Research and Analysis of Power Transformer Remaining Life Prediction Based on Digital Twin Technology

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***Abstract*—The existing life prediction methods of oil-immersed power transformers mainly calculate the hot spot temperature of the windings based on mathematical models, and it is difficult to achieve an accurate prediction of the remaining life. A method for predicting the remaining life of a transformer based on digital twin technology is proposed: establish digital twin of a transformer with digital twin technology, and using a multi-physics coupling method to calculate the change law of the digital twin's winding hot spot temperature parameters under different working conditions and different operating hours, thereby establishing a remaining life prediction model based on the digital twin's winding hot spot temperature data. Taking the SZ10-50000/110 model power transformer as an example, the results show that the remaining life prediction method based on digital twin transformers proposed in this paper can effectively predict the remaining life of the transformer in operation with an accuracy rate of 95%.**

Keywords—oil-immersed transformer, hot spot temperature, digital twin, life prediction

I. INTRODUCTION

Oil-immersed power transformer is one of the most important and expensive equipment to ensure the safe and stable operation of power grid [1]. With the bringing forward conception of digital south grid and digital national grid [2], the digitalization of oil-immersed power transformers is the only way for the development of smart grid. The 220 kV British Mountain Digital Twin Substation in Hainan [3] is the first time that the digital twin technology is applied to the power transformer in China Southern Power Grid. Under the framework of the digital grid, the research on the digital twin transformer[4] is of great significance.

At present, oil-immersed power transformers mostly use oil circulation to achieve thermal balance, but too high winding hot spot temperature will lead to accelerated insulation aging of transformers and doubled reduction of residual life [10]. The existing calculation methods of transformer winding hot spot temperature [11] include the empirical formulas in IEEE Standard C57.91-2011 and GB/T1094.7-2008 [12]. The hot spot temperature is calculated by giving different temperature coefficients of power transformers with different capacities, but the accuracy is low, which is not conducive to theoretical research. In reference [13], the problem of transformer temperature field is equivalent to the thermal circuit problem by equivalent thermal circuit model. This method has high calculation accuracy but difficult parameter selection, and the model establishment is more complex. In order to improve the speed of the finite element method in solving the fluid-solid coupling problem of temperature field, scholars in China and abroad often use the finite volume method in solving the fluid problem [14]. In reference [16], Monte Carlo simulation method is used to calculate the life loss problem. This method requires higher monitoring equipment for winding hot spot temperature, and the calculation accuracy is greatly affected by the model.

Aiming at the problems of fast calculation but low accuracy of formula method, long calculation cycle of finite element method, complex solution process and limited calculation accuracy by the level of calculation personnel, this paper establishes the electromagnetic-thermal-fluid multi-physical field coupling model of digital twin transformer, and analyzes the hot spots of transformer winding under different working conditions. The results of winding hot spot temperature based on digital twin technology meet the accuracy requirements, and the calculation speed is faster and the operation is simple, which is more in line with the development trend of digital power grid. Firstly, the digital space model of transformer is established. Then, according to the actual operating conditions of the transformer, the distribution of winding hot spots under different operating conditions and different operating time is simulated in digital space. Finally, a transformer residual life prediction model driven by twin data is established. Through the example analysis of 110kV transformer, the rationality and effectiveness of the remaining life prediction of in-service transformer are verified.

II. MAGNETIC - THERMAL - FLUID COUPLING RESIDUAL LIFE MODEL OF TRANSFORMER

A. Electromagnetic Coupling Model

The three-dimensional solution algorithm based on T-Ω bit group is used to analyze the electromagnetic field of transformer in three-dimensional harmonic field. In the T-Ω method, the magnetic field intensity is divided into two parts : the gradient of scalar potential in non-conductive region and the vector field vector prism element in conductive region. The mathematical model of T-Ω method for solving three-dimensional eddy current field of transformer is described by the following Table I.

TABLE I. VARIABLE SCOPE

Scope	Solution Region	Structural Parts
S_1	Hot-wire coil	Winding; Lead wire
S_2	Non-conductive region	Air
S_3	Conduction region	Iron heart.; Metal structural parts

The relationship between T and Ω in the corresponding action domain is as follows [17]:

$$\begin{cases} H = T - \nabla\Omega \in S_1 + S_3 \\ H = -\nabla\Omega \in S_2 \end{cases} \tag{1}$$

The boundary conditions for each domain:

$$\begin{cases} \nabla\times(\nabla\times T - J_s) + \mu\sigma\frac{\partial}{\partial t}(T-\nabla\Omega) = 0 \in S_1 \\ \nabla\mu(-\nabla\Omega) = 0 \in S_2 \\ \nabla\times\nabla\times T + \mu\sigma\frac{\partial}{\partial t}(T-\nabla\Omega) - \mu\sigma\frac{\partial\nabla\Omega}{\partial t} = 0 \in S_3 \\ \nabla\mu(T-\nabla\Omega) = 0 \in S_1 + S_3 \end{cases} \tag{2}$$

The governing equation in the vortex region is

$$\nabla\times\left[\left(\sigma+\varepsilon\frac{\partial}{\partial t}\right)^{-1}\nabla\times T\right] + \mu\frac{\partial}{\partial t}(T-\nabla\Omega) = 0 \tag{3}$$

The governing equation in the non-vortex region is

$$\nabla\cdot\left[\mu\left(H_s - \nabla\Omega\right)\right] = 0 \tag{4}$$

The eddy current loss is calculated by the following formula

$$P = \int_v \frac{J\bullet J}{\sigma}dv \tag{5}$$

where J represents the eddy current density of the unit, and P represents the ohmic loss. Average eddy loss of time harmonic field can be calculated by the following formula

$$P_e = \int_v \frac{\overline{J\bullet J}}{\sigma}dv = \int_v \frac{J_{0rms}\bullet J^*_{0rms}}{\sigma}dv \tag{6}$$

Among them, J0rms represents the average value in a period, J0 is a vector related to J, and Pe represents eddy current loss.

B. Thermal-fluid Coupling Model

The winding disk of the transformer can be approximately regarded as an axisymmetric cylinder, and the problem is transformed into the heat conduction problem in the two-dimensional axisymmetric cylindrical coordinate system. The temperature field control equation of the wire cake can be divided into two parts [18]:

$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial_r}\left(r\lambda\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + k_s\cdot\dot{q} = 0(\text{active area}) \\ \frac{1}{r}\frac{\partial}{\partial_r}\left(r\lambda\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) = 0(\textit{passive area}) \end{cases} \tag{7}$$

The boundary conditions are

$$\lambda\frac{\partial T}{\partial n} + h(T - T_\infty) = 0 \tag{8}$$

Among them, $\dot{q}$ the heat flux intensity, namely the transformer winding unit volume heat. λ is thermal conductivity, which has different values for wire and insulation paper.

The internal heat source distribution mainly includes resistance loss and eddy current loss. When calculating the temperature rise of winding disk, the heat source only exists in the conductor area.

$$\dot{q}_I = \sigma^2\rho_0\left[1+\beta\left(T_c - T_0\right)\right] \tag{9}$$

where σ represents the current density, A/mm^2, and ρ_0 represents the resistivity at T_0. T_0 represents the oil temperature, T_c represents the average temperature of the winding disk.

$$\dot{q}_w = f\sigma^2\rho_0\left[1+\beta\left(T_c - T_0\right)\right]\left(\frac{235+T_0}{235+T}\right) \tag{10}$$

where f represents the percentage of eddy current loss calculated by electromagnetic field in resistance loss. The calculated resistance loss and eddy current loss are added to the total loss of the winding disk area. The total calorific value per unit volume of the winding disk area is:

$$\dot{q} = \dot{q}_I + \dot{q}_w \tag{11}$$

Internal commutation characteristics of pancake winding under natural oil cooling can be described as

$$\begin{cases} N_{u_M} = \left[1.56\times10^{-5}\left(\frac{d_r}{L}\right)^{0.165}\mathrm{Re}_H^{2.4}\,\mathrm{Pr} + 0.012\left(Gr^*_{H\text{-}b}\,\mathrm{Pr}\right)^{\frac{3}{4}}\right]^{\frac{1}{3}} (\textit{bottom surface}) \\ N_{u_M} = \left[1.56\times10^{-5}\left(\frac{d_r}{L}\right)^{0.165}\mathrm{Re}_H^{2.4}\,\mathrm{Pr} + 0.004\left(Gr^*_{H\text{-}b}\,\mathrm{Pr}\right)^{\frac{3}{4}}\right]^{\frac{1}{3}} (\textit{top surface}) \\ N_{u_M} = \left[1.9\,\mathrm{Re}_v\,\mathrm{Pr}\frac{d}{L_1}\left(\frac{\eta_f}{\eta_w}\right)^{0.52} + 0.35\left(Gr_v\,\mathrm{Pr}\right)^{\frac{3}{5}}\right]^{\frac{1}{3}} (\textit{perpendicular}) \end{cases} \tag{12}$$

where d_r is the equivalent diameter of horizontal oil channel. H is winding disk height. L is winding disk width. d is the equivalent diameter of the vertical oil channel. L_1 is vertical channel height. Re_H is Reynolds number of natural oil flow. $\mathrm{Gr}_{H\text{-}b}^*$ represents the number of Grashovs at the bottom and top of a horizontal oil channel. Gr_v^* represents the number of Grashovs in the vertical oil channel. q_b and q_l represent the oil flow at the bottom and top of the horizontal oil channel, respectively, and q_v represents the oil flow in the vertical oil channel. λ is the thermal conductivity of oil, D is the equivalent diameter of the corresponding oil channel.

The convective heat transfer coefficient obtained from the above equation is:

$$h = \frac{N_{u_M} \cdot \lambda}{D} \tag{13}$$

C. *Mathematical Model for Calculating Residual Life*

The aging process and aging conditions of oil-immersed transformer insulation directly affect the residual life of transformer. At present, there is no brief and authoritative life termination criterion. According to GB/T 1094.7-2008 (Load Guide for Oil-immersed Power Transformer) [19], this paper obtains more accurate winding hot spot temperature through the simulation analysis of three-dimensional temperature field of transformer and the measurement of optical fiber probe, and calculates the life loss rate and life loss value of transformer in a period of time.

Relative aging rate of non-thermal modified paper:

$$V = 2^{(\theta_h - 98)/6} \tag{14}$$

where θ_h represents the hot spot temperature, °C. Relative aging rate of thermally modified paper:

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h + 273}\right)} \tag{15}$$

The thermal aging rate of insulating paper is extremely sensitive to hot spot temperature, and its lifetime loss can be written as :

$$L = \int_{t_1}^{t_2} V dt = \sum_{n=1}^{N} V_n \times t_n \tag{16}$$

where V_n is the relative aging rate within the nth time interval. t_n is the time of the nth time interval. In this paper, the residual life of transformer is speculated as

$$T = S - \Delta t \cdot \sum_{1}^{n} V_n \tag{17}$$

where T is the residual life of transformer after a period of operation. S is the service life set when the transformer is out of the factory.

Transformer insulation aging is a time function of temperature, acid content, oxygen content, etc., while most power transformers are often lower than, and the remaining life can be doubled according to the 6° rule. At the same time, due to the uneven distribution of winding insulation temperature, the relative aging rate cannot be used as a reference for the most serious aging situation under high temperature operation conditions, so this paper only considers the winding hot spot temperature as a control parameter.

III. Residual Life Prediction Method Based on Digital Twin

The basic idea of the remaining life prediction method based on digital twin is : the digital model of transformer is established by using digital twin technology, and the operating parameters of the entity running transformer are input into the model. According to the digital model, the parameters obtained are input into the self-programming to predict the remaining life of the transformer under rated load operation, under-load operation and emergency load operation for a period of time. The specific process is shown in Figure 1 and the digital twin system interface is shown in Figure 2.

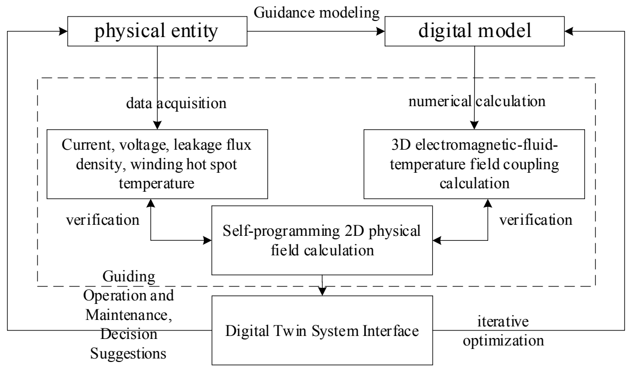

Fig. 1. Flow chart of life prediction of digital twins

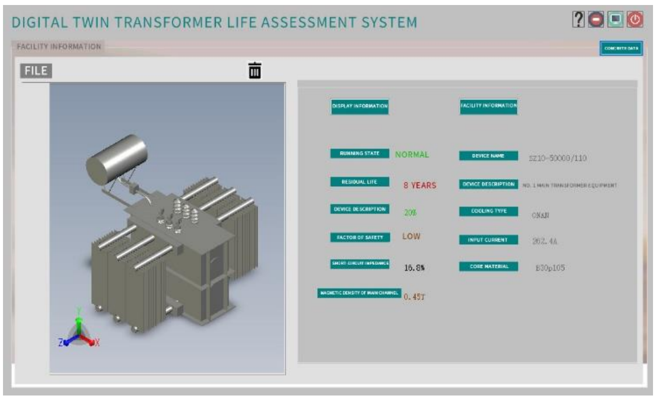

Fig. 2. Digital twin system interface

A. *Transformer Digital Space Modeling*

The digital twin of power transformer is essentially a model, which can only approximately describe the operation characteristics of the transformer. Due to the large capacity and body of the power transformer, when modeling the transformer with high process level, its credibility is high, and some unnecessary complex problems in the dynamic process can be ignored. The simplified model oriented to demand and avoiding complexity and the consideration of the whole life cycle make the overall simulation of the model more reliable and better guide the improvement and optimization of physical entities[20]. The simplified model is shown in Figure 3.

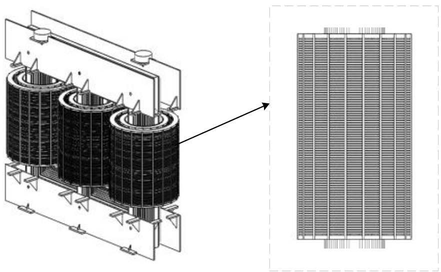

Fig. 3. Simplified model of transformer

B. Digital Calculation Method of Twins

The digital twin of power transformer should ensure the real-time and accurate transmission of data in the digital calculation. Considering that the three windings of the transformer are symmetrical in operation, the temperature field of one winding is focused on for calculation. At the same time, the circular wire cake is a geometric symmetrical structure, and the three-dimensional model is further transformed into a two-dimensional axisymmetric model. This method can fully consider the complexity of the oil channel between windings, ensuring the accuracy of digital calculation and accelerating the calculation speed. The flow chart of the calculation program is shown in Fig. 4.

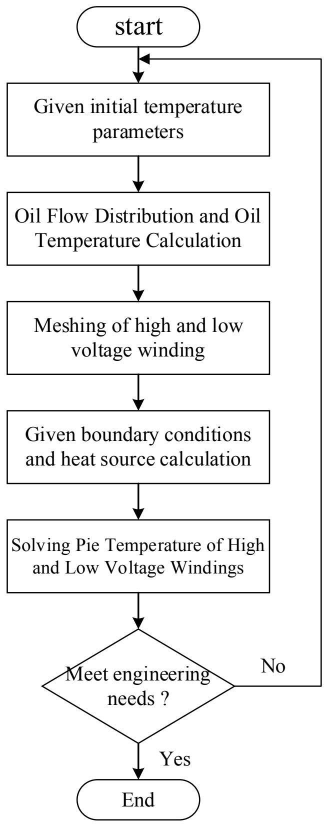

Fig. 4. Flow chart of hot spot temperature calculation

In this paper, through the establishment of mathematical model and the reasonable simplification of physical model, the calculation program of temperature field and hot spot temperature of transformer cake winding is compiled. The specific idea is: a set of algebraic equations of discrete unknowns in a given domain is defined to solve the equations. When meshing, the cladding and insulation paper parts are specially treated, and the axial winding is divided by uniform grid. Then the heat transfer conditions of each boundary are calculated, and the numerical solution of the temperature field is obtained by solving the discrete equations. In order to obtain satisfactory accuracy, the line-by-line iterative solution and the correction technology are introduced to accelerate the convergence speed of the equation.

C. Twin Residual Life Prediction Process

Considering that the life expectancy of power transformer is based on the continuous working conditions under ambient temperature and rated operating conditions, this paper assumes five working conditions, namely, short-term emergency load, long-term emergency load and rated load, 75 % load and 50 % full load. Assuming that the operation time of each working condition is specified, the aging degree of transformer under various working conditions in a cycle is calculated by program, and the boundary conditions are set. When the operation time is less than the specified value, the calculation stops. The specific process is shown in Figure 5.

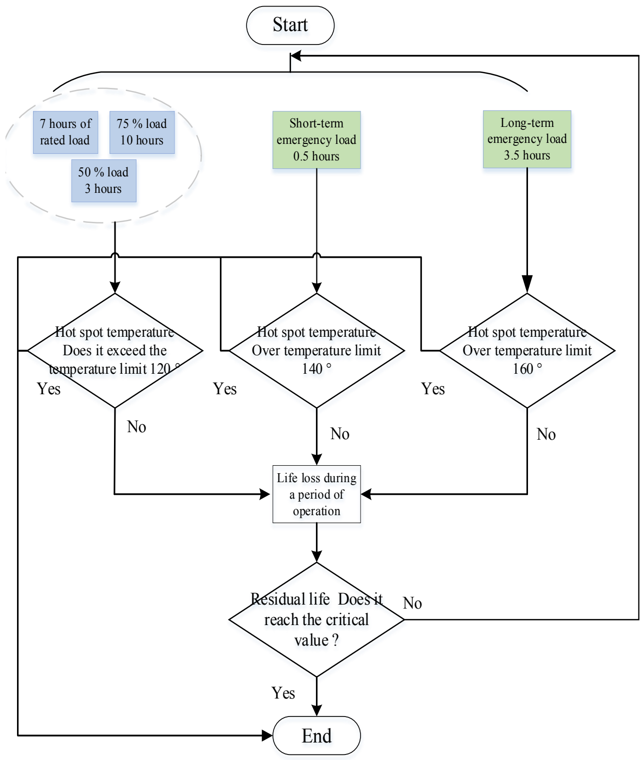

Fig. 5. Flow chart of remaining life prediction

IV. Case Analysis

A. Transformer Parameters

The specific parameters of SZ11-50000 / 110 oil-immersed power transformer are shown in Table II.

TABLE II. Basic Data of Transformer

parameter	SZ11-50000/110
number of phases	3
connection group	Ynd11
Diameter inside and outside high voltage coil	928/1151mm
Diameter inside and outside low voltage coil	632/852mm
High and low voltage current	262.4/1587.3A

Number of turns of high voltage coil	562
Number of turns of low voltage coil	94
Average temperature rise of oil(K)	28.7
top oil temperature rise(K)	52
average winding temperature rise(K)	62.2/62.8
winding hot spot temperature rise(K)	70.31/69.78
Type of silicon steel sheet	B30P105
impedance voltage	17%
cooling type	ONAF

B. Simulation Result

In the electromagnetic loss analysis of twin transformer, when the transformer working condition is rated load, the three-phase current is symmetrical, and the high and low voltage current values are 262.4 A and 1587.3 A, respectively. Given the magnetization curve and conductivity of the core material, the magnetic density curve of the main channel is shown in Figure 6.

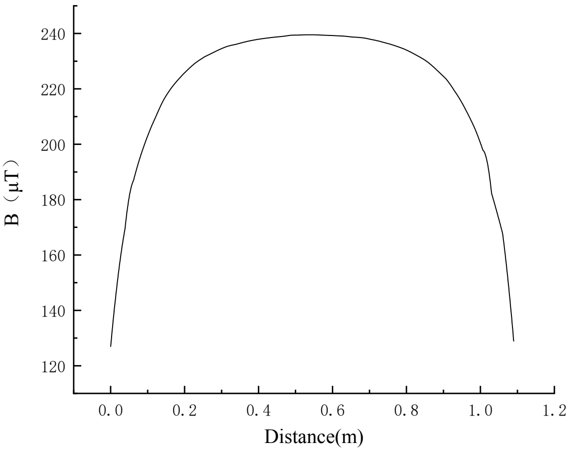

Fig. 6. Magnetic density curve of main channel

In the above figure, the magnetic density amplitude in the middle of the main channel is the largest, and the magnetic flux leakage field intensity is also the largest and mainly axial component. The two ends of the main channel begin to decrease gradually, and the magnetic lines at the end of the winding are dense and part of the magnetic lines bend and produce amplitude leakage. The formula of maximum magnetic flux leakage induction intensity is

$$B_m = \frac{\sqrt{2}\mu_0 NI}{H_w} \tag{18}$$

The maximum electromagnetic induction intensity Bm = 227.9μT is obtained by substituting the numerical value, and the maximum electromagnetic induction intensity Bm = 235.1μT is obtained by the calculation program in this paper. The error is 3.06 %. The calculation results meet the accuracy requirements. It is considered that the magnetic field distribution of the calculation program is correct.

The electromagnetic loss results are coupled to the temperature field according to the grid as the heat source to calculate the winding temperature of the digital twin under the rated load. At the same time, the results shown by the optical fiber temperature sensor are compared with the calculation results, as shown in Figs. 7 – 9.

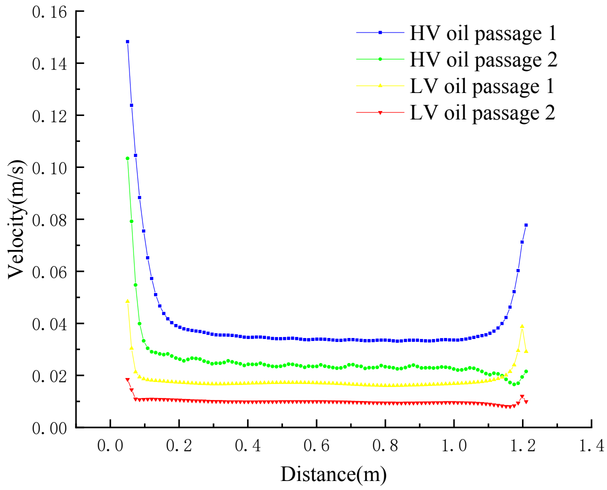

Fig. 7. Comparison of vertical flow velocity

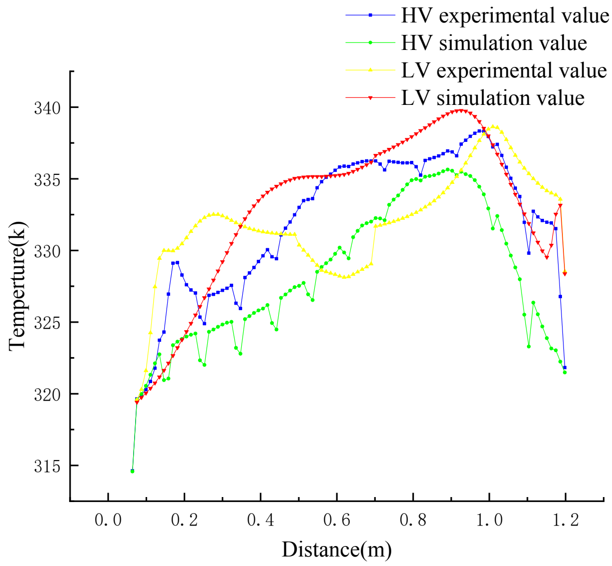

Fig. 8. Comparison of high and low voltage winding temperature with experimental value

Fig. 9. Temperature rise test instrument

Figure 7 shows the flow velocity of oil passage between high and low voltage winding. The flow velocity of vertical oil passage structure is the fastest at the highest point of the oil passage, due to the oil flow under the rated load, the speed is low. Figure 8 shows the temperature of high and low voltage winding. The highest calculated value of low voltage winding temperature is 339 K, the winding temperature is two troughs, and the middle temperature is valley bottom. Compared with the experimental results, the maximum error is less than 5 %, and the accuracy of life prediction based on hot spot temperature is more than 95 %. Fig. 9 shows the experiment using optical fiber temperature tester, and the experimental results verify the accuracy of the program calculation.

C. Analysis of Residual Life Based on Twin Data

The residual life calculation program is driven by the hot spot temperature data, and the hot spot temperature limits are not the same under each load condition. A set of hot spot temperatures are listed and the running time of each hot spot temperature is set to be 30 min for calculation and display, so as to simulate the life loss of the in-service transformer with 20 years remaining life after 300 min of operation. Part of data in the remaining life calculation program based on the digital twin are shown in Table III.

TABLE III. LIFE LOSS RESULTS TABLE

hot spot temperature θ_h	running time Δt	aging rate V_n	life loss $\Delta t \cdot V_n$
40	30min	0.00123	0.0369
45	30min	0.002192	0.06576
67	30min	0.027841	0.83523
74	30min	0.0625	1.875
79	30min	0.111362	3.34086
98	30min	1	30
121	30min	14.25438	427.6314
135	30min	71.83757	2155.127
137	30min	90.50967	2715.29
140	30min	128	3840

At this time, the life loss and residual life are:

$$\Delta t \cdot \sum_{1}^{n} V_n = 9174.20215(\text{min}) \tag{19}$$

$$T = S - \Delta t \cdot \sum_{1}^{n} V_n = 20 \times 365 \times 1440 - 9174.2 = 10502825.8(\text{min}) \tag{20}$$

As can be seen, according to the hot spot temperature given in the table running 300 minutes, life loss is much higher than the actual running time, about 30 times the actual running time.

V. CONCLUSION

In this paper, the hot spot temperature and residual life of the oil-immersed power transformer winding are taken as the research objects. In view of the limitation of the calculation accuracy and calculation cycle of the hot spot temperature of the current oil-immersed power transformer, a transformer residual life prediction method based on digital twinning technology is proposed. The life prediction of the transformer is preliminarily realized through the self-compiled program and the digital twinning evaluation system. The hot spot temperature calculation results meet the accuracy and the calculation time is short. The conclusions are as follows:

1) The modeling of power transformer digital twin is a process of cooperation between digital model and physical model. The model constructed in this paper simplifies the complex process and makes the simulation results closer to the actual situation. Compared with the experimental analysis of winding hot spot temperature, the error is less than 5%, indicating that the model used in this paper can truly reflect the life cycle of the transformer.

2) The temperature rise of power transformer digital twin is calculated by two-dimensional axisymmetric model. Compared with the results of three-dimensional multi-physics coupling analysis, the speed and accuracy meet the engineering needs, and can guide the action of physical entities timely and effectively. The next research direction is to use the results of three-dimensional physical field analysis to correct the error of two-dimensional field calculation, so that the calculation results are fast and the accuracy is improved.

3) The residual life prediction of digital twins of power transformer takes into account the accelerated aging of insulation life caused by the change of winding hot spot temperature, and the residual life of a practical product is evaluated. The feasibility of the proposed method is preliminarily proved, which also provides a reference for transformer maintenance and aging treatment.

4) The experimental study of digital twins is still on the way. Based on the current technology, the dynamic updating and real-time evolution of the digital model of power transformer are needed to realize the real digital twins.

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