Equivalent Model Design and Test for Short Circuit Cumulative Effect of EHV Transformer

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Abstract. The actual 500kV transformer in operation is difficult to have short-circuit and research properties of the test conditions of the cumulative effect, transportation and multiple tests are expensive. It is of great engineering practical value to replace the original model with the real model which has the similar physical characteristics and mechanical vibration to do short-circuit and research tests. Firstly, under the condition of which the real model and the original model have the similar physical characteristics constant and the mechanical vibration, according to the relation of physical quantities, the equivalent criterion is deduced. Then, according to the equivalent criterion of the original transformer and the true model, a true model of 110kV transformer is designed. Secondly, the simulation software is used to verify the correctness of the equivalent and analyze the stress and mechanical vibration of the original model and the true model. Finally, many tests and researches have been carried out for the cumulative effect of short circuit.

1. Preface

As the hub of the power system, power transformers are regarded as the heart of the power grid. The safe and stable operation of power transformers is of great significance to the reliability of the power grid. With the development of modern technology, the level of power grid operation has been continuously improved. The reliability of transformer operation has been effectively improved, and the probability of equipment failure has been significantly reduced. However, at present, the problem of transformer operation safety still exists, and various types of failures occur from time to time, causing huge losses to the economic development of the power grid. In the cases of 500kV transformer damage, the damage caused by the short-circuit fault accounts for a large proportion.

Power transformers will be subjected to a number of short-circuit impact in their services. The national standard GB1094.5-2008 and IEC60076-5: 2006 standard have proposed a test method to run 100% of short-circuit test in a transformer. However, the cumulative effects of multiple short-circuit shocks has not be mentioned in these standards. In recent years, 500kV oil-immersed transformers have a high failure rate, and various types of failures occur from time to time, which seriously affect the safe and stable operation of the power grid. Statistics show that from January 1, 2012 to August 30, 2013, a total 7 times of 500 kV transformer failures occurred in the southern region, severely affecting the reliable operation of the power grid, resulting in huge economic losses, including short-circuit damage ratio half, how to use realistic research conditions to carry out short-circuit strength and short-circuit cumulative effects is a matter of concern.

The type problems which lead to the transformers short-circuit have been around for a long time and are not solved. The Chinese national standard GB1094 and the international standard IEC60076 make corresponding provisions for the ability of a power transformer to withstand short-circuits [1-2]. China has always attached great importance to the study of the ability of the transformer to withstand short-circuits and established transformer short-circuit test stations to check the short-circuit capability of the transformer when it is delivered. To ensure quality, but in terms of current testing capabilities, high-voltage and high-capacity products of 500kV and above still do not have the ability to test. Using real products to conduct short-circuit cumulative effects research, the material cost is too high.

On the basis of considering the sudden short-circuit stress analysis of transformers, it is recognized that irreversible changes in the size or shape of the windings, such as changes in axial or radial dimensions, displacement of the active-part, winding distortion, bulging, and short circuit between turns, etc. Many people began to pay attention to the winding mechanical state assessment technology, that is, the study of winding deformation. Although theoretical research has made many achievements, it is still necessary to compare the theoretical calculation methods of actual transformers in engineering practice with the actual experimental results.

The problem of equivalent design between 500kV grade and above products and models is a good research method through the verification of model test. How to determine the equivalent principle in the model design method is the key technology of model test.

The equivalent model has more applications in the power system. Many scholars have carried out research on the application of scaled models of various research contents. The equivalent model is a special kind of scale model. Many scholars use the scale model to study the short-circuit problem of transformers.

The use of transformer true models with similar physical and mechanical vibrations characteristics instead of the original product for short-circuit tests and research tests has important engineering practical value. This paper is based on similar physical property constants and mechanical vibrations characteristics of the original model and the transformer product. According to the relationship between physical quantities, a simplified equivalent criterion was deduced. Then, based on the actual transformer product and equivalent criterion, a true transformer equivalent model of 110kV was designed, and then the simulation software was used to make the model. The comprehensive simulation analysis of stress and mechanical vibration between the model and the transformer product verified the correctness of the equivalent criterion. Finally, the experimental method for the study of short-circuit cumulative effects is discussed.

2. Equivalent criterion

The true model of the transformer is different from the simple scale model, and the equivalence relationship between the true model and the related physical quantity of the original product needs to be determined according to the research content, so that the purpose of studying the original product can be achieved through the true model test. The key to establishing the equivalent criterion is the selection of the scale ratio parameter and the equivalent parameter. In principle, the physical constants of the true model and the original product are the same, that is, the dielectric constant, conductivity, permeability μ, and resistivity ρ of the true model. The mechanical properties of the coil, the state under short-circuit conditions. The yield stress of the wire material, the σ-ε curve, and the short-circuit electromotive force are as the same as the original product. The coil wire type, structure type, spacer material, strut material, compression structure and original the model are as the same as the original product, that is, the scale ratio factor of these physical quantities is 1. Volume ratio design is scale ratio factor k.

Generally when studying transformer short-circuit problem, according to the different radial and axial damage forms were studied separately, the more common form of radial damage is the inner coil radial buckling instability, as shown in Figure 1. In the study of the buckling of the inner coil, this paper uses the standard IEC60076-5 method. When the winding is subjected to the annular compressive stress, the wire may be excessively bent inwards (forced warping) within the span between two adjacent supports , or due to the loss of stability caused by one or more places around the winding wire to severe deformation (free warping) and damage. The radial force verification method is currently unable to give a special calculation formula for the ultimate compression stress of the winding. Generally, it is recommended that the average ring compression stress on the continuous winding or helical winding (1) which made of conventional conductors or non-self-adhesive conductors should be $\sigma \leq 0.35R_{p0.2}$; (2) which made of self-adhesive wire should be $\sigma \leq 0.6R_{p0.2}$. In the equivalent design of the true model and the original product, the radial force compressive stress equivalent method is adopted, that is, the true model and the product have the same radial compressive stress.

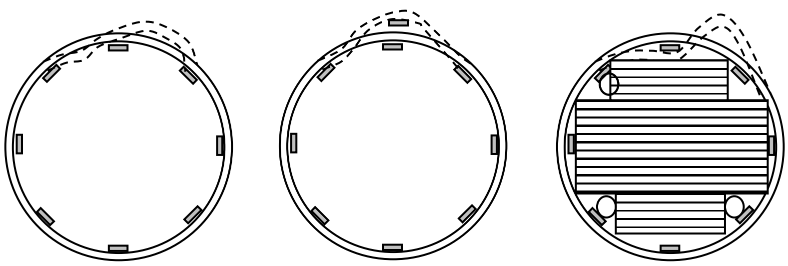

Fig 1 Radial instability of the inner coil

Transformer coils consist essentially of copper conductors, insulation pads, turn insulation, and end rings. The conductor can be considered incompressible, only a certain quality, and the rest of the insulation is considered as an elastomer, which can simplify the coil into a one-dimensional spring mass system (see Figure 2), which is the model used in the axial short-circuit vibration. In the method recommended in IEC60076-5, when the solid winding is subjected to excessive axial compressive force, it may lose its ability of mechanical stability. At this time, the winding is “inclined” as shown in Fig. 3, that is, in the width direction of the winding. In the same row of adjacent conductors, there is an overall inclination to the same direction. Therefore, the maximum axial compressive force F_c acting on the winding is required to be smaller than the ultimate force F_{tilt} induced by the collapse of the conductor when tilted. Safety factor $k=F_{tilt}/F_c$, there should be a sufficient safety factor between these two forces. For continuous winding or helical winding which made of normal conductors and non-self-transposed wire coils, the corresponding ultimate tilting force needs to be calculated by the following formula (1).

$$F_{tilt} = [K_1 \bullet E_0 \bullet \frac{n \bullet b_{eq} \bullet h^2}{D_{mw}} + K_2 \bullet \frac{n \bullet X \bullet b_{eq}^2 \bullet \pi \bullet D_{mw} \bullet \gamma}{h}] \bullet K_3 \bullet K_4 \bullet 10^{-3} \quad (1)$$

among them: M_i ------ Quality of conductor (copper), K_i -------Spring Coefficient of Insulation, C_i ------- Damping coefficient, P_i -------Axial Electric Power, i=1,2,........n.

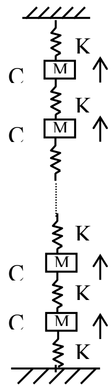

Fig. 2 Coil axial vibration spring system

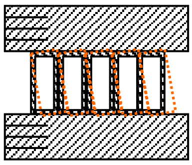

Fig. 3 Coil axial collapse

Where: n-stretch width of the number of conductor or combined conductor; Beq--the width of the conductor width; Dmw - the average diameter of the winding; X--winding pad cover factor;h - the number of conductor;

For the coefficients of K1, K2, K3, K4, E0, γ, and conductor and coils, see the Annex of IEC60076-5.

The true transformer model is a three-phase three-winding power transformer. High voltage ABC three-phase are manufactured as continuous, entangled, and helical type according to the common structure of the windings of the 500kV transformer.

The equivalent principle of the true model and 500kV products:

(1) The coil type is the same as the 500kV conventional product. The high-voltage windings are entangled continuous or inner screen continuous, the medium-voltage windings are continuous, and the low-voltage windings are helical.

(2) The conductor type is the same as the 500kV conventional product, the combined flat wire and single wire, and the conductor is a common specification for 500kV products;

(3) Copper conductor material, coil insulation material type is the same as 500kV conventional products, conductor yield stress $\sigma_{0.2}$, insulation paper, pad material, compression ratio, etc.; it can simulate the production of 500kV or higher voltage, larger capacity products.

(4) The specific support structure of the coil is the same as the 500kV conventional product.

(5) The production process and quality control, the true model is the same as the 500kV conventional product, the tightness of the winding and the drying process; it can simulate the actual production of 500kV or higher voltage and larger capacity products.

(6) Axial compressive stress is the same;

(7) Radial force equivalent principle is equivalent to stress σ;

(8) The axial force is equivalent to the safety factor k;

(9) The calculation and analysis methods are the same, using the same electromagnetic analysis software and calculation methods.

(10) The test impact factor is selected according to the requirements of the standard.

3. Transformer true model design

EHV equivalent short-circuit true model design scheme for three-phase three-winding transformer, three-column type core, high voltage winding, medium voltage winding, low voltage winding and oil tank, winding HV, MV, LV concentric set on the core. Transformer tank with a three-phase three-column active part body. The windings arrangement of the body from the core which is inside to outside is LV, MV, HV. The structure diagram shown in Figure 4. Winding form and cunductor gauge, material, manufacturing process are as the same as the ultra-high voltage transformer. The model designed by this method can be used to conduct short-circuit tests at major domestic high-current test centers to solve the problem that ultra-high-voltage 500kV or higher voltage and larger-capacity transformers which cannot be tested for short-circuit tests. The model test is used to verify the form of windings, conductor gauge, stress equivalent, safety factor equivalent, material, process manufacturing, the same system short-circuit strength test. And it also can be used to study the cumulative effect of multiple short circuit transformer. Through the equivalent model approach, it can not only reflect the short-circuit capability of the equipment itself, but also carry out short-circuit test research to meet the technical problems of equipment reliability prediction, cumulative effects and other work needs.

With regard to the design of true transformer test models, examples of technical solutions are as follows:

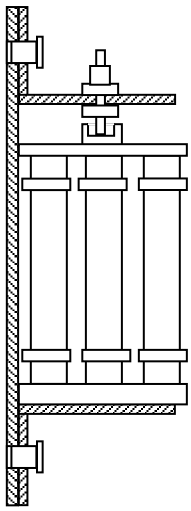

Fig. 4 Coil Structure

(1) Overall structure

Three-phase three-winding, rated capacity: 50/50/50MVA, voltage combination: 110/38.5/10.5kV, connection group: YNyn0d1l, core diameter: 700mm, window height: 1110mm. Principle of simulating the conventional 500kV transformer winding structure. According to different short-circuit resistance requirements, different coil structures are designed. LV windings are helical type. MV windings are continuous type. HV windings of the three-phases are sperated to common continuous, continuous inner-shied and inner-leaved continuous type. Conductor types are selected according to conventional 500kV transformers. Main production materials, winding methods, compaction and other process control are according to the conventional 500kV transformers which are without special strengthening.

(2) Coil structure

The A-column-axial model uses the safety factor k equivalent principle. The high-voltage coil adopts an inner-shied continuous type, and adopts 500kV high-voltage winding commonly used combined conductor. Total eight disks adopts inner-shied type (2P2), and other disks are continuous type. The size of the coil is 87.5mm in width and the height of the coil is 1000mm. The medium-voltage coil adopts continuous type and adopts paper-covered copper flat conductor. The size of the

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coil is 75mm in width and the height of the coil is 1000mm. The low-voltage coil adopts a single helical type and paper-covered copper flat conductor. The size of the coil is 39mm in width and the height of the coil is 1000mm.

The B-column-radial instability model adopts the equivalent principle is stress σ same. The high-voltage coil adopts continuous type and combined conductor. The size of the coil is 87.5mm in width and the height of the coil is 1000mm. The medium-voltage coil adopts a continuous type and paper-covered copper flat conductor. The size of the coil is 89mm in width and the height of the coil is 1000mm. The low-voltage coil adopts a single helical type, using paper-coated flat copper conductor. The size of the coil is 39mm in width and the height of the coil is 1000mm.

C-column-mixed equivalent model, that is, the axial safety factor k equivalent principle, radial instability using the stress σ equivalent principle. The HV coil adopts inner-leaved continuous type and combined conductor. The size of the coil is 83.5mm in width and the height of the coil is 1000mm. The MV coil adopts a continuous type and a paper-covered copper flat conductor. The size of the coil is 89mm in width and the height of the coil is 1000mm. The LV coil is helical type, using paper wrapped copper flat conductor. The size of the coil is 39mm in width and the height of the coil is 1000mm.

4. True Model Simulation

The simulation results of the short circuit strength of the true model and a conventional ODFPS-250000/500 product are shown in Table 1 to Table 3.

A-column-axial model safety factor vs. safety factor of real product against short-circuit current.

Tab. 1 Safety factor comparison between a column-axial model and real product.

		A-column			B-column			C-column		
Equivalent model		HV	MV	LV	HV	MV	LV	HV	MV	LV
H-L short circuit	Radial strength safety factor	2.0	/	2.0	2.0	/	40	2.0	/	40
	Axial strength safety factor	2.0	/	1.05	2.0	/	2.0	2.0	/	1.0
H-M short circuit	Radial strength safety factor	2.0	2.0	/	2.0	40	/	2.0	40	/
	Axial strength safety factor	1.07	2.0	/	2.0	2.0	/	2.0	1.0	/
500kV products		HV	MV	LV	HV	MV	LV	HV	MV	LV
H-L short circuit	Radial strength safety factor	2.0	/	2.0	2.0	/	44	2.0	/	44
	Axial strength safety factor	2.0	/	1.08	2.0	/	2.0	2.0	/	1.02
H-M short circuit	Radial strength safety factor	2.0	2.0	/	2.0	45	/	2.0	45	/
	Axial strength safety factor	1.09	2.0	/	2.0	2.0	/	2.0	1.05	/

Note: The safety factor of 2.0 means that the safety factor is sufficient. Table 2 and Table 3 are the same.

The B-column-radial model and real product can withstand the electrodynamic stress comparison under short-circuit current

The C-column-complete equivalent model and the real product can withstand the electro-dynamic stress comparison under short-circuit current. Take the true model A-column axial LV coil as an example. The model radial magnetic field and the product ODFPS-250000/500 radial magnetic distribution along the height of the coil (see Figure 5). The magnetic field distribution is similar, the value is different and the radial stress is differernt. According to the principle of the axial safety factor k is equal, the axial safety factor is equal. True model low-voltage coil axial strength safety factor is 1.05 and the product low-voltage coil axial safety factor is 1.08.

The axial magnetic field of the true model B-column MV coil and the product ODFPS-250000/500 MV coil (see Figure 6). According to the axial magnetic field to determine the radial buckling force, the magnetic field calculation results are different. The entire line radial pressure bending force is different. But the stress is equal on the cross section of the conductor. The buckling stress of the true model section is 40 MPa, and that of the ODFPS-250000/500 MV winding is 45 MPa.

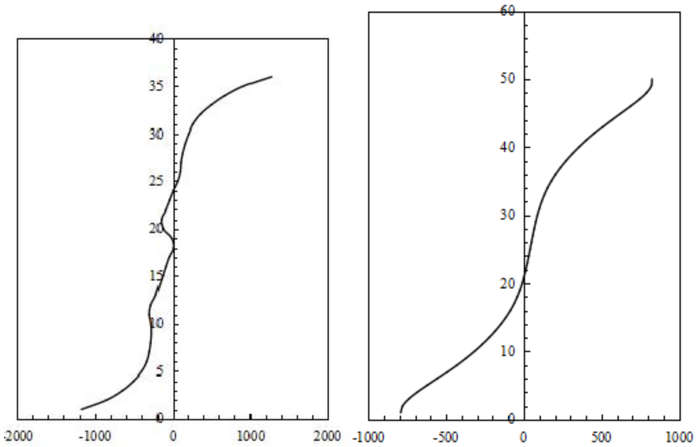

Fig. 5 Comparison of the radial magnetic field of the true model and the ODFPS-250000/500

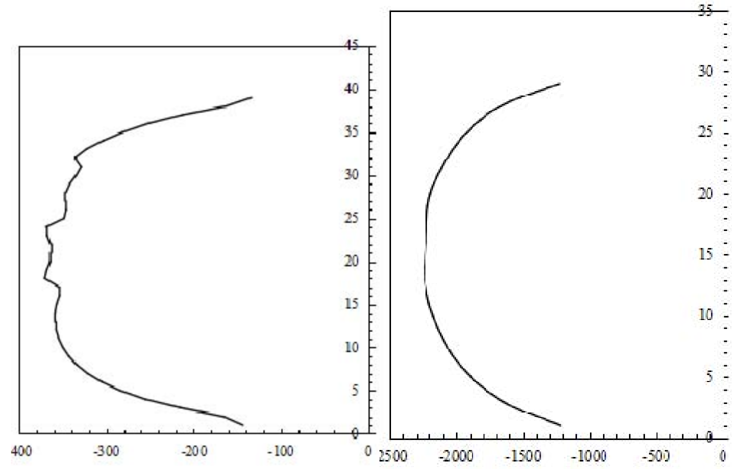

Fig. 6 Comparison of the axial magnetic field of the MV coil of the true model and ODFPS-250000/500

5. True Model Cumulative Short Circuit Test

Short-circuit accumulative effect test ABC three-phase test was performed. According to IEC60076-5 power transformer withstand short circuit capacity test times, each phase carries out three times test evaluations under 100% current. The test that considers the cumulative effect is to perform 100% current up and down tests several times. The test results are as follows:

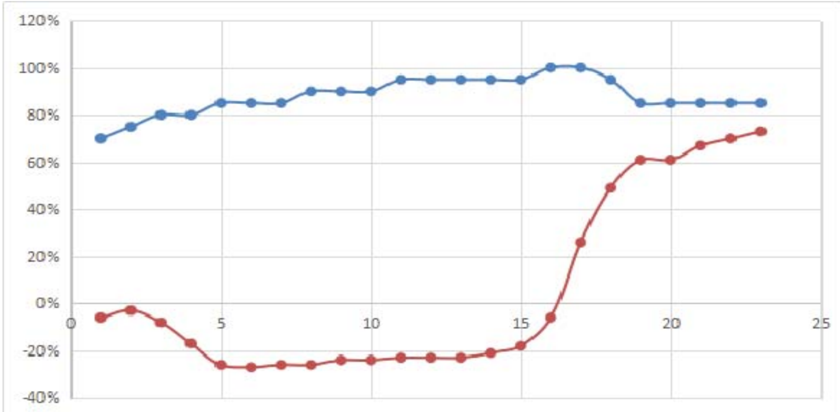

Fig. 7 A-phase axial model cumulative effect test current-impedance variation

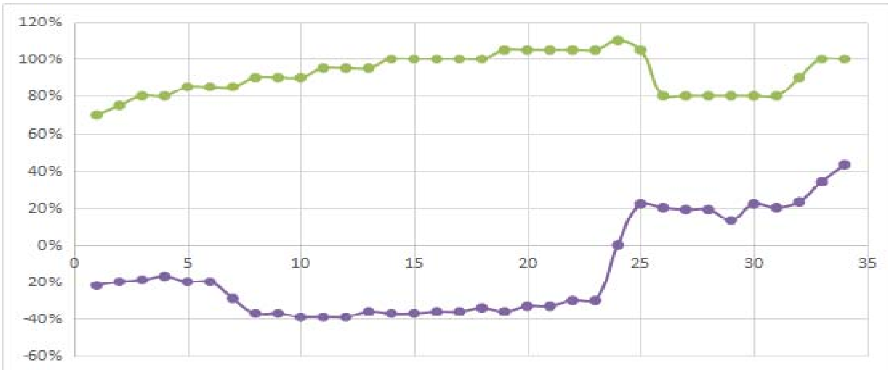

Fig. 8 Cumulative effect of B-phase radial model test current-impedance variation

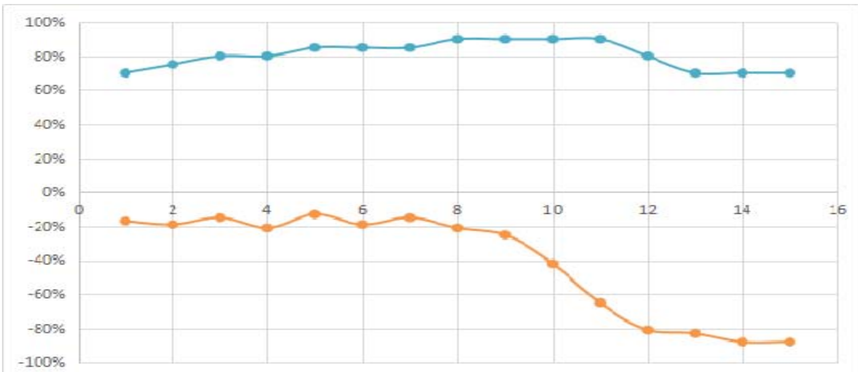

Fig. 9 Cumulative effect of C-phase comprehensive model test current-impedance variation

From the above test results, it can be seen that under the impact of close to 100% short-circuit current, with the increase of the number of short circuits, the impedance change mutates under the cumulative effect of a certain number of times. According to the national standard, Class III transformers per phase the difference between the short-circuit reactance and the original value is not more than 1% of the test qualification. According to the actual conditions of the product, the winding has undergone some degree of deformation.

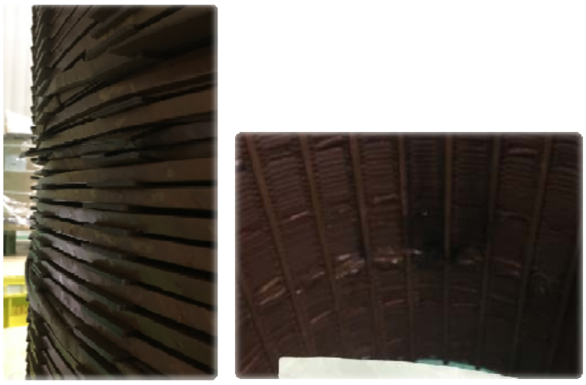

Fig.10 A-HV winding deformation after short-circuit test

Fig.11 B-MV and C-LV winding deformation after short-circuit test

6. Conclusion

(1) The premise of this paper is that the true model and the original model have the same physical characteristics and mechanical vibration characteristics. The materials and manufacture processes whcih the true model and the original model used are the same. And the simulation calculation method is the same. The volume scale of the product transformer and the true model is similar.

(2) According to the study of the transformer short-circuit strength, the radial and axial calculations are usually calculated separately. The stress in the radial buckling instability is calculated, and the safety factor of the axial force is calculated. The true model of the transformer is based on the equivalent criterion of this paper. The requirements of the design parameters, the original transformer model and the true model were calculated using electromagnetic and mechanical simulation software, which verified the rationality of the equivalent criteria in this paper.

(3) Under many times impact of close to 100% short-circuit current, the transformer impedance abruptly changes and the winding is deformed.

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