LCC) to ensure the thyristors' reliable operation under various voltage and current stresses [2]–[11]. The operating thermal characteristics of the saturable reactor are critical factors affecting its long-term operating reliability and aging characteristics. Therefore, studying the power losses, heat dissipation, and temperature distribution of the saturable reactor under rated conditions is vital to ensure the converter valve's long-term reliable and stable operation.

At present, research on saturable reactors have made some achievements. For example, [10] simulates the losses of a single core of a saturable reactor by the finite element method and obtains the power density of a single core and the distribution of core temperature; [11] found the core losses of the saturable reactor under different DC currents through the simulation of a 12-pulse converter valve circuit; [12] studied the temperature rise test method of the

saturable reactor cores and obtained its temperature distribution through pre-embedded optical fiber sensors inside the reactor.

Due to limitation of the current technology, it is difficult to directly measure iron losses under the operating conditions of the converter valve saturable reactor. Therefore, research on the power losses of saturable reactors mainly focus on circuit simulation and thermal simulation with reactor modeling, or alternatively, by measuring the core temperature with pre-embedded optical fiber sensors and obtaining the reactor core losses through data fitting. These methods are not sufficient to complete the theoretical derivation and calculation of core losses as neither sufficiently considers the theoretical derivation and quantification of air heat dissipation of the reactor in actual operation.

In this paper, the calculation method of the saturable reactor power losses is established. The saturable reactor finite element analysis is applied, and the iron core heat dissipation through air and water is studied through finite element analysis. The saturable reactor's iron core losses and temperature distribution are simulated and verified through the converter valve operation test. The research results of this paper could provide a reference for the design of a saturable reactor.

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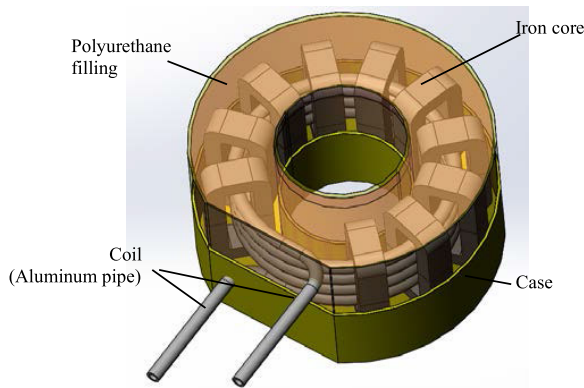


FIGURE 1. The composition of valve saturable reactor.

TABLE 1. Typical technical parameters of saturable reactor.

Name	Symbol	Parameter
DC current	I_d	5000A
Main inductance	L_H+L_σ	570 μ H
Voltage-time area	$\Delta\psi$	150mVs
Surge voltage	U	58kV

II. SATURABLE REACTOR COMPOSITION AND FUNCTION

At present, the saturable reactor applied in the converter valve of HVDC transmission projects is mostly a case structure with a single coil and with a circumferential radial core arrangement [13], as shown in Fig.1.

The main functions of the saturable reactor in the converter valve are the attenuation of oscillations, limiting the rate of current increase when turning on thyristors, and as a thyristor overvoltage protection system during lightning and steep-front impulses. The typical parameters of the converter valve saturable reactor of a ± 800 kV/5000A HVDC project are shown in Tab.1.

The saturable reactor has a non-linear magnetization curve and non-constant permeability. The permeability of the core is inversely proportional to the saturation of the core. When the magnetic induction intensity increases, the permeability will decrease, and the core will be close to saturation [14]. The equivalent circuit of a saturable reactor is shown in Fig. 2.

In Fig.2, L_s and R_s represent the air-core inductance and resistance, respectively; L_p and R_p are non-linear inductance and non-linear resistance of the iron core, representing the inductance and eddy current loss of the core, respectively. C_s is the stray capacitance between the two terminals of the reactor. L_p and R_p are functions of current and decay with the current after the reactor is saturated.

III. CALCULATION OF SATURABLE REACTOR LOSSES

The calculation of saturable reactor loss is an integral part of converter valve design. According to the component composition, it can be divided into coil loss and core loss. The coil loss is mainly caused by the resistance of the reactor coil when the valve is turned on, which can be calculated according to equation (1) [10]–[12]. The main losses in the reactor occur as coil loss, which is dissipated through the

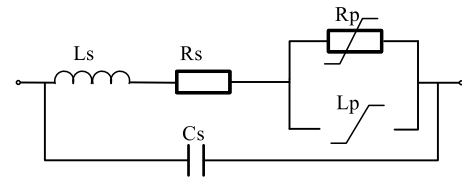


FIGURE 2. Equivalent circuit of valve saturable reactor.

water cooling system valve.

$$P_{Cu} = \frac{1}{3} I_d^2 \left(\frac{2\pi - \mu}{2\pi} \right)^2 R_{Cu} \quad (1)$$

where: P_{Cu} is the coil loss (copper loss); I_d is the valve current; μ is the commutation overlap angle; R_{Cu} is the DC resistance of the reactor.

Including hysteresis loss, eddy current loss, and additional loss, the core loss is mainly caused by the sharp change in the voltage and current of the saturable reactor at the moment the valve switches on and off. According to Bertotti's iron core loss calculation theory, the calculation equation for the total iron core losses per unit weight of silicon steel sheet under any magnetic flux density waveform is [15]–[19]:

$$P_{Fe} = P_h + P_c + P_e = k_h f B_m^\alpha + k_c (f B_m)^2 + k_e (f B_m)^{1.5} \quad (2)$$

where: P_{Fe} is the iron loss; f is the frequency; B_m is the magnetic flux density amplitude; k_h, k_c, k_e, α is the coefficient of the related material.

The core loss coefficient can be obtained through finite element simulation by applying the least square method to fit the measured loss curve [20]. The paper deepens theoretical research through equation derivation.

A. EDDY CURRENT LOSS

Eddy current loss is the main part of the core loss. It is of great significance to study the factors affecting the eddy current loss of the saturable reactor core during the operation of the converter valve [4]. The eddy current loss per unit weight of the monolithic silicon steel sheet of the saturable reactor is as equation (3):

$$P_c = k_c (f B_m)^2 \quad (3)$$

k_c is the classical eddy current loss coefficient, calculated as:

$$k_c = \pi^2 \sigma_{Fe} \frac{d^2}{6 \rho_{Fe}} \quad (4)$$

Then the eddy current loss of a single core of the saturable reactor is:

$$P'_c = \pi^2 \sigma_{Fe} \frac{d^2}{6 \rho_{Fe}} (f B_m)^2 m_{core} n_{si} \quad (5)$$

where: σ_{Fe} is the conductivity of the silicon steel sheet; d is the thickness of the silicon steel sheet; ρ_{Fe} is the density of the silicon steel sheet; m_{core} is the mass of a single core; n_{si} is the number of silicon steel sheets for a single core.

Furthermore, the calculation of the eddy current loss of a single saturable reactor is (6):

$$P'_c = \pi^2 \sigma_{Fe} \frac{d^2}{6} \left(\frac{dB}{dt} \right)_{\max}^2 V_{core} n_{si} n_L \quad (6)$$

where: $\left(\frac{dB}{dt} \right)_{\max}$ is the maximum change rate of core magnetic flux density; V_{core} is the core volume; n_L is the number of cores in a single reactor.

According to equation (6), after the saturable reactor is designed and manufactured, the core eddy current loss is mainly related to the core maximum flux density change rate during the converter valve operation. The periodic voltage stress of the thyristor at the moment of turn-on and turn-off is mainly borne by the saturable reactor. Then the rate of change of core magnetic flux density is determined by equation (7).

$$\left(\frac{dB}{dt} \right)_{\max} = \frac{\pi}{3} \frac{U_{dio} \sin \varphi}{n_r N A_{Fe}} \quad (7)$$

where: n_r is the number of saturable reactors in a single valve; N is the turns of the saturable reactor winding; A_{Fe} is the cross-sectional area of a single core; φ is the firing angle or extinguishing angle of the converter valve.

By substituting equation (7) into equation (6), the eddy current loss can be written as:

$$P'_c = \frac{\pi^2 \sigma_{Fe} d^2 V_{core} n_{si} n_L}{6 n_r^2 N^2 A_{Fe}^2} \left(\frac{\pi}{3} U_{dio} \sin \varphi \right)^2 \quad (8)$$

It can be seen from equation (8) that the eddy current loss of the saturable reactor is related to the iron core design, the number of reactors in a single valve, and the steady-state operating conditions of the converter valve.

B. HYSTERESIS LOSS

Hysteresis loss is the energy lost due to repeated friction of the magnetic domain in the magnetization process when the core material is repeatedly magnetized during the operation of the saturable reactor [21]. The hysteresis loss of the same iron core is only related to the magnetic flux density and frequency. The hysteresis loss per unit weight of the monolithic silicon steel sheet of the saturable reactor is:

$$P_h = k_h f B_m^\alpha \quad (9)$$

where: k_h is the hysteresis loss coefficient. [13] gives the loss measurement and data fitting methods.

According to the literature [22], the calculation method of the core hysteresis loss of a single valve reactor is derived:

$$P_h = M k f \quad (10)$$

where: k is the characteristic coefficient of hysteresis loss, which can be measured through experiments [18].

C. ADDITIONAL LOSS

The relaxation effect causes additional loss in the iron core, which is much smaller than the hysteresis loss and eddy current loss. The additional loss calculation is as [4]:

$$P_e = k_e (f B_m)^{1.5} \quad (11)$$

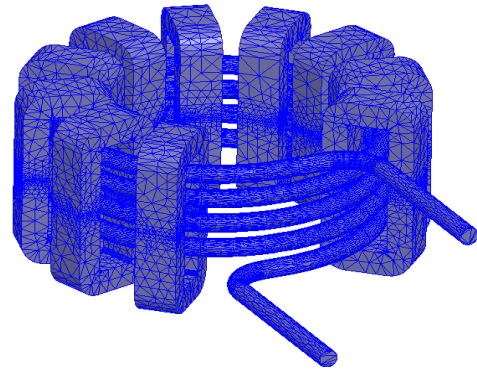


FIGURE 3. Finite element model of saturable reactor.

where: k_e is the additional loss coefficient. Reference [20] gives the loss measurement and data fitting methods.

IV. SATURABLE REACTOR MODELING AND CORE LOSSES SIMULATION

Based on the finite element analysis method, the saturable reactor is modeled, the iron core electromagnetic transient process is simulated, and the iron core power loss density distribution is obtained. In order to ensure reliability and calculation accuracy, the complete cores and coil of the saturable reactor are simulated, and the number of excitation sampling points is increased. The meshed finite element model of the saturable reactor is shown in Fig.3.

According to the operating conditions of the converter valve, the saturable reactor losses are simulated. The voltage, current and power losses of a saturable reactor in one cycle are shown in Fig.4. According to the simulation waveforms, the core losses are mainly generated at three moments: when the thyristors are turned on, when the thyristors are turned off, and when the valve voltage steps due to other valves switching on and off.

The saturable reactor losses in one cycle can be calculated as:

$$P_T = \frac{1}{T} \int_0^T P_{Fe} dt \quad (12)$$

where: P_T is the average loss of the saturable reactor; P_{Fe} is the instantaneous power loss of the core.

Using the saturable reactor coil as the excitation source, its transient electromagnetic conditions and the field distribution of the iron core are analyzed under the operating conditions of the converter valve. The simulation step length is set to $10\mu s$, and the simulation time is 20ms. The instantaneous magnetic flux density of the iron cores at the moment of saturation is shown in Fig.5.

According to finite element simulation analysis, the losses density distribution of the iron cores at different times is obtained, as shown in Fig.6. The simulation results show that the distribution of loss density is uneven among the iron core. The uneven distribution of loss density in space, the position difference in cores placement, and spatial heat dissipation lead to the uneven distribution of reactor core temperature and

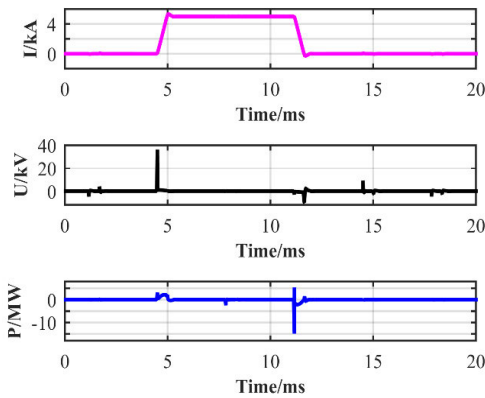


FIGURE 4. Simulated voltage, current and power losses of saturable reactor.

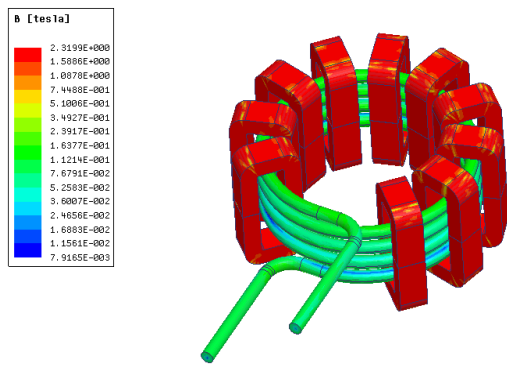


FIGURE 5. Instantaneous magnetic flux density distribution of the iron cores.

case temperature. The electromagnetic transient simulation shows that the core losses of a single saturable reactor under rated operation conditions are 395W.

V. STUDIES OF SATURABLE REACTOR HEAT DISSIPATION AND TEMPERATURE FIELD SIMULATION
A. IRON CORE THERMAL RESISTANCE MODEL

The structural composition of the saturable reactor from the inside to the outside is cooling water→aluminum tube (coil)→cross-linked polyethylene(XLPE)→polyurethane (PU)→iron core→polyurethane(PU)→case. When the saturable reactor is under operation, the aluminum tube coil is forced to dissipate heat through the cooling water circuit, and its heat dissipation efficiency is much higher than that of the iron core, so the iron core has the highest temperature in the saturable reactor. There are two paths for heat dissipation of the iron core: one is to transfer the cooling water inside the aluminum tube coil through the polyurethane and cross-linked polyethylene, and the other is to dissipate heat to the air through the polyurethane and the case. The thermal resistance model of the saturable reactor is shown in Fig.7.

While the converter valve is operating in a steady-state condition and the flow of the cooling water circuit inside the saturable reactor is relatively stable, its material and structural

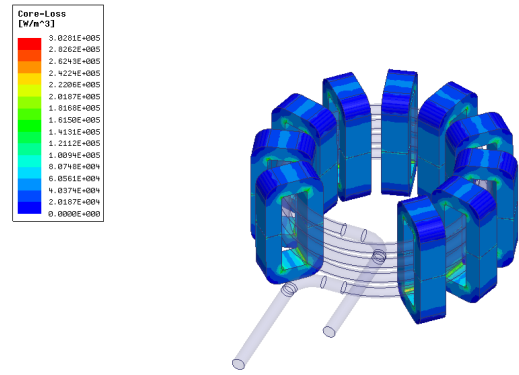


FIGURE 6. Saturable reactor core loss density distribution.

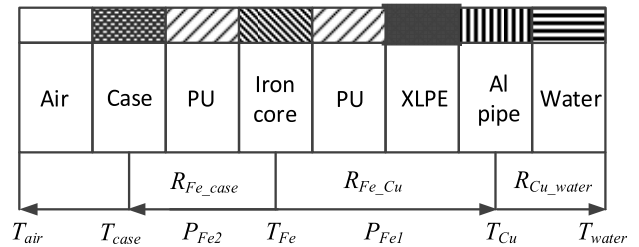


FIGURE 7. Thermal resistance model of saturable reactor.

TABLE 2. The relation between electrical circuit and heat circuit.

Electrical circuit	Resistance	Voltage	Current
Thermal circuit	Thermal resistance	Temperature	Power

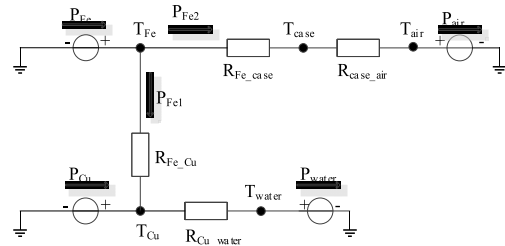


FIGURE 8. Equivalent thermal circuit of saturable reactor heat dissipation.

properties are determined. The thermal resistance from the aluminum tube coil to the cooling water circuit (R_{Cu_water}), the thermal resistance from the iron core to the aluminum tube coil (R_{Fe_Cu}), and the thermal resistance from the core to the SMC case (R_{Fe_case}) are fixed physical quantities that can be measured. The flow of heat by heat transfer resembles the current flow of the electrical circuit, and the corresponding relationship between heat transfer and the physical quantities of the circuit is established, as shown in Tab.2.

The equivalent circuit method is adopted to transform the heat flow equation into a circuit equation [23] to get the quantitative solution of the saturable reactor’s heat transfer and temperature distribution. According to the structure of the saturable reactor, the heating condition of the coil and the core, and the corresponding heat dissipation path, the equivalent heat dissipation circuit can be obtained, as shown in Fig.8.

Where T_{Fe} is the iron core temperature, t_{case} is the case temperature, T_{air} is the ambient temperature, T_{Cu} is the coil temperature, T_{water} is the cooling water temperature.

It is calculated that the thermal resistance R_{Fe_Cu} from the core to the aluminum tube coil is 205K/kW, and the thermal resistance R_{Fe_case} from the core to the case is 127K/kW.

B. CALCULATION OF THE HEAT DISSIPATION OF THE REACTOR

The following calculations are based on a typical ±800kV/5000A UHVDC project with rated system parameters and operating conditions. The parameters of the valve saturable reactor are as shown in Tab.1.

1) FORCED HEAT DISSIPATION BY THE COOLING WATER CIRCUIT

According to equation (13), the calculated heat dissipation through the reactor’s cooling water is 3.1 kW.

$$P_{water} = \rho C_w Q_w (T_{out} - T_{in}) \quad (13)$$

where: ρ is the cooling water density; C_w is the specific heat capacity of the cooling water; Q_w is the cooling water flow rate; T_{out} is the reactor outlet water temperature; T_{in} is the inlet water temperature.

2) CONDUCTION HEAT DISSIPATION INSIDE THE REACTOR

When the reactor reaches a steady state, the iron cores are a high-temperature area while the winding and the case are the low-temperature areas. The heat is conducted from the iron cores to the coil and the case. Heat conduction can be quantified by thermal resistance, as shown in equation (14):

$$R_{\theta} = \frac{T_2 - T_1}{P} \quad (14)$$

where: T_2 is the temperature of the heat source; T_1 is the temperature of the terminal; P is the thermal power.

3) HEAT DISSIPATION FROM THE REACTOR CASE TO AIR

When the heat is conducted to the saturable reactor case, the temperature of the case is higher than the temperature of the surrounding air and heats the air near the case, which causes heat to dissipate from the surface of the case through convection. According to equation (15), the convection heat dissipation from the reactor case is about 136W.

$$P_{FreeConvection} = hA_{reactor}(T_{reactor} - T_{air}) \quad (15)$$

where: h is the convective heat transfer coefficient; $A_{reactor}$ is the surface area of the reactor; $T_{reactor}$ is the surface temperature of the reactor; T_{air} is the air temperature.

4) HEAT RADIATION OF THE REACTOR CASE

According to the Stephen-Boltzmann law of thermodynamics, the thermal radiation power of the saturable reactor case is determined by the surface area of the reactor, the surface radiation coefficient, and the temperature difference between the surface of the reactor and the surrounding air. According

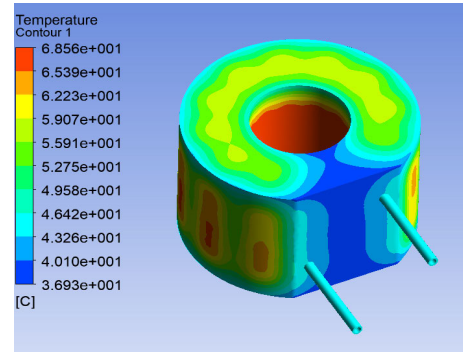


FIGURE 9. Temperature distribution of saturable reactor.

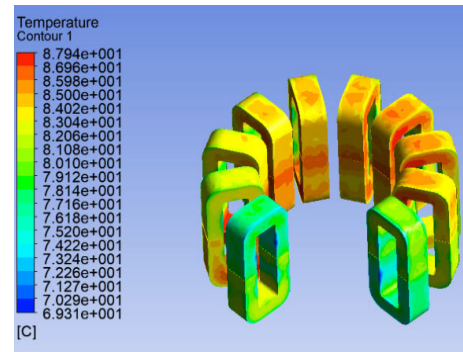


FIGURE 10. Temperature distribution of iron cores.

to equation (16), the calculated thermal radiation power of the reactor is 72W.

$$P_{Radiation} = \sigma A_{reactor} \varepsilon (T_{reactor}^4 - T_{air}^4) \quad (16)$$

where: σ is the Stefan-Boltzmann constant; ε is the radiation coefficient.

C. TEMPERATURE FIELD SIMULATION

In order to study the spatial temperature distribution of the saturable reactor and iron cores, the power loss density obtained through the electromagnetic field finite element analysis is applied as the heat source input of the thermal simulation software. The influence of coil heating, cooling water heat dissipation, and air heat dissipation are introduced into the thermal simulation program. The simulated temperature distribution of the saturable reactor case and iron core are shown in Fig.9, 10, and 11.

It can be seen from the simulation result in Fig.9 that the surface temperature distribution of the saturable reactor case is relatively uneven. The average temperature of the case is about 60°C, and the maximum temperature is 68.6°C. The maximum temperature is located in the inner ring of the case near the iron core, which is caused by insufficient air heat dissipation. The temperature at the aluminum pipe inlet and outlet area is relatively low since the iron cores are sparsely arranged in that area. The simulation result in Fig.10 shows that the temperature distribution among iron cores is uneven too. The highest temperature is about 87.9°C, which is mainly distributed in the area where iron

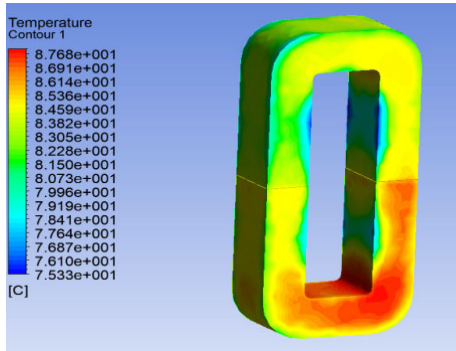


FIGURE 11. Temperature distribution of a single iron core.

TABLE 3. Maximum continuous operating duty test parameters.

Parameters	
Firing voltage	22.25kV
Extinction voltage	-23.2kV
Extinction voltage with overshoot	-37.85kV
DC current	5311A
Valve module cooling water inlet temperature	45°C

cores are concentrated. The simulation results in Fig.11 show the temperature distribution of a single iron core. The temperature in the iron core is mainly affected by the shape of the case and the spiral arrangement of the reactor cooling pipe. The highest temperature is at the corner of the iron core window, with the longest distance to the case. It could be the thermal aging weak point of the polyurethane elastomer. The thermal simulation shows that the heat dissipation to the air of a single saturable reactor is 204W.

VI. TEST VERIFICATION

In order to verify the accuracy of the thermal simulation of the saturable reactor during the operation of the converter valve, the maximum continuous operating duty tests of a converter valve module were carried out in a synthetic test circuit [24]. The optical fiber temperature sensors are embedded on the surface of the iron cores during the reactor manufacturing process so that the iron core temperatures can be monitored in real-time during the test.

A. TEST PARAMETERS

The test was carried out according to the requirements of section 9.3.2 of the IEC60700-1 standard. This test simulates the actual maximum continuous operating duty conditions of the converter valve, including the saturable reactor, which can reflect the actual temperature rise of the reactor. The test object comprises seven thyristor levels of a valve module in series with a saturable reactor. The test parameters are listed in Tab.3, and the test waveforms are shown in Fig.12.

B. TEST RESULTS AND ANALYSIS

The temperature curves of the saturable reactor cores measured by fiber optical sensors in the maximum continuous operating duty tests are shown in Fig.13. After 6 hours of operation, the temperature of iron cores reached a stable state, and there were specific differences in the temperature of the

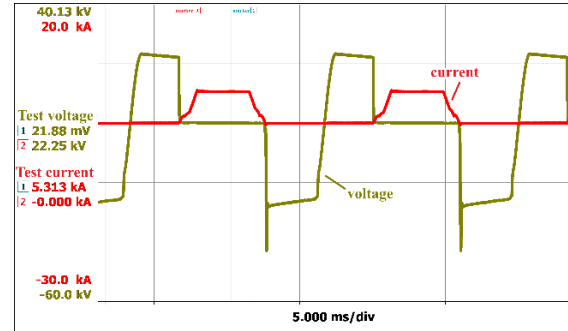


FIGURE 12. Voltage and current in maximum continuous operating duty test.

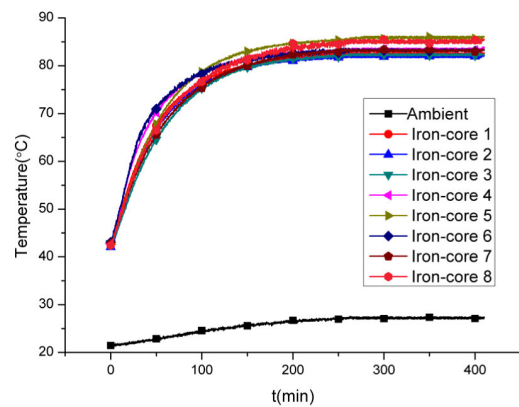


FIGURE 13. Temperatures in the test.

iron cores at different positions. The measured temperature range of the iron cores in the reactor was 82-86°C. The temperature rise of the iron cores was consistent with the simulation results, which verified the accuracy of theoretical analysis and simulation. The maximum temperature of the reactor case measured by the infrared imager during the test is 61.2°C, which is somewhat lower than the simulation result of 68.5°C. The main reasons are 1) limited by the layout of the laboratory and the location of the test object, the highest temperature point of the inner ring of the reactor case may not be measured. 2) The infrared imager needs to maintain a sufficiently safe distance from the test object during the test. The measurement distance could introduce some measurement deviation. 3) The air conditioning system in the laboratory cooled off the reactor case.

VII. CONCLUSION

The operating losses, heat dissipation, and temperature distribution characteristics of the saturable reactor used in the converter valve of HVDC transmission are studied in this paper.

1) The calculated equation for the saturable reactor eddy current loss is analyzed according to the operating conditions of the converter valve.

2) Taking the ±800kV/5000A UHVDC project and rated operating conditions as an example, the simulated core loss of a single saturable reactor is 395W.

3) The thermal resistance model of the saturable reactor is established, and the heat dissipation characteristics are

simulated. The simulation results show that the heat dissipation through the reactor cooling circuit is 3.1kW, the heat dissipation through the air convection of the reactor case is 136W, and the heat dissipation through the heat radiation of the reactor case is 72W.

4) The thermal resistance model of the saturable reactor is established, and the spatial temperature distribution, with the maximum temperature of 87.9°C, is obtained by simulation. The operational type test of the converter valve verifies the correctness of the above-mentioned heat dissipation analysis and temperature simulation study.

REFERENCES

- [1] Z. Y. Liu, "Research of global clean energy resource and power grid interconnection," *Proc. CSEE*, vol. 36, no. 19, pp. 5103–5110, Oct. 2016.
- [2] T. Keim and A. Bindra, "Recent advances in HVDC and UHVDC transmission [happenings]," *IEEE Power Electron. Mag.*, vol. 4, no. 4, pp. 12–18, Dec. 2017.
- [3] Z. Y. Liu, *Global Energy Interconnection*. New York, NY, USA: Academic, 2015.
- [4] C. Liu, S. Hu, K. Han, Q. Hu, S. Gao, and W. Yao, "Electric-field distribution and insulation status of ± 800 kV UHVDC converter valve after implanting full-view micro-sensor detector," *IEEE Access*, vol. 7, pp. 86534–86544, 2019.
- [5] E.-C. Nho, B.-M. Han, Y. H. Chung, S. T. Baek, and J.-H. Jung, "Synthetic test circuit for thyristor valve in HVDC converter with new high-current source," *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3290–3296, Jul. 2014.
- [6] H. Sun, X. Cui, L. Qi, and Q. Wang, "Calculation of overvoltage distribution in HVDC thyristor valves," in *Proc. IEEE Electromagn. Compat.*, Apr. 2010, vol. 21, no. 7, pp. 540–543.
- [7] C.-L. Liu, Q. Shuai, L. Qi, X. Cui, C. Fang, and X. Wei, "Quantitative analysis of voltage distribution within ± 1100 kV HVDC converter valve tower under various transient over-voltage conditions," in *Proc. IEEE Lightning Protection*, Oct. 2014, pp. 1558–1564.
- [8] P. Chen, B. K. Sun, and F. Ji, "Fault mode analysis and accelerated life test method of the saturable reactor prototype for ± 1100 kV UHVDC converter valves," *High Voltage Eng.*, vol. 42, no. 8, pp. 2612–2617, Aug. 2016.
- [9] L. C. Liu, K. Yue, and L. Pang, "Design and implementation of synthetic test system for thyristor unit of HVDC converter valve," *Power Syst. Technol.*, vol. 40, no. 3, pp. 756–761, Mar. 2016.
- [10] Y. Mi, S. Deng, and L. Gui, "Simulation study on iron-core loss and temperature distribution of saturable reactor for ± 1100 kV UHVDC converter valves," *High Voltage Eng.*, vol. 44, no. 10, pp. 3359–3367, Oct. 2018.
- [11] F. Ji, J. Cao, P. Chen, and J. Liu, "Simulation study on iron-core loss of saturable reactor at rectifier valve side in HVDC transmission line," *Power Syst. Technol.*, vol. 38, no. 10, pp. 2680–2684, Oct. 2014.
- [12] B. H. Liu, J. L. Wang, L. Z. Pan, Y. Yang, Y. Shi, and M. Li, "Temperature rise test and comparative analysis of saturable reactors for new generation of ± 800 kV/8 GW UHVDC converter valve," *Electr. Power Construct.*, vol. 41, no. 10, pp. 90–97, Oct. 2020.
- [13] Z. Juanjuan, "A method and system for analyzing thermal characteristics of saturable reactor," Patent CN 110 781 570 A, Feb. 11, 2020.
- [14] J. C. Zhao, "Study on the basic principle of saturable reactor for HVDC converter valve," *Electron. Test.*, vol. 23, no. 1, pp. 44–45, Dec. 2016.
- [15] L. Zhang, R. Gou, N. Liu, Y. Lou, and W. Qiao, "Study on performance of saturable reactor used in HVDC converter valve," *High Voltage App.*, vol. 53, no. 11, pp. 46–50, Nov. 2017.
- [16] S. Barg, K. Ammous, H. Mejibri, and A. Ammous, "An improved empirical formulation for magnetic core losses estimation under nonsinusoidal induction," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 2146–2154, Mar. 2017.
- [17] L. Liu, D. L. Wang, H. Huang, L. Zheng, F. Yang, and C. Zhou, "Design and research on heat dissipation of saturable reactor in ± 1100 kV/5455 A UHVDC converter valve," *High Voltage App.*, vol. 56, no. 7, pp. 23–28, Jul. 2020.
- [18] H. Huang, X. Zhang, L. Liu, T. X. Fang, F. Yang, and L. Zheng, "Experimental study on iron core loss of valve reactor for HVDC transmission," *Electrotech. Electr.*, vol. 2019, no. 5, pp. 49–52, Jan. 2019.

- [19] L. P. Zhang, W. Chen, and J. H. Wang, "Research on the measurement and modeling of the core loss of fast saturable inductor," *Proc. CSEE*, vol. 38, no. 15, pp. 4593–4600, Aug. 2018.
- [20] W. Gong, S. Huang, Y. Yang, L. Rao, and Y. Zeng, "Realization of the method of extracting iron loss coefficient of silicon steel sheet in ANSYS Maxwell," *Electr. Mach. Control Appl.*, vol. 43, no. 4, pp. 82–85, Aug. 2016.
- [21] N. Zhang, L. Li, and X. Wei, "Calculation method and experimental verification of core losses under non-sinusoidal excitation," *Trans. China Electrotech. Soc.*, vol. 31, no. 17, pp. 224–232, Sep. 2016.
- [22] *Determination of Power Losses in High-Voltage Direct Current (HVDC) Converter Stations With Line-Commutated Converters*, Standard IEC 61803, 2016.
- [23] J. B. Zhang, H. Huang, and X. Zhang, "Calculation research of thyristor's junction temperature with high voltage direct current converter valve," *Electrotech. Electr.*, vol. 2017, no. 8, pp. 24–26, Jun. 2017.
- [24] *Thyristor Valves for High Voltage Direct Current (HVDC) Power Transmission—Part 1: Electrical Testing*, Standard IEC 60700-1, 2015.



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