Fast Calculation of DC Bias of Double Winding Transformer Based on Interpolation Method

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Abstract: Aiming at the problem of slow calculation speed and low calculation efficiency of DC biasing of transformer, the excitation current with less influence of saturation degree and the load current with smaller amplitude change are selected as the coordinates to form the sampling plane, and the DC bias in the transformer is studied. Under the influence of strong nonlinearity, the reasonable planning of the sampling interval constitutes a dynamic inductive surface. The fast calculation of the DC bias of the double-winding transformer is realized by two-dimensional interpolation of the dynamic inductor surface, which is compared with the conventional field-circuit coupling method. The accuracy of the method satisfies the requirements of DC bias. This method greatly reduces the calculation time and extends the application prospect of the field-circuit coupling method.

1. Introduction

With the gradual expansion of the power system and the continuous improvement of the voltage level, the quasi-DC component generated by the geomagnetic storm and the HVDC transmission single-maximum return line operation has an increasing influence on the power grid[1-4]. In order to study the DC bias mechanism more deeply, researchers analyze the law of DC bias, reduce the computational cost of studying DC bias, and expand the application of DC bias calculation in the prevention of geomagnetic storm disasters, in need of fast and accurate DC bias calculation. As an important part of the power system, the double-winding transformer has a large number of components affected by the geomagnetic storm in a large scale. The fast calculation of the DC bias of the double-winding transformer is of great significance for the prevention of geomagnetic storms in power systems and transformers.

Because the transformer has the characteristics of fast change of inductance and strong nonlinearity under the influence of DC bias, the numerical calculation of DC bias is faced with problems such as large time constant and poor convergence. With the deepening of research on DC bias magnetism[5-6], the current methods for DC bias calculation of transformers are becoming more and more mature. There are three main methods: harmonic balance finite element method[7-9], Magnetic circuit-circuit coupling method[10] and magnetic field-circuit coupling method, wherein the field-path coupling method can be divided into direct field-circuit coupling and indirect field-circuit coupling. The indirect field-circuit coupling method has a good calculation accuracy and good evaluation of the DC bias magnetic properties of the transformer. But there are still problems such as too long calculation time and poor convergence. Tan Ruijuan solves the problem that the time constant of the transformer is large and the calculation does not converge through series resistance, and the error caused by the series resistance is corrected by voltage compensation. However the calculation of the inductance still occupies large computational resources and the solution efficiency is low. The calculation time of the road coupling method is still very long. Tan Ruijuan, Deng Tao and others have greatly improved the efficiency of inductor acquisition by interpolating the dynamic inductor-excitation current curve, reducing the DC bias calculation time to the second level and interpolating the initial value-DC current component curve. The calculation efficiency is further improved, and the DC bias calculation time is reduced to the millisecond level, which greatly expands the application prospect and application of the DC bias calculation. In addition, some scholars have used experimental methods to analyze the effects of DC bias on transformers.

Under the DC bias, the excitation current can respond sensitively to the change of excitation. The amplitude of load current is relatively stable. So we select the excitation current-load current as the sampling plane. The density of the inductor sampling points is reasonably selected to form a dynamic inductive surface. The dynamic inductance surface is subjected to two-dimensional interpolation to obtain the dynamic inductance, and the interpolation dynamic inductance surface method is proposed. The method is fast in calculation, and the efficiency is increased by a thousand times compared with the conventional field-circuit coupling method. The calculation method is directed to a two-winding transformer. As long as the dynamic inductance surface of the transformer is obtained, the fast calculation of various conditions of the transformer and the DC bias magnetization under various DC can be realized.

2. Principle of Field-circuit Coupling Method

With the deepening of the research on DC bias magnetism, the field-circuit coupling method applied to the DC bias calculation of transformers becomes more and more perfect. The field-path coupling method divides the DC bias magnetic transient calculation of the transformer into the coupling calculation between the magnetic field and the circuit through the time domain field coupling model based on the edge finite element method. The schematic diagram shows the following:

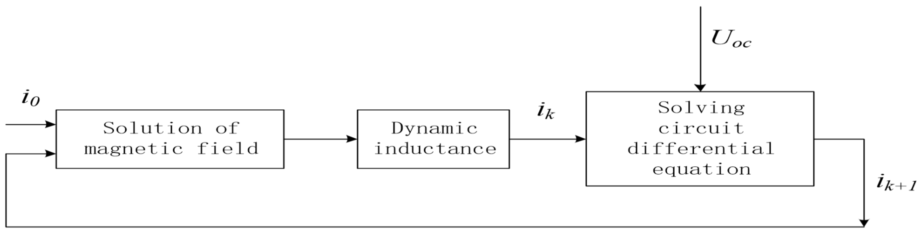


Figure 1: Field circuit coupling method schematic.

By inputting the initial value of the current as the current excitation into the magnetic field model, and then performing the finite element calculation, the dynamic inductance parameters are obtained, and the inductance parameters are substituted into the circuit equation, and the value of the circuit equation is solved by the Runge-Kutta method. So we get the Solution as current value of the next moment. This cycle is repeated until the calculation results are stable.

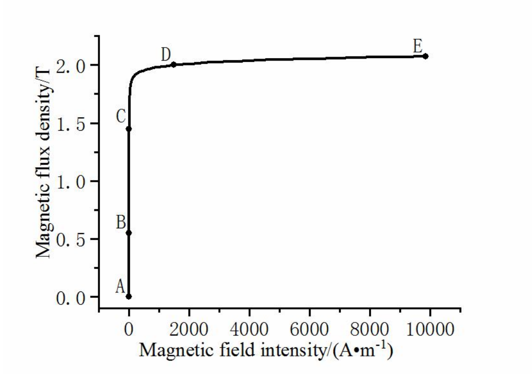


Figure 2: Magnetization curve.

Figure 2 shows the magnetization curve of the autotransformer. During the process of magnetization curve from A to E, the slope of the curve first decreases and then increases, and decreases till the end. According to the degree of saturation, the magnetization curve can be roughly divided into three segments. AC, the segment is an unsaturated segment with a large slope of the magnetization curve. the DE segment is a saturated segment, and the slope of the magnetization curve is small; the CD segment is a transition segment, and the slope of the magnetization curve rapidly transitions from a larger value to a smaller value. According to the law of electromagnetic induction, the slope of the magnetization curve becomes smaller with the greater the saturation of the transformer.

Figure 3 is a circuit model of a two-winding autotransformer. In Figure 3, L1 and L2 are self-inductance parameters of the primary and secondary windings, and M_{12} is a mutual inductance parameter between the primary and secondary windings respectively. The circuit model connects the electromagnetic relationship between the primary and secondary sides of the transformer through mutual inductance and self-inductance. The circuit equation is intuitive and easy to understand. i_1 and i_2 are divided into current values that have not been normalized to the primary side, and u1 is the voltage value of the high voltage winding, which is the superposition of the DC voltage and the AC voltage, i.e. $u_1=u_s+U_{dc}$. The original secondary side turns ratio of the two-winding transformer is k, and the exciting current is $i_c=i_1+i_2/k$.

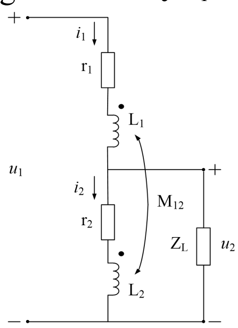


Figure 3: Mutual inductance circuit model.

According to the topology diagram of the circuit, the circuit equation of the mutual inductance circuit model is obtained as shown in Equation (1).

$$\begin{bmatrix} L_1+M_{12} & L_2+M_{12} \\ M_{12} & L_2 \end{bmatrix} \begin{bmatrix} \frac{di_1}{dt} \\ \frac{di_2}{dt} \end{bmatrix} = \begin{bmatrix} u_s+\mathrm{U}_{dc} \\ 0 \end{bmatrix} - \begin{bmatrix} r_1 & r_2 \\ -Z_l & Z_l+r_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{1}$$

The equation is a variable coefficient nonlinear differential equation, and the change of the inductance parameter will affect the calculation result. When the transformer is in a DC bias working environment, on the one hand, the voltage will be superimposed with a DC voltage, i.e. Udc. On the other hand, DC bias will cause dynamic changes in the inductance parameters.

3. Variation Pattern of Dynamic Inductance

3.1. Sampling Method of Dynamic Inductance

It is known from the calculation principle of the inductor that the inductance parameter of the double-winding transformer is determined by the primary current and the secondary current. When calculating the inductance parameters by finite element, it is also necessary to apply current excitation to the primary secondary winding, namely i_1 and i_2. However, due to the influence of DC bias, the saturation of the excitation increases, and the generated excitation current is large. According to the calculation formula of the excitation current $i_c=i_1+i_2/k$, the excitation current pair will affect the primary and secondary currents i1 and i_2 , causing serious current distortion, and there is a superposition of DC components. When sampling and drawing the dynamic inductance parameter surface, the magnitude of the original secondary current is difficult to reflect the degree of excitation saturation of the transformer, and the sampling density cannot be reasonably selected according to the degree of excitation saturation. Considering the variation law of the excitation curve, when the excitation current is small, the inductance value changes drastically. In this paper, the excitation current is used as one of the coordinates of the coordinate system of the sampling plane. Since no DC component flows through the load, the load current , i.e. reduced to the high voltage side is only distorted by the influence of DC, and is not offset by the DC component. Therefore, the amplitude of the waveform is relatively stable and can be used as an inductive sampling plane. One of the coordinates, the load current *iL' = k(i2-i1)*. When converting it to a matrix, the expression is as in Equation (2), which defines the transformation matrix in the formula as Tn.

$$\begin{bmatrix} i_c \\ i_L^{'} \end{bmatrix} = \begin{bmatrix} 1 & 1/k \\ -k & k \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \tag{2}$$

Taking the excitation current as the abscissa, the load current calculated on the high voltage side is the ordinate, which constitutes the sampling plane of the equivalent inductance parameter, selects a specific point on the coordinate plane, and changes the linear value to obtain the current value of the primary and secondary windings. The finite element solves the electromagnetic field and obtains the self-inductance and mutual inductance parameters. According to the definition of the equivalent inductance parameter, the equivalent inductance parameter is obtained. The sampling process is shown in Figure 4.

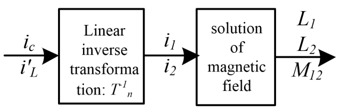
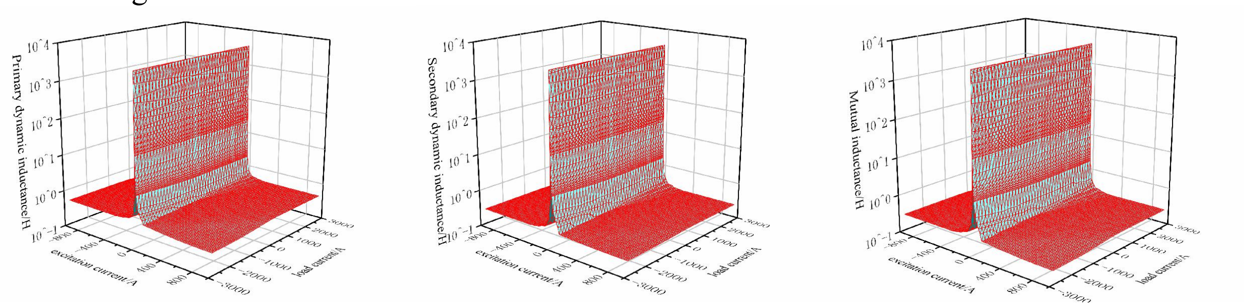


Figure 4: Equivalent inductance sampling process.

3.2. Dynamic Inductive Surface

According to the magnitude of the inductance change, the sampling density is reasonably set, and finally the surface of the original secondary side self-inductance parameter and the mutual inductance parameter is obtained, which is simply referred to as a dynamic inductance surface, as shown in Figure 5.



a）Primary inductance　　b）Secondary inductance　　c）mutual inductance

Figure 5: Dynamic inductance surface.

It can be seen from Figure 5 that the dynamic inductance parameters L_1, L_2, and M_{12} are not much different from each other, and are mainly affected by the excitation current. When the excitation current is small, the excitation of the transformer is not saturated, and the dynamic inductance value is relatively large. With the excitation current increases, the saturation of the transformer increases rapidly, and the dynamic inductance rapidly transitions from a larger value to a smaller value.

4. Interpolation Dynamic Inductance Surface Method and Its Application

4.1. Interpolation Dynamic Inductance Surface Method

According to different DC bias level and rated current, the excitation current-load current plane is determined, and the sampling is sequentially performed on the plane to obtain the equivalent inductance parameter. The transformer has strong nonlinearity under DC bias and large variation of inductance value. In the unsaturated section and transition section of the transformer, the inductance of the AD segment corresponding to the excitation curve of Figure 2 is quite severe, and the sampling point is appropriately increased. After entering the saturation, corresponding to the DE segment of the excitation curve, the sampling point can be appropriately reduced, and the equivalent inductance surface is determined. Interpolation Equivalent Inductance Surface Method Calculation Process: Given the initial value of the current, the equivalent inductance value is obtained by interpolating the equivalent inductance surface, and the circuit equation is numerically solved to obtain the next moment. The current value is cycled back and forth until the calculation is stable.

The sampling interval of the large excitation current is 0.01A, and the interval of the small excitation current is 1A. the interval of the load current is 10A. The equivalent inductance surface is obtained, and the equivalent inductance surface is interpolated. The process of solving the magnetic field with the finite element method is instead by interpolation. Taking 100A DC current on the high voltage side of the autotransformer as an example, the conventional field coupling method and the DC bias calculation of the interpolated equivalent inductive surface are respectively performed, and the stabilized excitation current is obtained as shown in Figure 6.

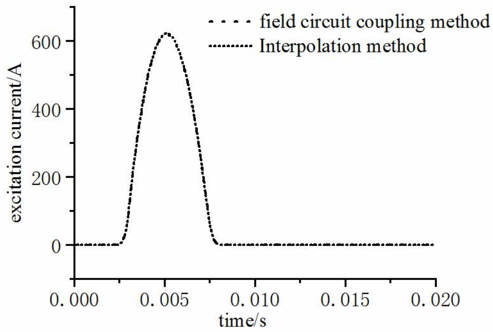


Figure 6: Excitation current under different calculation methods.

The maximum error of the two algorithms is 0.38%, which proves that the interpolation equivalent inductance surface method has a high accuracy and meets the requirements of DC bias calculation. The conventional field coupling method takes nearly ten hours to calculate, while the interpolation equivalent inductive surface method uses only 35 seconds. Compared with the conventional field-path coupling method, the calculation speed of the interpolation equivalent inductance surface method is more than a thousand times, the efficiency is greatly improved, the calculation time is greatly reduced, and the application prospect is also broader.

4.2. Application Prospects

In the mechanism research and impact analysis of transformer DC bias, it is necessary to analyze the DC bias under different DC and different working conditions. In the process of analysis, the finite element program is repeatedly used to obtain the inductance parameters. There is a large number of repetitions of the inductance parameters between the calculation of each DC operating condition, the calculation of each voltage compensation and the calculation of each cycle, and the repetition of the inductance parameters each time does not make the calculation result more Accurate, just in the vicinity of the resulting trajectory, wasting a lot of computing resources and prolonging the research cycle of transformer DC bias. By performing reasonable sampling on the excitation current-load current plane, the equivalent inductance surface is obtained. By interpolating the equivalent inductance parameters, the problem of difficult inductance acquisition and high calculation cost can be solved once and for all, and the DC bias calculation time of the transformer is permanently reduced.

China's power system is large in scale, and there are many transformers in operation. The geomagnetic storm causes the transformer's reactive power consumption to increase. A large amount of reactive power consumption will lead to voltage reduction, reactive power compensation reduction, such a vicious cycle, and even lead to voltage collapse of the power grid. The interpolation equivalent inductance surface method is fast, and the calculation of DC bias can be performed in a short time according to the obtained current value, which provides a fast and effective calculation result for the prevention and control of geomagnetic storm.

5. Conclusion

The dynamic inductance parameters L_1, L_2, M_{12} have little difference between each other, mainly affected by the excitation current. When the excitation current is small, the excitation of the transformer is not saturated, and the dynamic inductance value is relatively large. As the excitation current increases, the transformer is saturated. The degree increases rapidly and the dynamic inductance quickly transitions from a larger value to a smaller value.

As long as the sampling interval is reasonable, the calculation accuracy of the interpolation equivalent inductance surface method satisfies the calculation requirements. Compared with the conventional field coupling method, the calculation efficiency is greatly improved, and the calculation time of DC bias is shortened from ten hours to tens of seconds.

Acknowledgments

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