Simulation modeling study on short circuit ability of distribution transformer

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Abstract. Under short circuit condition, the oil immersed distribution transformer will endure combined electro-thermal stress, eventually lead to the mechanical damage of the inner winding of distribution transformer, therefore it is necessary to study the short circuit ability of the oil immersed distribution transformer. In this paper, the typical current waveform of the distribution transformer under the short-circuit condition is analyzed theoretically. The short circuit fault simulation model of distribution transformer is built on the MATLAB/Simulink simulation platform, the short circuit waveform of the single phase, double phase and three phase short circuit is obtained. Further on the ANSYS simulation platform, three dimensional solid modeling of the three-phase five column transformer is carried out, the harmonic and transient field are applied to analyze the magnetic field distribution of the key components in distribution transformer under the short circuit condition, the internal cause of large short-circuit force in the winding of the distribution transformer under the short circuit condition is analyzed to certain extent. The results of the modeling and simulation show that the three phase short circuit current is larger than the single-phase and bi-phase short circuit current. Its value is 1.45 times the normal running current, which is the gradual damping asymmetrical short-circuit current. Magnetic induction intensity is in-homogeneous in the circumferential direction of the core column, and the degree of in-homogeneity varies along height. The magnetic density distribution under the short circuit condition is more than 6 times as much as the the normal condition. From the point of view of simulation modeling, short circuit ability of the oil immersed distribution transformer is analyzed, distribution characteristics of short circuit current and magnetic field of oil immersed distribution transformer under short circuit condition have been obtained, the theoretical reference value of the state characteristics and protection measures of oil immersed distribution transformer under the overload condition can be provided.

1. Introduction

In process of operation, transformers may be impacted by short-circuit current as well as various over-voltages. For example, when the transformer is in normal operation, the secondary side of transformer will suddenly be short-circuit fault, and the large over-current will appear in the winding. Under the action of short-circuit current, on the one hand, it will cause huge electric force in each part of transformer, on the other hand, it will make the temperature of transformer winding rise rapidly. Although this process lasts for a short time, it is severe test to the stability and heat resistance of transformer withstanding short-circuit. Short-circuit test is the mechanical strength endurance test of transformer under strong current [1]. It is examination of the comprehensive technical ability and technological level of transformer manufacturing. Therefore, short-circuit test is the special test item. If power transformer is damaged by short circuit in the operation of the system, it will lead to the large
area of power outage, and its maintenance period will be more than half a year, which will cause huge losses. At the same time, it is very difficult to repair damaged transformer winding on site. The repair of transformer is not only limited by the lifting conditions of the site, but also stringent to climatic environment and seasonal requirements [2]. It is difficult to meet the requirements of the maintenance process on site. It is almost impossible to repair the damaged transformer winding in good condition on site. Many transformers are short-circuit faulted [3].

The most transformer faults are caused by inter-turn and inter-phase short-circuit. Short-circuit fault of transformer will produce the short-term over-current which intrudes into transformer winding. It will produce large electromagnetic force between the winding of the transformer and lead to transformer winding deformation. At the same time, a large amount of heat will be generated after over-current passes through the winding of transformer. Under the superposition of heat, the insulation of transformer is damaged, which leads to the transformer outage and the large-scale blackout. Therefore, it is necessary to check the short-circuit current withstanding level of the transformer before it is put into operation or in process of transformer operation. At present, only a few national test stations are able to complete large transformer short-circuit test under short-circuit conditions. However, the establishment of the test station requires a large initial investment, and during test process, the factory or repaired transformer should be sent to the test station for short-circuit capability test. The test cost is high. The internal structure of the transformer winding is shown in Figure 1. For small-capacity distribution transformer, it is necessary to develop complete set of the short-circuit test device to realize on-site verification of short-circuit capacity of transformer. It can be seen that development of complete set of short-circuit test device of the distribution transformer can better solve the timeliness and rapidity of the on-site test, and has the good application prospect [4,5].

![Figure 1. The internal structure of transformer winding](image)

Distribution transformer will produce huge short-circuit force in winding in case of the sudden short-circuit. If the transformer design is not perfect and short-circuit resistance is not enough, such short-circuit force will cause damage to winding insulation and structural parts, affect the insulation performance of the transformer, and make winding loose, twisted and deformed, and lead folded. Even whole winding collapses, or the winding burns down due to the inter-turn short circuit caused by insulation damage [6]. In view of this, this paper firstly deduces analytical formula of short-circuit resistance of distribution transformer, and gets the typical waveform of short-circuit current of distribution transformer based on the theoretical formula. The short-circuit lumped circuit model of transformer winding is established in the MATLAB/SIMULINK computing environment, waveform characteristics of current in different types of short-circuit conditions are simulated. A three-dimensional finite element simulation model of transformer winding is established. The short-circuit current waveform is applied to finite element model. The magnetic density distribution characteristics of transformer winding under the short-circuit condition are obtained. From the point of view of simulation modeling, the short-circuit resistance of the oil-immersed distribution transformer is theoretically analyzed, and the oil-immersed distribution is obtained. The distribution characteristics of short-circuit current and the magnetic field of the electric transformer under short-circuit condition provide theoretical reference for the understanding the state characteristics and protection measures of oil-immersed distribution transformer under over-load condition.
2. Theoretical Analysis of Short Circuit Resistance of Distribution Transformer

The short-circuit electro-dynamic force is proportional to the square of the short-circuit current after the short-circuit of low-voltage side port of the transformer. In the calculation of winding strength, the maximum electromagnetic force on the winding is used, so it is important to determine the peak value of short-circuit current corresponding to the maximum electromagnetic force. There are two parts in short circuit current: periodic component and non-periodic component. The magnitude of non-periodic component is related to the instantaneous occurrence of short circuit [7]. In calculation of electromagnetic force of transformer winding, not only the leakage magnetic field should be accurately analyzed, but also the short-circuit current should be determined. In the process of the transformer operation, there are various short-circuit conditions. The three-phase short-circuit at the low-voltage side port is the most serious damage to the winding. The relevant transformer standards also stipulate that the three-phase short-circuit electromagnetic force at the low-voltage side port is used as design checking calculation condition. Therefore, the simplified equivalent circuit of the transformer with three-phase short circuit at the low-voltage side port is shown in Figure 2.

![Figure 2. Simplified equivalent circuit of transformer winding](image)

Let the applied voltage of the equivalent circuit shown in Figure 2 to be:

\[ u = U_m \sin(\omega t + \theta) \] (1)

According to principle of electrotechnics, the expression of steady-state current \( i_1 \) is as follows:

\[ i_1 = \sqrt{2} I_0 \sin(\omega t + \theta - \phi) \] (2)

\[ I_0 = \frac{U_m}{\sqrt{2Z}} = \frac{U_m}{\sqrt{2\sqrt{L^2 + R^2}}} \] (3)

In formula \( i_0 \), the effective value of short-circuit steady-state current and the phase angle of the power supply voltage in short-circuit are respectively calculated. Before short-circuit occurs, the transformer may be in load operation, but because the load current is much smaller than the short-circuit current, it is usually omitted. The sudden short-circuit of transformer is assumed to occur under no-load condition. After sudden short-circuit of the transformer, the short-circuit current in winding is equal to the sum of steady-state component and transient component. The expression of short-circuit current is as follows:

\[ i_k = i_1 + i_2 = \sqrt{2} I_0 \left[ \sin(\omega t + \theta - \phi) - \sin(\theta - \phi) \exp\left(\frac{-R}{X} \omega t\right) \right] \] (4)

In general transformers, the formula at this time (4) can be simplified as follows:

\[ i_k = i_1 + i_2 = \sqrt{2} I_0 \left[ -\cos(\omega t + \theta) + \cos(\theta) \exp\left(\frac{-R}{X} \omega t\right) \right] \] (5)

The typical short-circuit current wave-forms are obtained from expression (5) as shown in Figure 3.
As can be seen from Figure 3, if duration of short-circuit test current is long enough, asymmetric current containing first peak value will change to the square root of symmetric current \( I \). The deviation of peak current obtained in the test should be less than 5% and deviation of symmetric current should be less than 10%. The test should be carried out when the phase current reaches the maximum asymmetric value. The first peak of asymmetric test current (kA) is calculated according to formula (6):

\[
\hat{i} = I \times k \times \sqrt{2} = I \times F
\]  

(6)

In Formula (6), asymmetric short-circuit current coefficient \( F \) is determined according to the data in Table 1. Under the sudden short circuit condition of distribution transformer, the total current of short circuit current and its steady component act on transformer winding, which causes the average temperature of the transformer winding to rise. The temperature rise of transformer winding is related to the duration of short-circuit current and multiple of steady-state short-circuit current. When secondary side of the transformer is short-circuit suddenly, the short-circuit current flowing through the winding can reach several times or even tens of times of the rated current. Short-circuit loss of transformer is tens to hundreds of times of the rated operation.

### 3. Theoretical short-circuit current waveform simulation of distribution transformer

Using the three-phase saturated transformer module in Sim Power Systems, the simulation models of current and short-circuit current for no-load closing of SF10-90000/220 transformer are established in the Matlab7.0/Simulink. The transformer module in simulation model chooses three-phase double-winding saturated Yn/D11 transformer module to simulate and analyze the short-circuit current of single-phase, two-way and three-way short-circuit to ground respectively. The solution method used in the simulation is ode23tb. The simulation model in Simulink is shown in Figure 4.

Figure 4 includes the equivalent power supply, distributed transmission lines, transformers and the power system loads. The grounding fault of the transmission system is simulated by slitting switch, and current variation of the transformer's high voltage winding is emphasized in the simulation process. The short-circuit over-current situation is illustrated by the simulation results. Figure 5 is the typical current waveform of transformer after short-circuit. It can be seen that after single-phase, double-phase and three-phase short-circuit occurs, the short-circuit current increases tens of times instantaneously from the normal operation condition, and the current characteristics are quite different under the three conditions: under single-phase short-circuit condition, the A-phase current increases instantaneously, but the B-phase and C-phase current increases slightly. Under the condition of two-phase short circuit, the increase of A and C phase currents is larger than that of B phase currents; under the condition of three-phase short circuit, the increase of A phase, B phase and C phase amplitudes is larger, so the current under the condition of three-phase short circuit is the most stringent and the winding damage of distribution transformer is most serious. It is explained by single-phase
short-circuit that the short-circuit current of windings reaches 225A from the transient peak current 327A to steady-state short-circuit current 225A generally undergoes the 3-4 current waveform periods, i.e. 0.06-0.08s, and the $F$ value of asymmetric short-circuit current coefficient is about 1.45, which is mainly caused by the decay process of the non-periodic component of short-circuit current.

Figure 4 Matlab/Simulink calculation model

(a) Single phase short circuit

(b) Dual-phase Short Circuit
Therefore, if only mechanical effect of short-circuit current on the winding of distribution transformer under the short-circuit condition is examined, the short-circuit current of 0.5s is usually applied. If thermal effect of transformer winding under short-circuit current is further examined, the short-circuit current of transformer should be applied for long time to meet long-term thermal effect on the oil-paper insulation of the transformer.

4. Theoretical Finite element electromagnetic analysis of distribution transformer winding short circuit

In ANSYS environment, field-circuit coupling FEM calculation of transient electromagnetic field of three-phase five-column transformer under short-circuit condition is carried out. Taking three-phase five-column transformer as example, three-dimensional finite element simulation model is established under the ANSYS simulation environment. Figure 6 shows that the model considers the components of the mixed insulating oil, transformer winding, iron core, pulling plate, clamp, oil tank and electromagnetic shielding. The permeability of insulating oil is considered to be 1, and the winding of transformer is considered to be 1. The permeability and resistivity of the core are 1 and 1120, 1 and 0.909e-6 for the clamp, 400 and 0.173e-6 for tank, 1 and 2.21e-8 for the electromagnetic shield, respectively. In ANSYS, three-dimensional simulation model is partitioned by finite element method as shown in Figure 7.
The high voltage winding and the low voltage winding are considered simultaneously in transformer winding. Scanning method is used for meshing, free meshing method is used for iron core part, and the set frequency is 50 Hz in resonance method. Using ANSYS finite element software and APDL language programming, secondary development is carried out[8]. After meshing, the total number of units is 274927. The eddy current loss of transformer external tank is focused on. The total value of eddy current loss is 19722.5885W. The distribution of eddy current is shown in Figure 8. The eddy current loss distribution cloud chart in Figure 8 shows that heat source of the oil tank during the operation of the transformer is mainly induced eddy current heating under the current-carrying condition of the internal winding, and the eddy current distribution of the oil tank is extremely uneven under the short-circuit condition. On the other hand, the distribution of magnetic lines of transformer components is focused on as shown in Figure 9. The figure shows that under the action of sudden short-circuit current, the magnetic lines of transformer components are mainly distributed in the core and winding parts, and the distribution of magnetic lines near middle of the core is relatively dense, and the magnetic lines at both ends are divided.
At the same time, the axial magnetic density distribution of transformer winding is intercepted as shown in Figure 10. Figure 10 shows that the distribution of the axial magnetic density line is not uniform. There are two peaks and a trough in the middle, which is mainly affected by the metal structure such as the iron core and yoke. The key parameters such as asymmetric component duration and overshoot coefficient of short-circuit current waveform of distribution transformer are analyzed from the viewpoint of theoretical analytical formula and the simulation calculation model[9,10]. At the same time, the stress of winding magnetic line under short-circuit condition is analyzed by three-dimensional finite element simulation calculation model.

5. Conclusion
In this paper, the key parameters such as the asymmetric component duration and the overshoot coefficient of the short-circuit current waveform of distribution transformer are analyzed from viewpoint of theoretical analytic formula and the simulation calculation model. At the same time, the distribution and force of the winding magnetic line under short-circuit condition are analyzed by three-dimensional finite element simulation calculation model. The results show that the three-phase short-circuit current is larger than the single-phase and the double-phase short-circuit current, its value is 1.45 times of normal operation current, and it is asymmetric short-circuit current with gradual attenuation. The distribution of the magnetic induction intensity in the circumferential direction of iron core column is not uniform, and the degree of non-uniformity varies with height, and the magnetic density is divided under the short-circuit condition. From the point of view of FEM modeling, anti-short-circuit capability of the oil-immersed distribution transformer is analyzed theoretically. The distribution characteristics of short-circuit current and the magnetic field of oil-immersed distribution transformer under the short-circuit condition are obtained.

6. References

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