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Leakage Inductance Characteristics of Power Transformer Winding Fault Based on ANSOFT

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Abstract

The development momentum of the power industry is pushed by the increasing demands and continuous progress in all sections of the economy. The improvement of the voltage grade of transmission lines is imminent, and the capacity of a single transformer continuously increases, thereby resulting in the serious problem of magnetic leakage, which that can aggravate the stray loss of transformers and the degree of winding deformation. The simulation model of leakage inductance under the different fault states of transformer winding was proposed on the basis of finite element method to reduce the threat to the safe and stable operation of power grids caused by the winding insulation damage from magnetic leakage. ANSOFT software was used to establish the physical model of 800 kVA and 10 kV true distribution transformers, and the leakage inductance values of transformer winding with a three-phase grounding short circuit, a turn-to-turn fault, and an inter-turn fault were analyzed. Finally, the accuracy of the model was verified through the finite element simulation. Results indicate that the leakage inductance of transformer increases by 30% in a three-phase short circuit, the leakage inductance is negatively correlated with the number of fault turns in a turn-to-turn fault, and the leakage inductance has a nonlinear positive correlation with the number of fault turns in an inter-turn fault. The proposed method provides references for the detection and evaluation of transformer operation fault.

Keywords: transformer; winding fault; leakage inductance; electromagnetic field; finite element method

1. Introduction

As an important power equipment in the transmission network, the safe and stable operation of transformers is related to the safety of the entire system; hence, the cause of its failure needs special research attention [1]. At present, the transformers in a power system have two fault classifications, which are based on the different locations of transformer faults[2, 3, 4, 5, 6]. Transformer faults can be divided into ontology and external faults. According to the statistical analysis of previous types of transformer fault, ontology faults, which are internal faults, account for a large proportion. When a transformer has an internal fault and the ontology is seriously damaged, electrical and non-electrical characteristics can be observed, and fault detection is relatively easy. Currently, numerous transformer internal fault detection studies mainly focus on this phenomenon. However, the research on hidden and potential fault detection in transformers is still in its infancy. Meanwhile, the “hidden danger” of transformers and the slight fault of transformer winding have not been investigated [7, 8, 9]. Existing literature shows that transformer winding is deformed when the transformer suffers from external faults during operation, thereby developing into internal inter-turn fault, which causes transformer fault [10].

Although the “healthy state” of internal winding in the normal operation of a transformer is poor and still not evident, it has already entered an adverse operation state. This feature describes a hidden fault, which has the property of trigger and accumulation [11, 12]. At present, the detection of hidden fault mainly depends on the analysis of oil chromatography, which is difficult to combine with mature protection theory and the engineering application of large transformers. The detection and quantification of this hidden fault in large transformers through electrical quantity have been reported rarely. In the actual operation of a power system, different short-circuit faults, which cause large electromagnetic shock in the system due to the short-circuit current, are inevitable. This shock deforms the winding of the transformer, which can influence the normal operation of the transformer and even

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lead to the failure of its operation.

Thus, this study used the finite element method to propose the leakage inductance characteristics of the power transformer winding fault based on $ANSOFT$. The leakage inductance characteristics of 800 kVA and 10 kW three-phase oil-immersed distribution transformers, which can be more accurately predicted under the conditions of three-phase grounding short circuit, turn-to-turn fault, and inter-turn fault, were investigated by establishing a two-dimensional ($2D$) simulation model of transformer winding deformation degree and its characteristics. Furthermore, the results can provide reference for the detection and evaluation of transformer operation fault.

2. State of the art

The main influence of leakage magnetic field has two aspects. One is to accelerate the thermal aging of the internal metal structure of the transformer and paper insulation. The other is to produce a large electromagnetic force for the interaction between the current that flows through the winding and the leakage magnetic flux. Therefore, experts all over the world have not only studied the numerical value of the transformer leakage magnetic field in recent years, but also achieved corresponding results in the calculation of the short-circuit electromagnetic force of winding.

The numerical solution of the electromagnetic field problem has been developed rapidly with the development of computer and programming technology. The solution can be extensively applied in solving the electromagnetic field problem. Currently, the most commonly used calculation methods include the least square, finite element, integral equation, and finite difference methods. Tsukerman I.A., Konrad A., and Lavers J.D. proposed the use of least square means to calculate the leakage inductance of transformers and applied it to transformer protection [13]. Silvester and Chari used the methods of $2D$ high-order finite element and $2D$ finite element with vortex term to calculate the constant magnetic field of a transformer. O.W. Anderson used the axisymmetric finite element method to manage the magnetic field leakage of transformers [14, 15]. In Britain, Coulson used the finite element method to calculate and analyze the electromagnetic field distribution in a transformer based on the three-dimensional (3D) simulation model of the transformer [16]. In the United States, Kumbhar G. B. effectively simulated the electromagnetic operation process of a transformer by simplifying the geometric model of a transformer and applying the magnetization curve of the core in the model [17]. Dr. Wang Shenghui of Shenyang University of Technology used the $A - V - A$ method to calculate and analyze the 3D transient field of a transformer [18]. Liu Xiaoli and Bi Yanjun of Harbin University of Technology analyzed the transient leakage magnetic field of a cable transformer using the field circuit coupling and mirror image methods. Chongyou Jing, an engineer of Tianwei Transformer Factory in Bao Ding, obtained the converter transformer model under the non-sinusoidal condition and the distribution of the transient leakage magnetic field around the winding using a finite element simulation tool [19]. Xiaopo Ou of Guangdong Power Grid Company used the finite element method to calculate the transformer short circuit impedance to obtain the distribution of the leakage magnetic field and the leakage inductance parameters [20]. Jianmin Wang of Baoding Tianwei Group not only investigated the transient electromagnetic field characteristics of the UHV DC converter transformer, but also calculated the transient electromagnetic field and harmonic loss of the converter transformer [21]. The magnetic leakage field of a high-voltage converter transformer was calculated and analyzed in Reference [22], and the short-circuit impedance and the leakage magnetic field distribution were obtained.

The short-circuit electromagnetic force of the transformer winding in the short-circuit state can cause serious mechanical damage to the transformer, bend or damage the winding, and even cause the transformer to explode. In addition, the monitoring of transformer short-circuit condition requires the use of a special test instrument. The requirements for test tools increase with the transformer capacity. Therefore, establishing the transformer numerical simulation model for predicting the short-circuit electromagnetic force of winding is crucial. S.V. Kulkarni took the lead in solving the electromagnetic field of a transformer with tap winding using the field circuit coupling method [23]. Jawad Faiz and Tahere Noori of Iran used the $2D$ and $3D$ finite element methods to deal with the short-circuit electromagnetic force of the core transformer [24]. Given that the short circuit electromagnetic force is mainly based on the overall fault of the transformer's primary and secondary windings, the electromagnetic force at a fixed winding position cannot be analyzed. Then, Hyun-Mo Ahn of South Korea divided the high- and low-voltage windings of a 50 kVA dry transformer into several parts and calculated the vector magnetic bits, magnetic flux density, and electromagnetic force of each partial winding based on the finite element method [25]. In the literature [26], the simulation model of the three-phase core transformer was established by using the electromagnetic field simulation software $ANSYS$, and the electromagnetic force on the winding was analyzed on the basis of the finite element method [27]. Jingqiu Qiao and Yunmiu Tang of China used a three-phase transformer with a rated working condition of 17 MVA as the simulation model. The finite element method was used to calculate the frequency spectrum distribution of the axial and radial electromagnetic forces when the winding was short-circuited in different initial states. Their results indicate that the calculation formula of the traditional electric power can basically meet the engineering requirement, but the numerical calculation can calculate the axial electric power [28]. Shuang Liu of Shenyang University of Technology used the finite element method to calculate the short-circuit electromotive force, which considers the properties of insulating materials, winding displacement, mechanicalproperties and elasticity. Meanwhile, a software for calculating the $2D$ transient symmetry field and the winding short-circuit strength was developed, and the calculation speed was improved on the basis of Windows platform [29]. Luliang Wang of Harbin University of Technology established a $2D$ axisymmetric field-circuit coupling model of a transformer by using the $ANSYS$ software and obtained the radial and axial force distributions of transformer windings under the three-phase symmetric short circuit condition. Although the ampere-turn imbalance and the leakage magnetic field distribution between winding coils were considered, the interaction of each phase winding was ignored, and the result contained a certain error [30, 31].

This study used the finite element method to establish the simulation calculation model of the transformer winding electromagnetic field, the leakage inductance characteristics of power transformers under a three-phase grounding short circuit, a turn-to-turn fault and an inter-turn fault were simulated and examined. The accuracy of the model was verified by finite element simulation, which provides reference for the detection and evaluation of transformer operation fault. The remainder of this study is organized as follows: section 3 describes the principle of finite element simulation and the construction of the transformer mathematical model, the parameters of transformer leakage inductance, and the finite element simulation model; section 4 discusses the use of the finite element method to calculate the transformer leakage inductance parameters and the analysis of the characteristics of a three-phase short circuit, a turn-to-turn fault and an inter-turn, and finally, the leakage inductance characteristics under different working conditions are obtained; section 5 summarizes the conclusions.

3. Methodology

3.1. Principle of finite element simulation

The core idea of finite element is summarized as variation and discretization. Variation establishes the "weak form" of the finite element. For example, the second-order partial differential equation under given boundary conditions is transformed into solving the extreme value of the first-order partial differential equation, thereby approximately simplifying the complex problem [32, 33, 34, 35]. Discretization divides the entire continuous solution region into many small subregions, thereby obtaining the results in each small subregion, and then adds the results of each small subregion to obtain the solution of the entire region. The finite element method is briefly summarized as follows: (1) the problem of solving the partial differential equation is transformed into solving a conditional variation problem [36]; (2) the entire solution domain is divided by partition unit as a triangle or quadrangle while constructing the linear interpolation function; (3) by constructing linear algebra equations, the extreme value of the universal energy function is transformed into the extreme value of energy function; (4) the linear algebra equation is solved.

Maxwell of $ANSOFT$ Company is a powerful $2D/3D$ electromagnetic field analysis software based on the finite element method. It includes a user-friendly interface, an advanced adaptive grid segmentation algorithm, and a powerful data processing ability and is preferred by research developers over other finite element software. The modeling and simulation steps based on the $ANSOFT$ Maxwell software are shown in Fig. 1.

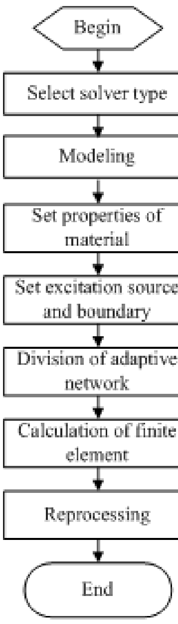

Figure 1: Calculation process of ANSOFT

3.2. Equivalent model of transformer

Transformer is an important electrical equipment in a power grid. To study transformers, the physical model of transformers must be simplified into a mathematical module, and the complex problem of magnetic coupling must be transformed into a simple circuit problem. Therefore, an equivalent circuit transformer model exists. The common equivalent model of a double-winding transformer is the T-type equivalent model as shown in Fig. 2.

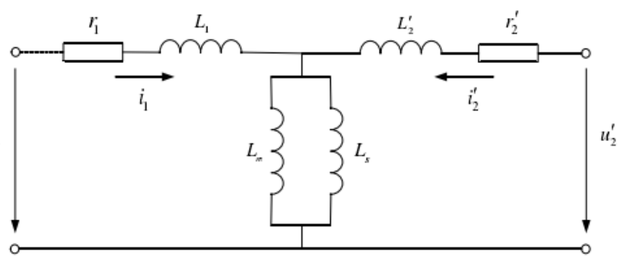

Figure 2: T-type equivalent model of double-winding transformer

In the T-type equivalent model as shown in Fig. 2 , the parameters of each side of the transformer are calculated by the same side voltage level. r_1 and L_1 respectively represent the resistance of the original winding and the leakage inductance of the winding as shown in Fig. 2; r_2' andL_2' represent the resistance of the secondary winding and the leakage inductance of the winding calculated at the primary side;

u_1 and i_1 respectively represent the voltage and current values of the original winding side winding while the transformer is in operation; u_2' and i_2' respectively represent the voltage and current values of the secondary side winding of the original side while the transformer is running. In the equivalent transformer circuit diagram, in addition to these parameters, two important parameters characterize the excitation branch, namely, instantaneous excitation inductance L_m and short circuit turn leakage inductance L_s. However, these two parameters are unavailable in some situations. In the analysis of a specific operation state, the resistance of the excitation winding can be ignored, and the excitation branch only has the instantaneous excitation inductance L_m. In the analysis of the internal inter-turn fault of the transformer, in addition to calculating instantaneous excitation inductance L_m, the value must be calculated after it is parallel with short circuit turn leakage inductance L_s.

According to the circuit principle, the formula is obtained according to the T-type equivalent model of the transformer as shown in Fig. 2:

$$u_1 = r_1 i_1 + L_1 \frac{di_1}{dt} + \frac{L_m L_s}{L_m + L_s} \cdot \frac{d(i_1 + i_2')}{dt} \tag{1}$$

Formula 2 can be obtained by dividing Formula 1.

$$u_1 = r_1 \left(i_1 + i_2'\right) + (L_1 + \frac{L_m L_s}{L_m + L_s}) \cdot \frac{d(i_1 + i_2')}{dt} - r_1 i_2' - L_1 \frac{di_2'}{dt} \tag{2}$$

The resistance and leakage inductance on the original side of the transformer are small and can be ignored. Thus, Formula 3 can be expressed as follows:

$$u_1 = r_1 \left(i_1 + i_2'\right) + (L_1 + \frac{L_m L_s}{L_m + L_s}) \cdot \frac{d(i_1 + i_2')}{dt} \tag{3}$$

When the transformer is in normal operation, the short circuit turn leakage inductance can be ignored. Thus, Formula 4 is expressed as follows:

$$u_1 = r_1 \left(i_1 + i_2'\right) + (L_1 + L_m) \cdot \frac{d(i_1 + i_2')}{dt} \tag{4}$$

3.3. Calculation of transformer leakage inductance parameters based on finite element analysis

If the transformer is in normal operation, according to Formula 4, $L_k = L_1 + L_m$ can be the equivalent instantaneous inductance of the transformer. If the transformer fails internally, the equivalent instantaneous inductance of the transformer can be defined as $L_k = L_1 + \frac{L_m L_s}{L_m + L_s}$ according to Formula 3. The equivalent instantaneous inductance consists of two parts. The first part is the leakage inductance of the original side winding L_1. The second part is the parallel value of short circuit turn leakage inductance L_s and instantaneous excitation inductance L_m.

When $\triangle i_1 = i_1 + i_2'$, Formula 3and Formula 4 can be unified as follows:

$$u_1 = r_1 \triangle i + L_k \cdot \frac{d\triangle i}{dt} \tag{5}$$

The sampling period is T. By discretizing the differential Equation 5, Formula 6 is obtained:

$$\begin{cases} u_1(k) = r_1 \triangle i(k) + L_k \frac{\triangle i(k+1) - \triangle i(k-1)}{2T} \\ u_1(k+1) = r_1 \triangle i(k+1) + L_k \frac{\triangle i(k+2) - \triangle i(k)}{2T} \end{cases} \tag{6}$$

The calculation formula of equivalent instantaneous inductance L_k of the transformer can be obtained by simultaneously eliminating the original side winding resistance r_1 from Equation 6:

$$L_k = 2T \frac{u_1(k) \cdot \triangle i(k+1) - u_1(k+1) \cdot \triangle i(k)}{\triangle i^2(k) - \triangle i(k-1) \cdot \triangle i(k+1) - \triangle i(k) \cdot \triangle i(k+2) + \triangle i^2(k+1)} \tag{7}$$

3.4. Establishment of finite element simulation model for transformer leakage inductance magnetic field

The 800 kVA and 10 kV three-phase three-column oil-immersed distribution transformer are selected as the simulation models. The main parameters of the transformer are shown in Table 1.

In the simulation model, the effects of the transformer structure, the coil skin, the iron core clamp, the fuel tank, and the support beam on the leakage magnetic field can be simplified and even ignored. The current is set to uniform distribution mode in the winding zone, and the traverse vortex is ignored. The high- and the low-voltage winding have the same height, the demagnetization effect of the coil conductor is not considered, and each switch is evenly distributed.

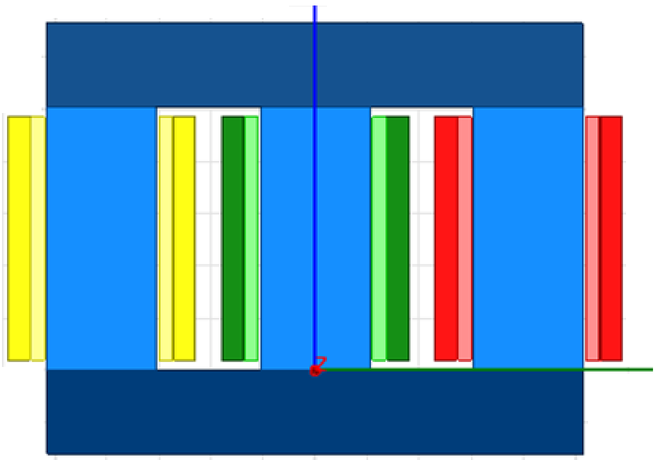

Figure 3: $2D$ model diagram of the transformer

The cross-section of the three-phase distribution oil immersed transformer is selected to establish the model as shown in Fig. 3. The dark blue part is the upper and lower yokes of the transformer, the light blue surface is the core column, and the three-phase winding of transformer ABS is marked red, green, and yellow from right to left. The characteristic parameters of the iron core, the winding, and the

Table 1: Parameters of the real-scale transformer

Name	Dimension, mm	Name	Dimension, mm
Core diameter	210	Height of iron window	505
Width of iron window	160	Height of upper and lower iron yoke	825
Fuel tank width	540	Height of fuel tank	1120
High-voltage coil	Ø276-360	Height of high-voltage winding	468
Low-voltage coil	Ø220-271	Height of low-voltage winding	465
Number of high-voltage winding	955	Number of low-voltage winding	21
Parameter name	Parameter value	Parameter name	Parameter value
Rated capacity	800 kVA	Rated voltage	$10 \pm 2 \times 2.5\%/0.4$(kV)
Rated current	46.19/1154.7(A)	No-load current	0.18%
Loss of short circuit	8200 W	Impedance voltage	4.5%
Connection group number	$Dyn11$	Core material	B23P090

insulating oil are shown in Table 2. Fig. 4 shows the magnetization curve of the core in semi-logarithmic coordinates.

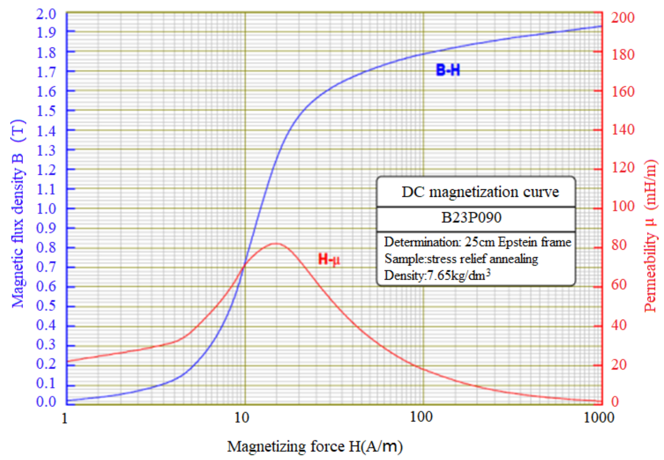

Figure 4: Magnetizing curve of the transformer iron core

The excitation source adopts the external circuit, and the external circuit adopts the same $DTn11$ connection group as the transformer. The infinity boundary is set as the balloon boundary condition, which ensures that the boundary can be infinity without setting a large boundary while reducing the number of computational grids. Several units are set to the maximum number (3000) by using the triangulation unit and the automatic subdivision algorithm. The solution termination time is set to 100 ms, the period to 5, and the step size to 1 ms.

4. Result Analysis and Discussion

4.1. Three-phase grounding short circuit

When the transformer fails, the winding has a large transient current, which leads to the complete damage of the transformer and serious power grid outage. Therefore, the magnetic leakage field in the case of transformer failure must be studied. The three-phase short circuit fault position is set to occur on the low voltage side of the transformer external circuit, as shown in Fig. 5. When the initial phase angle of a phase is set to 0° and the corresponding short circuit time is 30 ms, the three-phase short circuit is the worst, that is, the transformer is under the load condition from $0 \sim 30$ ms. The three voltage control switches are closed after 30 ms, and the three-phase short circuit of the transformer is obtained.

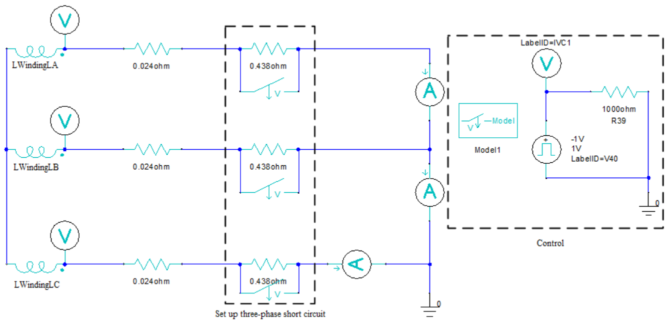

Figure 5: Three-phase short circuit of the secondary side

The current of A-phase of the low-voltage side can be obtained by simulation (Fig. 6).

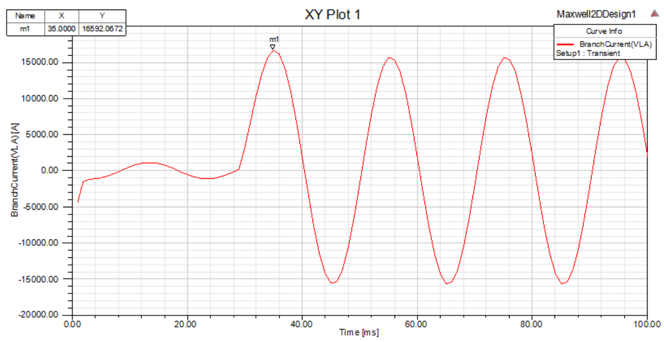

Figure 6: Low-voltage side current of A-phase when shorted

Fig. 6 shows that after the three-phase short circuit, the short circuit current on the low-voltage side increases sharply, accompanied by a certain transient process. When the short circuit time is $1/4$ cycles, which is 40 ms, the maximum value of 16.7 kA is reached, the short circuit steady state process is started, and the current remains very large. A large current often produces a large electromagnetic force, which causes winding deformation and insulation damage.

The magnetic leakage field distribution of the three-phase transformer at 40 ms is shown in Fig. 7 .

In Fig. 7, the maximum magnetic density of the transformer is 2.6 T, and the core is saturated. The leakage inductance of the transformer is 76.7 mH, which is approximately

Table 2: Properties of the materials in the transformer

Transformer component	Material	Conductivity	Relative dielectric constant
Winding	Copper	58000000	1
Iron core	Iron	4550000	Nonlinear
Transformer oil	Insulation oil	0	2.4

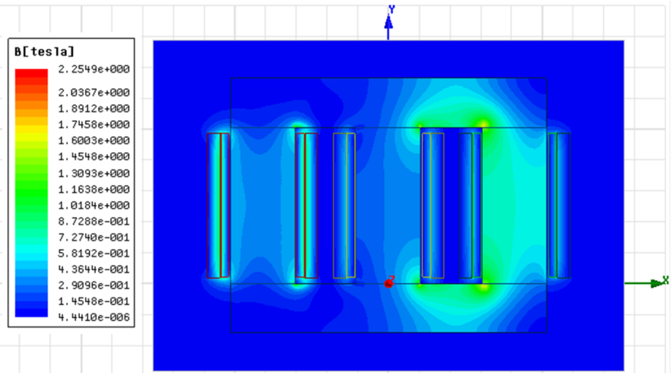

Figure 7: Magnetic density distribution during shorted fault

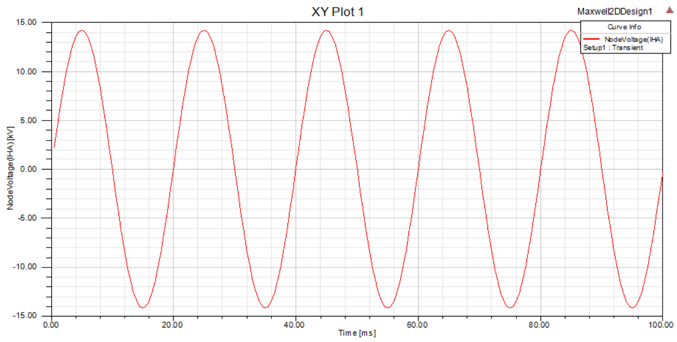

Figure 9: Phase voltage of primary side with turn-to-turn fault

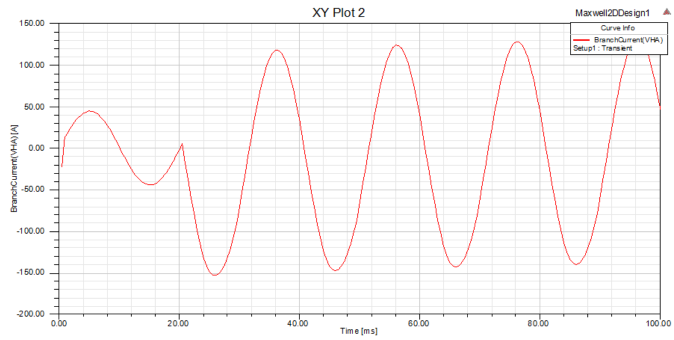

Figure 10: Phase current of turn-to-turn fault

30% higher than that of the normal operation.

4.2. Turn-to-turn fault

If the end of the winding has a turn-to-turn fault for the primary side winding of the transformer's A-phase, then the black part of the winding in the $2D$ model represents grounding, the number of turns is 8% of the total turns, and inter-turn fault occurs at 30 ms. The A-phase high-voltage winding is divided into normal and fault winding, and a wire grounding is drawn from the middle (Fig. 8).

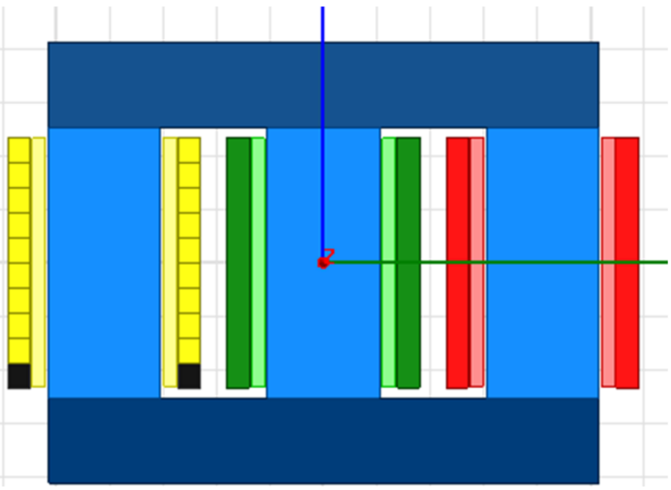

Figure 8: Turn-to-turn fault of A-phase primary side winding

The voltage and current of the primary side of the fault phase can be obtained by simulation (Fig. 9 and Fig. 10).

In Fig. 10, the currents of A-phase and B-phase enter the transient process, the primary side is grounding because the winding grounding, and the current increases sharply. The current of C-phase is consistent with that when the primary side uses the triangle connection method. The calculated leakage inductance of A-phase is 58.8 mH.

The leakage inductance results of the transformer with different grounding are shown in Fig. 11 by constantly changing the grounding position, that is, changing the number of turns of fault winding.

In Fig. 11, the leakage inductance has a nonlinear negative correlation with the number of fault turns. When the number of fault turns is small, the leakage inductance is close to that in normal operation.

4.3. Inter-turn fault

Assuming that the primary side winding of the A-phaseof the three-phase transformer has an inter-turn fault, the A-phase in the model is divided into 10, the number of turns in each group is 90 turns, and the black part represents the occurrence of inter-turn fault (Fig. 12).

The voltage and current of the fault phase of the primary side are obtained by simulation as shown in Fig. 13 and Fig. 14.

Similarly, by increasing the number of fault turns, the black (fault) area of the winding in the $2D$ model of the corresponding turn is increased, and the relationship between leakage inductance and the number of fault turns is shown in Fig. 15.

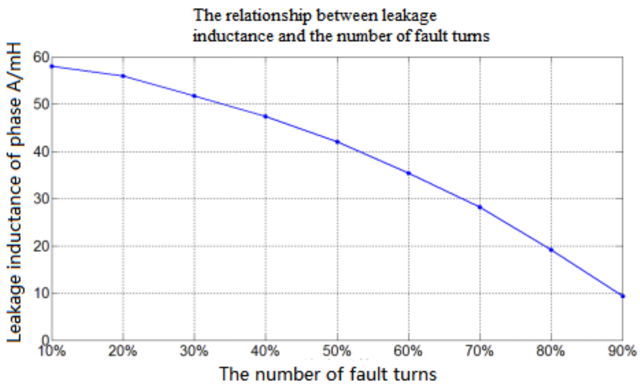

Figure 11: Relationship between leakage inductance and the number of fault turns

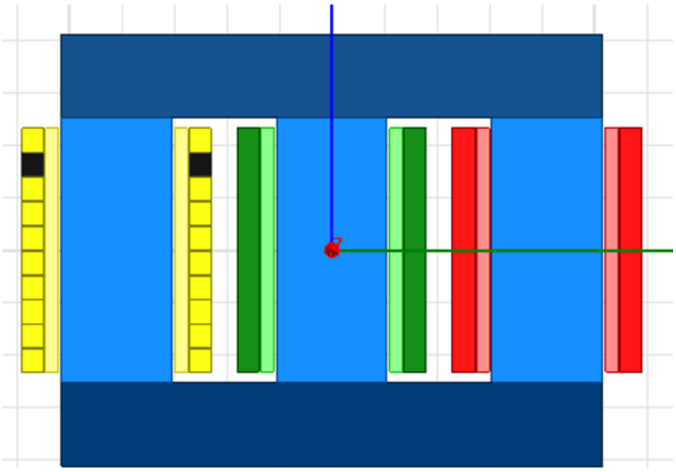

Figure 12: Inter-turn fault of phase A primary side winding

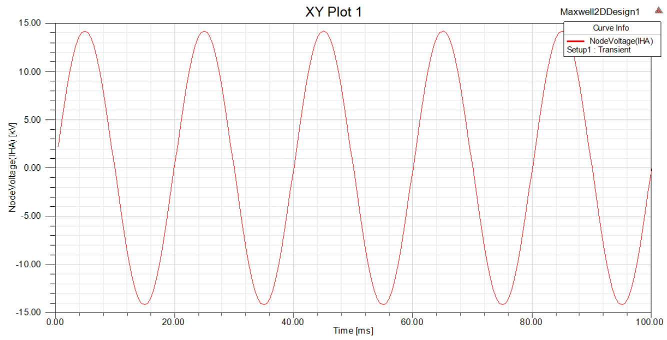

Figure 13: Phase primary side voltage with inter-turn fault

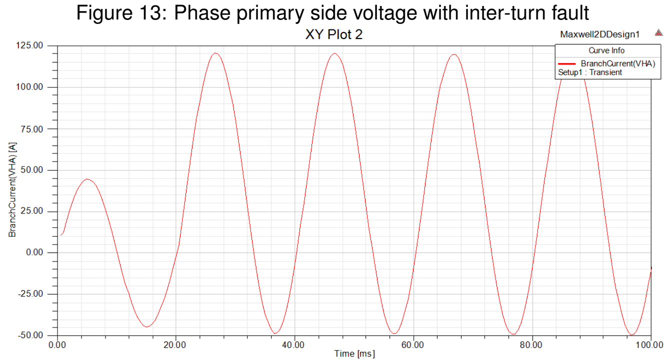

Figure 14: Phase primary side current with inter-turn fault

Fig. 15 shows that a nonlinear positive correlation exists between leakage inductance and the number of turns of the inter-turn fault. The leakage inductance tends to increase with the number of turns of the inter-turn fault.

5. Conclusion

To reduce the winding insulation damage caused by transformer magnetic flux leakage, which can pose a great threat to the safe and stable operation of power grids, 800 kVA and 10 kV three-phase oil-immersed distribution transformers were selected as physical models, and the leakage inductance characteristics of the power transformer under the conditions of three-phase grounding short circuit, turn-to-turn fault, and inter-turn fault were studied using an $ANSOFT$ software. Finally, the following conclusions could be obtained:

(1) When three-phase short circuit occurs on the secondary side of the transformer, the secondary side current increases sharply, the iron core reaches saturation, the leakage magnetic field increases correspondingly, and the leakage inductance of the transformer increases by 30% compared with that in normal operation.

(2) When the turn-to-turn fault of transformer occurs, the leakage inductance is negatively correlated with the number of fault turns, and the leakage inductance tends to decrease with the increase in the number of grounding fault turns.

(3) When the inter-turn fault of transformer occurs, the leakage inductance is positively correlated with the number of turns in inter-turn fault. The leakage inductance tends to increase with the number of turn-to-turn fault turns.

Starting from the causes of transformer winding insulation damage, this study conducted a research of the leakage inductance characteristics under power transformer winding fault based on $ANSOFT$. The accuracy of the model was verified by finite element simulation, which provides a refer-

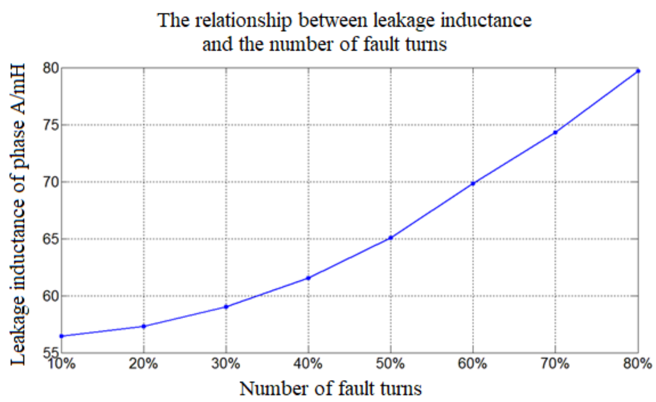

Figure 15: Relationship between leakage perception and the number of fault turns with inter-turn fault

ence for detection and evaluation of transformer operation fault. Owing to the lack of actual field fault monitoring date, an on-line monitoring system for transformer winding deformation must be designed in future research. By doing this, the running state data can be collected in real time according to the transformer operation process to judge the real-time shape of transformer winding according to the parameters and determine the reasonable maintenance time of transformers after comprehensive analysis. This system can not only ensure the maximum operation life of transformers, but also prevent the interruption of operation because of failure.

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