Short Circuit Electromagnetic Force Analysis of 500 kV Autotransformer Based on Field-Circuit Coupling

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Abstract As transformer capacity and voltage levels continue to rise, the short-circuit resistance of transformers has become an important factor affecting the stability of the power grid. When a short-circuit fault occurs, the interaction of short-circuit current and leakage magnetic field will generate large electromagnetic forces in the winding, which will lead to winding deformation or even cause the transformer to withdraw from operation. Therefore, it is crucial to calibrate and analyze the short-circuit electromagnetic force of the winding. Currently, the short-circuit electromagnetic force is mainly studied using the traditional finite element analysis method. Combining the field-circuit coupling method with the traditional finite element method can more accurately simulate the circuit state during a short-circuit

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fault and thus obtain a more accurate leakage magnetic field distribution. In this paper, the leakage magnetic field distribution of a 500 kV autotransformer is simulated and analyzed based on the field-circuit coupling method, and the short-circuit electromagnetic force distribution is obtained. At the same time, the case of axial offset of the winding is considered, and the effect of the offset on the short-circuit electromagnetic force distribution is compared and analyzed.

Keywords Autotransformer · Field-circuit coupling · Short circuit electromagnetic force · Finite elements method

1 Introduction

In recent years, with the gradual increase of the power grid and the continuous increase in voltage levels, external short-circuit shocks have become serious problems of power transformers [1, 2]. With the rise in system capacity and individual transformer capacity, the operation of transformers has become even more severe. A short-circuit current produces high magnetic field, resulting in high short-circuit electromagnetic force. If the transformer lacks sufficient ability of short-circuit resistance, this short-circuit force will destroy the winding, causing severe deformation of the coil and even causing the transformer as a whole to withdraw from operation, thus causing serious effects on the power system [3–5]. Therefore, for power companies, an accurate assessment of the short-circuit resistance of transformers is important for the healthy management of transformers and the stability of the power grid. The multi-physics simulation can simulate the leakage magnetic field and the forces on the winding under a variety of short-circuit fault conditions, thus effectively reducing the failure rate of the transformer and improving the stability of the equipment.

Li Debo et al. [6] analyze the structural force and pressure-acoustic fields of transformers based on multi-physics field simulations and obtains noise spectral profiles. In reference [7], the transformer winding deformation after a short-circuit fault was analyzed based on the finite element method, considering the non-linear elastic properties of the pre-stress and shims. In reference [8], two-dimensional axisymmetric modeling of the transformer winding based on magnetic-structural coupling was carried out to analyze the elastic–plastic deformation of the winding. In reference [9], a combination of flexural analysis methods considering initial defects and finite element methods was used to investigate the auxiliary instability of transformer windings with multiple short circuits. In reference [10], the field-circuit coupling method was combined with a three-dimensional finite element simulation method to obtain the leakage magnetic field distribution and current distribution patterns of a phase-shifted rectifier transformer. In reference [11], the transient waveforms of winding currents after the short-circuit faults were obtained using the field-path coupling method. Most of the existing studies use traditional finite element methods to simulate the physical field of windings under short-circuit, and relatively few studies consider the field-circuit coupling method. The basic principle of the field-circuit coupling method is to simulate multiple physical fields inside the model and connect them with circuit parameters outside. Compared to traditional finite element methods, the field-circuit coupling method can simulate the actual fault situation more accurately, calculating the leakage magnetic field by electromagnetic induction and thus obtaining the time-domain distribution of the current.

Under the same capacity and voltage level, autotransformers are relatively smaller in size and require less material than independently wound transformers, and the losses of transformers are greatly reduced, easy to transport and install, and operate more efficiently [12, 13]. Due to the above-mentioned advantages, autotransformers are widely used in voltage classes of 500 kV and above. Due to the direct electrical connection between the primary and secondary sides of autotransformers, the short-circuit electromagnetic force on the winding of autotransformers are greater than those on independently wound transformers under the same short-circuit fault conditions. However, there are few simulation studies on the electromagnetic force of autotransformers, so it is essential to carry out relevant research. The field-circuit coupling method facilitates the intuitive connection between electricity and magnetism and has unique advantages in the analysis of autotransformers.

In this paper, the field-circuit coupling model is combined with the finite element multi-physics field simulation method to obtain the leakage magnetic field of a 500 kV autotransformer under a short-circuit fault and to analyze the short-circuit electromagnetic force distribution of the medium-voltage and high-voltage windings. The effect of winding offset on the leakage magnetic field distribution of the transformer and the winding force is also compared by considering the case of axial offset of the winding relative to the center position.

2 Simulation Model of the Transformer

2.1 Geometry Model

The actual structure of the transformer is complex, containing a core, winding, pad, brace, structural parts, oil tank, etc. Regarding the characteristics of short-circuit conditions, the following assumptions are declared in the analysis of the magnetic field. The eddy current demagnetizing effect of the wire and skin effect is not considered, the current density within the wire cake is considered to be uniformly distributed, and the winding copper wire conductivity is constant. The influence of the core puller, clamp, etc. on the leakage flux distribution in the oil tank is not considered. The geometry of the simulation model of the autotransformer is shown in Fig. 1.

In this paper, a 500 kV autotransformer is simulated and modeled. According to the actual magnetic circuit characteristics of this transformer, a two-dimensional axisymmetric finite element analysis can basically reflect the actual leakage field. The main parameters of the autotransformer are shown in Table 1.

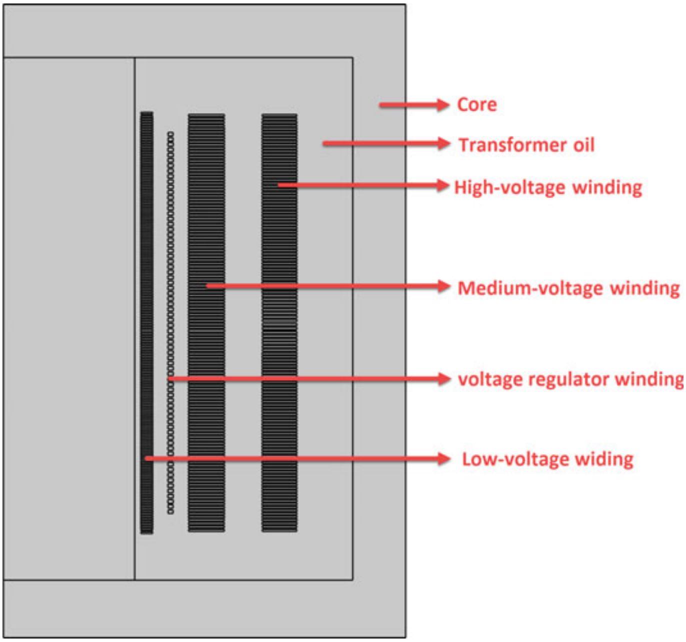


Fig. 1 Simulation model of an autotransformer

Table 1 Main parameters of a 500 kV autotransformer

Parameters	Low-voltage winding	Voltage regulator winding	Medium-voltage winding	High-voltage winding
Rated capacity/MVA	80	/	334	334
Rated voltage/kV	40.5	/	252	550
Number of turns	81	32	312	367
Inner radius/mm	649	778	875	1223
Outer radius/mm	704	800	1043	1385

2.2 *The Field-Circuit Coupling Model*

The "field-circuit coupling" method refers to the method in which the transformer is solved by finite element modeling inside the transformer and treated as a circuit element outside, which is connected to an equivalent closed circuit according to the respective circuit parameters. This method facilitates the solution of the electromagnetic field problem in case of a short circuit on one side of the winding and the simulation of the transient process with the help of an applied voltage source. When creating the transformer short-circuit model, a node of the line cake ground in the field is used as the node of the equivalent circuit to complete the circuit to achieve

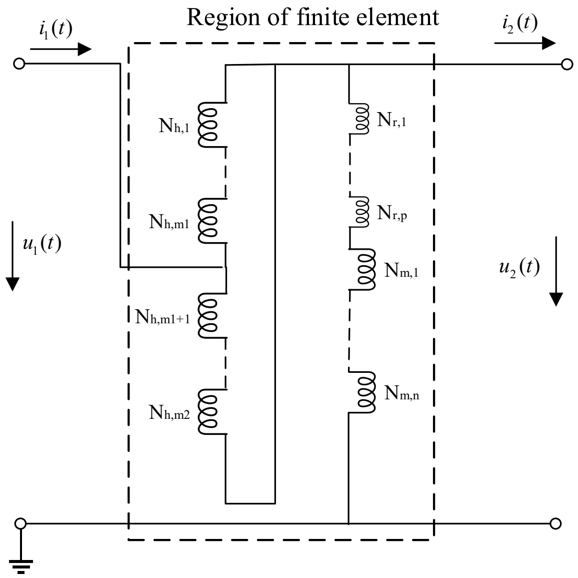


Fig. 2 Schematic diagram of field-circuit coupling model

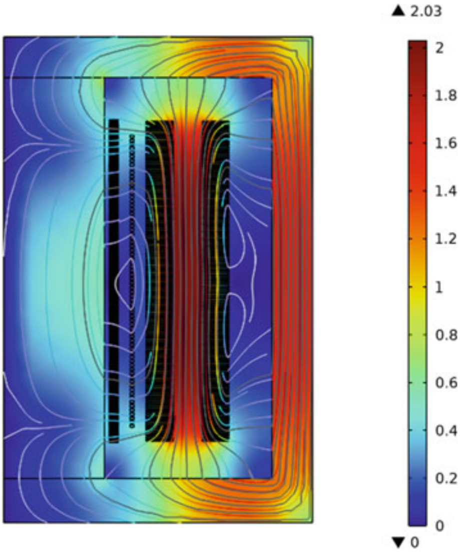
coupling, while the line cake elements are connected in series with the supply voltage and load resistance to form an equivalent closed circuit. The schematic diagram of the field-circuit coupling for autotransformer high-mid operation is shown in Fig. 2. In the figure, $N_{h,1}$,…, $N_{h,m1}$,…,$N_{h,m2}$ are the number of turns per pie for the high voltage winding, $N_{m,1}$, $N_{m,2}$,…, $N_{m,n}$ are the number of turns per pie for the medium voltage winding, $N_{r,1}$, $N_{r,2}$,…, $N_{r,p}$ are the number of turns per pie for the regulating winding, where the HV winding is connected to the circuit in parallel.

3 Analysis of Leakage Magnetic Field and Electromagnetic Force

3.1 Distribution of Leakage Magnetic Field

In this paper, the transformer leakage magnetic field distribution at the peak moment of the current is obtained based on the field-circuit coupling method and the finite element method for a three-phase symmetric short-circuit failure during the high-medium operation mode of the transformer, as shown in Fig. 3. From the figure, the magnetic flux of the transformer is concentrated between the HV and MV windings with a peak value of 2.03 T, which is due to the opposite direction of transformer HV winding and MV winding currents during the high-medium operation mode, and the magnetic field is superimposed and enhanced at the location between the windings. From the magnetic line distribution, most of the magnetic lines are distributed in

Fig. 3 Leakage magnetic field distribution of windings



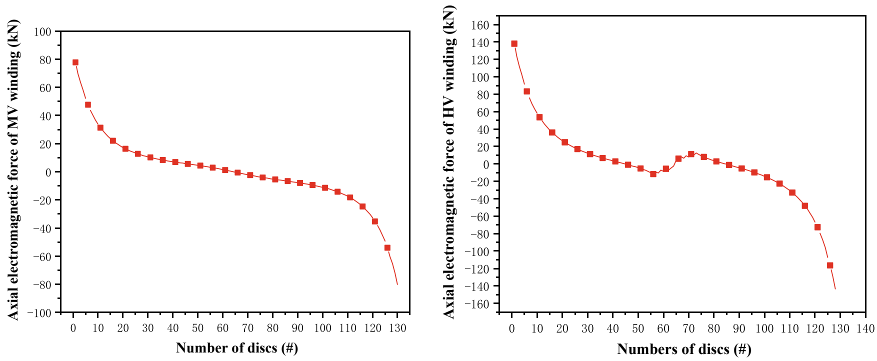
the axial direction between the HVand MV windings, forming the axial magnetic density.

3.2 Distribution of Axial Electromagnetic Force

According to the magnetic field distribution, the axial short-circuit electromagnetic force distribution of the HV winding and the MV winding is calculated, as shown in Fig. 4. The axial force distributions of the HV and MV windings have similar trends, with the end of the winding subjected to a larger axial force, while the middle part is subjected to an axial electromagnetic force close to 0. This is due to the fact that the radial leakage magnetic density component shows a trend of high at both ends and low in the middle, and the axial force is determined by the distribution of the radial magnetic field.

3.3 Distribution of Radial Electromagnetic Force

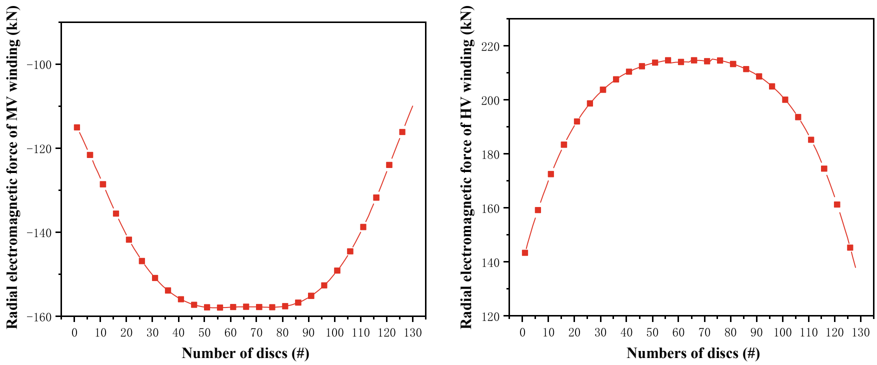
The distribution of the radial electromagnetic force in the MV winding and the HV winding is shown in Fig. 5. The distribution of the radial force in the MV winding and the HV winding has a similar trend, but in the opposite direction. This is due to the fact that according to the principle of Lorentz force, in the case of opposite currents flowing through the MV and HV windings, the inner MV winding is



(a) MV winding (b) HV winding

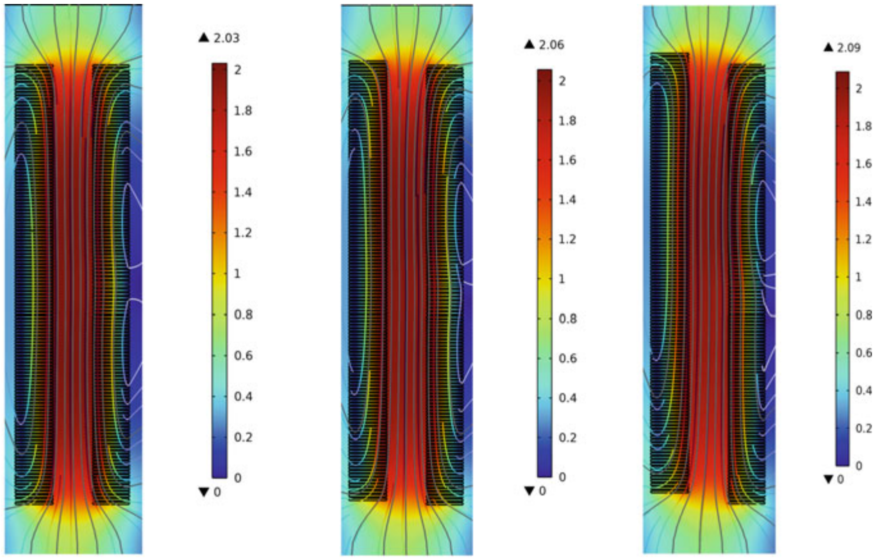
Fig. 4 Distribution of axial electromagnetic force of MV winding and HV winding

influenced by the inward radiation electromagnetic force while the outer HV winding is influenced by the outward radiation electromagnetic force. For both windings, the radial electromagnetic force component in the middle of the winding is significantly larger than that in the end of the winding, because the axial component of the magnetic field determines the magnitude of the radial electromagnetic force. In the middle of the winding, most of the magnetic lines are distributed in the axial direction, and the axial component of the magnetic field is large; while at the end of the winding, the magnetic lines are shifted, and the radial component gradually increases, which leads to an increase in the amplitude of the radial force.



(a) MV winding (b) HV winding

Fig. 5 Distribution of radial electromagnetic force of MV winding and HV winding



(a) Offset 0mm **(b) Offset 20mm** **(b) Offset 50mm**

Fig. 6 Distribution of leakage magnetic field during winding excursions

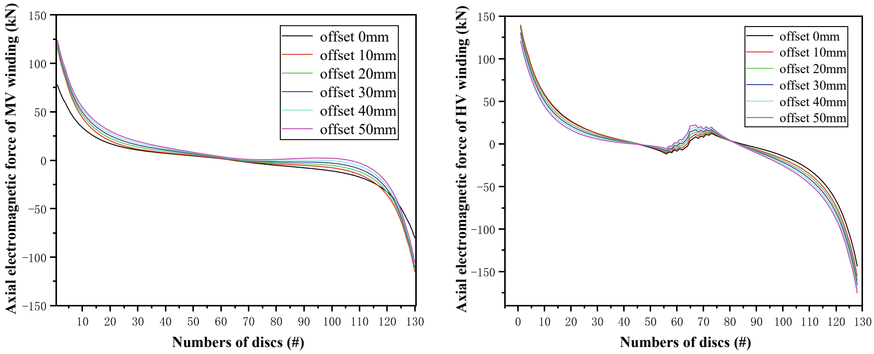
4 Analysis of Leakage Magnetic Field and Electromagnetic Force During Winding Excursions

4.1 Distribution of Leakage Magnetic Field

Due to the uncertainties in the transformer manufacturing and assembly process, the transformer windings may experience offset relative to the center position, which may lead to significant changes in the electromagnetic force. In this paper, we consider the case where the MV winding is offset in the axial direction and analyze the leakage magnetic field, as shown in Fig. 6. Relative to the peak leakage field, the winding offset does not change the magnetic field distribution much, and the peak leakage field increases by about 0.06 T for an axial offset of 50 mm in the MV winding. But due to the change in the relative position of the winding, the electromagnetic force will change accordingly.

4.2 Distribution of Axial Electromagnetic Force

In this paper, simulation analysis is performed for a total of six cases where the medium-voltage winding is offset in the axially forward direction, and the winding



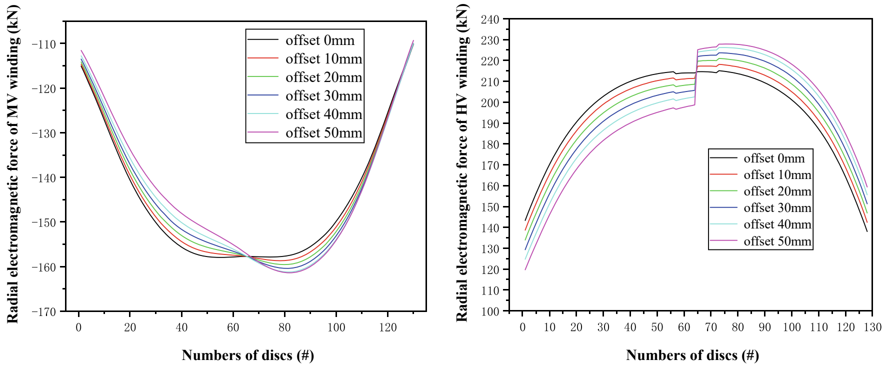
(a) MV winding (b) HV winding

Fig. 7 Distribution of axial electromagnetic force of MV and HV windings during excursions

offset is between 0 and 50 mm, as shown in Fig. 7. From the figures, it can be seen that for the end of the MV winding, the absolute value of the axial electromagnetic force increases after the offset occurs, which indicates that the force at the end of the winding is enhanced in the original direction. For the middle part of the MV winding, the axial electromagnetic force undergoes an overall small shift relative to the zero point as the offset increases due to its axial offset relative to the center position. The force in the middle of the HV winding is similar to that of the MV winding, and the axial electromagnetic force on the edge of the high-voltage winding decreases with increasing winding offset, but the change is relatively small.

4.3 Distribution of Radial Electromagnetic Force

The distribution of the radial force on the MV winding and the HV winding in the case of winding offset is shown in Fig. 8. The force of both after the occurrence of winding offset has changed significantly. For the medium-voltage winding and the HV winding, the absolute value of the electromagnetic force in the lower part of the winding decreases as the offset increases, while the absolute value of the electromagnetic force in the upper part of the winding increases. This is due to the change in the axial magnetic field caused by the offset of the MV winding, which leads to the imbalance of the forces in different parts of the winding.



(a) MV winding (b) HV winding

Fig. 8 Distribution of radial electromagnetic force of high voltage winding during excursions

5 Conclusions

In this paper, based on the combination of field-path coupling and finite element method, a multi-physics field simulation is carried out for a 500 kV autotransformer to obtain the leakage magnetic field distribution during a short-circuit failure, and the electromagnetic force distribution of the winding is analyzed and calculated, and the electromagnetic force simulation is also carried out for the fault case of axial excursions of the MV winding, and the following conclusions are obtained.

(a) In the case of autotransformer high-mid operation and short circuit on the medium-voltage side, the leakage flux is mainly concentrated in the channel between the medium-voltage winding and the high-voltage winding with a peak value of 2.03 T. The axial short-circuit electromagnetic force of the MV winding and the HV winding shows a trend of high at the end and low at the middle, and has symmetry. The radial electromagnetic force of MV winding and HV winding tends to be low at the end and high at the middle, and the direction of the radial electromagnetic force of the two windings is opposite.

(b) After the axial offset of medium voltage winding, the change of the leakage field is relatively small, about 0.06T. With the increase of offset, the axial electromagnetic force in the middle of MV winding and HV winding has a small offset relative to the zero point, while the absolute value of axial electromagnetic force at the end of MV winding increases and the absolute value of radial electromagnetic force at the end of high voltage winding decreases. After the offset of the winding, the radial electromagnetic force of both MV winding and HV winding shows a trend of decreasing axial electromagnetic force at the lower part of the winding and increasing axial electromagnetic force at the upper part of the winding.

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