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Research on optimization strategy of transformer economic operation mode considering digital twin technology

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Abstract: *Considering the overall environment of the power field, power transformer is one of the most important energy consuming devices in the substation, and the digital analysis technology of power transformer carbon footprint has become one of the hot issues. Taking a certain brand power transformer as an example, the no-load loss, load loss and stray loss of power transformer under different load conditions are calculated and analyzed by using electromagnetic finite element numerical analysis method, and then the digital twin model of power transformer is built. Combined with the digital twin model of power transformer, the carbon footprint of transformer is analyzed. Finally, the economic load coefficient of transformer is determined, and the optimal economic operation mode of substation is established. This method can provide a scientific basis for the construction of digital, low-carbon and energy-saving substations, while meeting the optimal efficiency and the fastest solution.*

Keywords: *power transformer; substation; digital twin; carbon footprint; loss; load factor*

1. Introduction

China's 14th Five Year Plan points out that the power industry is in urgent need of upgrading from physical power grid to digital power grid through digital transformation to accelerate digital development, build a digital China, and drive the change of production mode through digital transformation. The substation is an important node of the transmission system, and the power loss of the main power transformer accounts for about 20% of the substation loss. Therefore, based on the digital twin technology, the carbon footprint of power transformers is analyzed to provide a scientific basis for the construction of digital, low-carbon and energy-saving substations [1]. At present, the scheme and application of transformer digital twin technology are still in the preliminary exploration stage. The digital twin model of power transformer includes structural parameters, electromagnetic principle and operation state. Therefore, it is difficult to construct a reasonable model without affecting the analysis results [2-6]. Experts and scholars at home and abroad have done relatively extensive research on the low carbon design of transformer equipment, and have made certain phased achievements. The specific operation of the low-carbon design of power transformer products started early and was relatively mature, while the research on the economic operation mode of transformers started late. Now it is a hot issue in the research, and no systematic method has been formed. It is still in the primary stage [7,8]. Taking a SZ11-31.5MVA/66kV main transformer as an example, based on electromagnetics, finite element analysis and numerical analysis theory, this paper constructs a digital twin model of transformer. Through the calculation of no-load loss, load loss and stray loss under different load conditions, it analyzes the carbon footprint of transformer, determines the economic load factor of transformer, and then establishes the optimal economic operation mode of substation.

2. Physical model

The three-dimensional finite element mathematical analysis model of the transformer magnetic field is shown in Figure 1, and the winding connection mode is shown in Figure 1. The model is simplified as follows:

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(1) The higher harmonic component of the excitation current is not considered;

(2) Ignore the clamping stiffeners, oil guide box of oil tank, etc;

(3) Ignore the influence of leads and switches on the magnetic field.

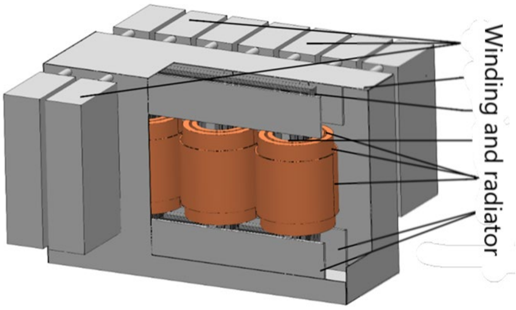

Figure 1: Simulation model diagram of transformer

3. Mathematical model

In this paper, the three-dimensional solution method based on T - Ω bit group is used to calculate and analyze the electromagnetic field. The magnetic field strength in this method is described as the sum of two parts of scalar potential gradient and vector edge element (used to represent the vector field in the conductor). The mathematical model for solving the three-dimensional eddy current problem of transformer can be described by the following formula [9]:

$\nabla \cdot J = 0$, introduction of vector potential T:

$$\nabla \times T = J = J_S + J_E \tag{1}$$

J_S is the source current density (Js=0 in the non-conductive parts and iron core), and JE is the eddy current density.

The vector bit in the eddy current area (including oil tank, clamp, pulling plate and other metal conductor parts) is defined as follows:

$$J_E = \nabla \times T \tag{2}$$

Where, T is the vector potential.

$$H = T - \nabla\Omega \tag{3}$$

Wherein, Ω is scalar magnetic potential.

The first equation form of Maxwell equations in non eddy current region (source current region) is:

$$\nabla \times H = J_S \tag{4}$$

Therefore, it is unnecessary to introduce the vector potential T in the non eddy current region. Therefore, the calculation formula of magnetic field strength is as follows:

$$H = K_s - \nabla\Omega \tag{5}$$

$$H_s = \frac{1}{4\pi}\int_{\Omega_s} \frac{J_S \times r}{r^3} d\Omega \tag{6}$$

Since the thickness of a single silicon steel sheet is 0.3mm, the iron core is stacked, and the permeability is anisotropic. Assuming that the z direction is the silicon steel sheet stacking direction, the permeability tensor is:

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$$\mu=\begin{bmatrix} c\mu_x & 0 & 0 \\ 0 & c\mu_y & 0 \\ 0 & 0 & \frac{\mu_0}{1-c} \end{bmatrix} \tag{7}$$

In the three-dimensional eddy current region of transformer core, the conductivity of silicon steel sheet is also anisotropic. Assume that the electrical conductivity in the rolling direction of silicon steel sheet is σ. The conductivity tensor is:

$$s=\begin{bmatrix} \sigma & 0 & 0 \\ 0 & \sigma & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{8}$$

When the electromagnetic field is analyzed by the time harmonic algorithm, the time average ohmic loss (eddy current loss) can be calculated by the following formula:

$$Pe=\int_V \frac{\overline{J\cdot J}}{\sigma}dv=\int_V \frac{J_{0rms}\cdot J_{0rms}^*}{\sigma}dv \tag{9}$$

Where, J_0rms is the average value of J_0 in a period, and J_0 is the vector related to J.

Hysteresis loss in stray loss can be calculated by introducing B-Loss curve on the basis of magnetic leakage field calculation:

$$P_h=\sum_{i=0}^{N} P_h^{(i)}\left(B_m^{(i)}\right)\rho V^{(i)} \tag{10}$$

The total loss P is:

$$P=P_e+P_h \tag{11}$$

The power consumed by the power transformer is:

$$\mathrm{W}=\int_{t_1}^{t_2} Pdt=\sum_{n=1}^{N} P_n\times t_n \tag{12}$$

Where Pn is the loss power in the nth time interval; Tn is the time of the nth time interval.

The thermal power plant needs to consume about 0.33kg standard coal for every 1kWh of electricity generated, which will produce about 0.87kg CO2. Therefore, the carbon footprint of power transformer can be expressed as:

$$\mathrm{C}_{\mathrm{co}_2}=\mathrm{c}\times W \tag{13}$$

$\mathrm{C}_{\mathrm{co}_2}$ Is the mass of electric energy loss converted into emissions; C is the reduction coefficient.

Digital twin technology takes physical entities as objects, mathematical models as images, and dynamic monitoring data as bridges to build a strong coupling real-time mapping model between physical entities and virtual entities.

The digital twin model established in this paper is based on a large number of 3D magnetic field calculations, and then digitizes and models the transformer carbon footprint analysis problem to eliminate the uncertainty of the transformer entity model. On the basis of correct model, the carbon footprint of transformer can be basically correctly solved by inputting complete operation data. The correctness and effectiveness of this method can be verified and confirmed through simulation and monitoring operation data.

4. Calculation results and analysis

In this paper, starting from 50% load, the step size increases by 10%, and 9 working conditions are analyzed. The leakage magnetic field, eddy current field and structure loss of each operating condition

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are calculated, and then the digital twin model of transformer is built to calculate and analyze the carbon footprint of transformer in the whole life cycle.

The iron core is the main magnetic flow path of the transformer, and the magnetic density distribution is shown in Figure 2. It can be seen from the figure that the maximum magnetic density appears at the center of the main column, about 1.74T.

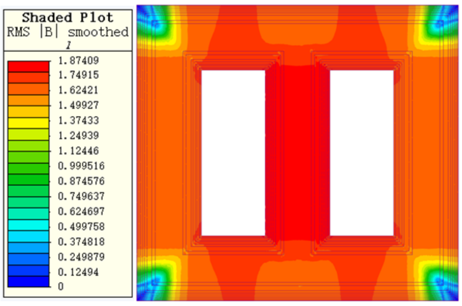

Figure 2: Magnetic flux distribution of core

The magnetic flux leakage distribution in the metal structure is shown in Figure 3. In the figure, the magnetic flux density of the clamp outside the iron core window is the largest, about 0.31T, and the magnetic flux density of the oil tank at the corresponding position of the winding end is the largest, about 0.18T.

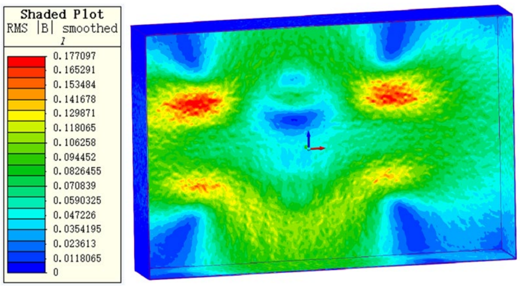

Figure 3: Magnetic flux distribution of steel structure

Analysis of other working conditions

Nine groups of numerical analysis were conducted for this product according to different loads. The eddy current distribution of the fuel tank under 0.5 and 1.3 times of load conditions is shown in Figure 4. It can be seen that the eddy current distribution law of the fuel tank is roughly the same, and the maximum eddy current density amplitude is 2.7 × 104A/m3, min. 1.2 × 104A/m3。

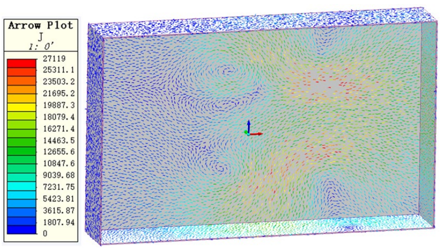

Figure 4: Eddy Current Distribution of Tank

The values of no-load loss, resistance loss, structural component loss, stray loss and total loss under various working conditions are shown in Figure 5. It can be seen from the figure that with the increase of load, the total loss of transformer will increase nonlinearly.

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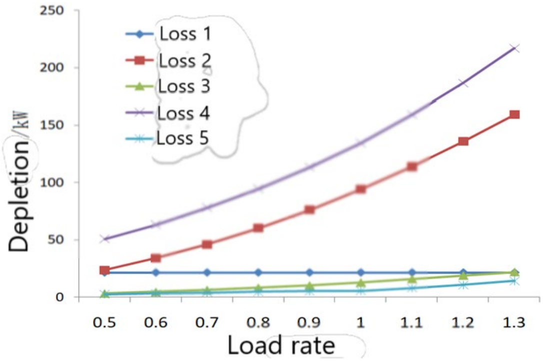

Figure 5: Loss curves under various conditions

It can be seen from the above analysis that the lower the transformer load rate is, the smaller the loss is, but the lower the transformer utilization rate is. The distribution trend is shown in Figure 6. It can be seen from the figure that when the load rate of the main transformer is about 0.8, the economy and environmental protection of the transformer are optimal.

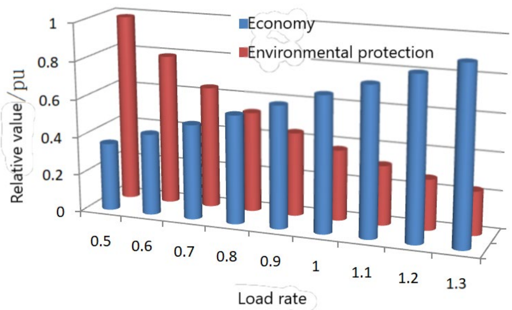

Figure 6: Transformer working point

Carbon footprint analysis

In this paper, through a large number of numerical calculations, a transformer digital twin model is built. The transformer life-cycle carbon footprint analysis system based on digital twin technology is shown in Figure 7. This system can be used for the full life cycle carbon footprint analysis of transformers in service.

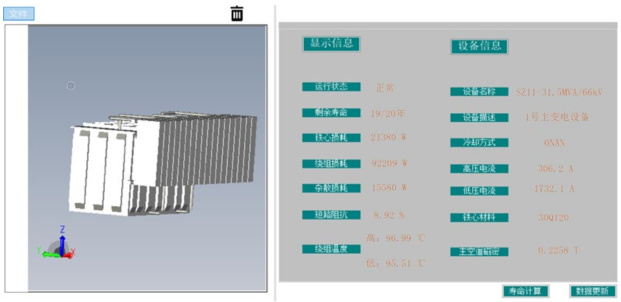

Figure 7: Transformer carbon footprint analysis system

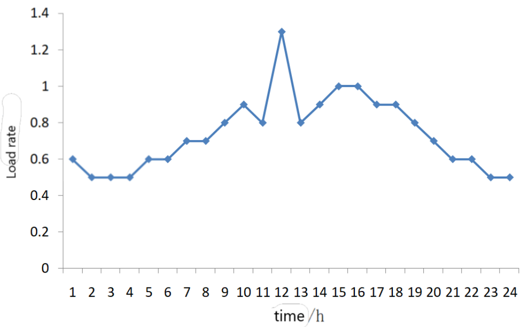

Figure 8: Load rate curve of transformer one day

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The carbon footprint analysis system is driven by the load rate data. Taking the operation data of the main transformer in a substation near the thermal power plant on a certain day as an example, the average hourly load rate of the transformer is shown in Figure 8. The carbon footprint of the transformer on that day, and the transformer generates 2438.5 kg CO_2 that day.

5. Conclusion

This paper takes 31.5MVA oil immersed power transformer as the research object, builds the transformer digital twin model, and builds a transformer carbon footprint analysis system based on digital twin technology. Combined with a large number of electromagnetic finite element numerical analysis, the conclusions are as follows:

(1) In this paper, the digital twin transformer is constructed through a large number of electromagnetic field finite element numerical calculations, which can quantitatively analyze the carbon footprint of each stage;

(2) The carbon footprint analysis model of substation main transformer is systematically proposed, which can calculate the carbon footprint distribution in each stage of the whole life cycle. Based on this model, the carbon emissions of a certain transformer are calculated, and the feasibility and effectiveness of this model and method are verified;

(3) Through the loss analysis of the transformer digital twin, combined with the utilization rate of the transformer, the economic load coefficient of the transformer is proposed. Under this load condition, the operation mode of the substation is optimal in terms of economy and environmental protection.

Through calculation and analysis, the feasibility of the method proposed in this paper is preliminarily proved, which provides a scientific basis for building digital, low-carbon and energy-saving substations.

References

[1] Gao Yang, He Xing, Ai Qian. Multi Agent Coordinated Optimal Control Strategy for Smart Microgrid Based on Digital Twin Drive [J]. Power System Technology, 2021, 45(07): 2483-2491.
[2] P. Moutis and O. Alizadeh-Mousavi, "Digital Twin of Distribution Power Transformer for Real-Time Monitoring of Medium Voltage From Low Voltage Measurements," in IEEE Transactions on Power Delivery, vol. 36, no. 4, pp. 1952-1963, Aug. 2021
[3] JIANG Youhua, YI Gang, HUANG Rong-chang, et al.Transformer State Detection and Evaluation Technology Based on Multi-source Information Fusion[J].Journal of Shanghai Electric Power University, 2020, 36(05): 481-485.
[4] I. E. Kolesnikov, A. V. Korzhov and K. E. Gorshkov, "Digital Program for Diagnosing the Status of a Power Transformer, 2020 Global Smart Industry Conference (GloSIC), 2020, pp. 315-321.
[5] HE Xing, AI Qian, ZHU Tian-yi, et al. Opportunities and challenges of the digital twin in power system applications[J].Power System Technology, 2020, 44(06): 2009-2019.
[6] XIANG Chenmeng, ZENG Si-ming, YAN Peng, et al.Typical Application and Prospect of Digital Twin Technology in Power Grid Operation[J].High Voltage Technology, 2021, 47(05): 1564-1575.
[7] Yang Dong, Liu Jingru, Yang Jianxin, et al. Carbon footprint analysis of wind turbines based on life cycle assessment [J]. Journal of Environmental Science, 2015, 35 (3): 927-934
[8] Zhao Yanwei, Hong Huanhuan, Zhou Jianqiang, etc. Overview and prospect of research on low carbon design of products [J]. Computer Integrated Manufacturing System, 2013, 19 (5): 897-908
[9] JING Yongteng, WANG Ning, LI Yan, et al. Research on temperature rise of transformer windings with electromagnetic-thermal-flow weak coupling [J].Electric Machines and Control, 2019, 23(10): 41-48.