Research on Engineering Method of Winding Current Distribution and Mechanical Force for Special Transformer

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Abstract

In order to study the leakage magnetic field, the current and short-circuit force distribution of windings for the special transformer, firstly, the three dimensional leakage magnetic field calculation model and the corresponding equivalent circuit are established by taking advantage of field-circuit coupled method(FCCM). Then, the leakage magnetic field, short-circuit impedance and branches current distribution of low voltage winding are analyzed and verified. Finally, on the basis of the winding current distribution rule summarized by above analysis, the leakage magnetic field distribution and mechanical forces are obtained by using simplified calculation model and FEM analysis software. The verification of the magnetic field distribution and impedance ensure the reasonability of the calculation method. Therefore, this paper provides engineering practical and efficient calculation approach of parameters design for special transformer.

Keywords: special transformer; FCCM; current distribution; mechanical force; engineering method.

I. Introduction

Recently, the special transformers with high current and many parallel branches are widely used in the actual industry. Compared with the ordinary power transformer, this type transformer has obvious differences in the structure performance. On the one hand, low voltage winding(LVW) current is as high as 40 kA to 100 kA. In order to reduce the loss of winding and prevent local overheating, the LVW is designed with dozens of parallel branch.

On the other hand, for the convenience of copper bus, the LVW are arranged on the outside of high voltage winding(HVW). As a result, the leakage magnetic field produced by the low voltage high-current copper bus would bring impact on the tank and performance parameters of the winding. If special transformer is short-circuited, winding short-circuit current can be up to several times or more than ten times that of the normal current. The leakage magnetic field and current in winding will product great short-circuit mechanical force, and the mechanical force may cause instability or winding deformation. At present, this kind of complex engineering problems is difficult to solve by traditional design method or experimental method, because of the constraints of test conditions and cost. So it is significant to research on winding current distribution and relevant characteristic parameters for this type transformer.

Due to the parallel branches current in the windings is unknown, therefore, Firstly, the 3D leakage magnetic field calculation model and the corresponding equivalent circuit are established by using FCCM. Then, winding current distribution is obtained by numerical calculation. Secondly, on the basis of the got current distribution, the simplified calculation model was established, and the winding leakage magnetic field distribution and the short-circuit mechanical force results is given by using FEM and special software. The calculated result or method is verified by the comparison of the calculated and measured

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values of magnetic flux density and short-circuit impedance [1-2].

II.Three-dimensional calculation Model and Numerical Analysis

The high voltage and low voltage windings of three phases for special transformer adopt triangle connection. The arrangement of winding from inner to outer side is Core-HVW- LVW.

II.1. *The calculation model and equivalent circuit*

Based on the structural symmetry,the solve region is a half of the special transformer along the centre plane of the three phases. The boundaries are far enough from the core and the windings. The 3D calculation model is shown in figure 1.

For the convenience of measuring LVW current of each parallel branch, special transformer is tested without tank. The boundaries of the calculation model are all Dirichlet type condition and to a certain distance from the windings.

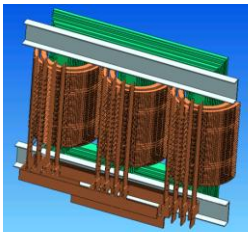


Fig. 1. The 3D calculation model

According to the different turns and oil duct size of winding discs, the HVW is divided into three ampere-turns regions. The LVW contains 32 parallel branches. Therefore, three phase equivalent circuits of the HVW and the LVW corresponded to FCCM is shown in figure 2 and figure 3 respectively. Because of three phase symmetry, there are only two independent current sources in the equivalent circuit of figure 2[3].

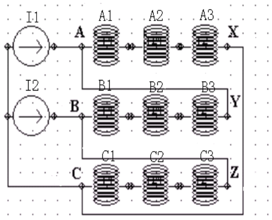


Fig. 2. Equivalent circuit of HVW

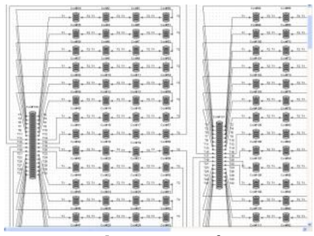


Fig. 3 Equivalent circuit of LVW

Table 1. The comparison of the calculated and measured current in LVW

Branch number	The calculated current and the ratio of to average value (A)		The measured current and the ratio of to average value (A)		Error (%)
1	187.60	1.500	186.50	1.503	0.59
2	120.75	0.966	119.00	0.959	1.47
3	102.85	0.822	103.00	0.830	-0.15
4	115.00	0.920	112.00	0.902	2.68
5	115.20	0.921	114.00	0.918	1.05
6	121.35	0.970	117.50	0.947	3.28
7	120.15	0.961	118.50	0.955	1.39
8	123.85	0.990	122.50	0.987	1.10
9	121.65	0.973	120.50	0.971	0.95
10	125.20	1.001	125.50	1.011	-0.24
11	122.95	0.983	122.50	0.987	0.37
12	125.90	1.007	126.00	1.015	-0.08
13	124.00	0.992	122.50	0.987	1.22
14	125.85	1.006	126.00	1.015	-0.12
15	123.70	0.989	123.00	0.991	0.57
16	126.05	1.008	126.00	1.015	0.04
17	123.90	0.991	124.00	0.999	-0.08
18	126.40	1.011	127.00	1.023	-0.47
19	123.80	0.990	126.00	1.015	-1.75
20	125.50	1.004	126.50	1.019	-0.79
21	123.50	0.988	124.00	0.999	-0.40
22	124.70	0.997	125.50	1.011	-0.64
23	123.45	0.987	122.50	0.987	0.78
24	122.65	0.981	123.50	0.995	-0.69
25	123.20	0.985	123.00	0.991	0.16
26	119.60	0.956	118.50	0.955	0.93
27	121.20	0.969	121.00	0.975	0.17
28	115.45	0.923	112.50	0.906	2.62
29	115.00	0.920	113.50	0.914	1.32
30	103.25	0.826	99.50	0.802	3.77
31	120.95	0.967	121.00	0.975	-0.04
32	187.25	1.497	179.00	1.442	4.61

II.2. *The verification of Short-circuit impedance*

The short-circuit impedance can be got by the magnetic field energy method:

$$U_k = \frac{4\pi f W}{VA} \qquad (1)$$

Where *VA* is the single-phase rated capacity of the transformer, kVA; *f* is frequency, HZ. The calculated and measured value is 6.83% and 6.92%. The relative error is -1.3%,which meets the design demand of special transformer.

II.3. *The low voltage winding current distribution and the verification*

The winding current distribution of special transformer is obtained by using the 3D FCCM. one phase current distribution results for the parallel branch of LVW is shown in table 1.

The relative error between the calculated values and measured values is with 3% which meets the design demand. It can be known from the table 1 that the winding current distribution regularity of special transformer is obtained.

III.The Engineering Method of Winding Leakage Magnetic Field and Its Related Performance Parameters

Because 3D calculation is difficult to satisfy the requirement of transformer design in the time of modeling, calculating and so on, 2D simplified calculation model is established according to the regularity of current distribution obtained from 3D calculation. The leakage magnetic field, short-circuit impedance and the short-circuit mechanical force are calculated and analyzed respectively.

III.1. *The simplified calculation model*

Based on the structural symmetry, the simplified model is a half of the single phase along the core center line. Assumes that the winding current distribution is uniform in each region and the winding total ampere turns is zero.

According to the above assumptions, the boundary value problems of the magnetic field solved by using vector magnetic potential ***A*** is as follows.

$$\begin{cases} \frac{\partial}{\partial_x}\left(\frac{1}{\mu}\frac{\partial(A_Z)}{\partial_x}\right)+\frac{\partial}{\partial_y}\left(\frac{1}{\mu}\frac{\partial(A_Z)}{\partial_y}\right)=\sigma\frac{\partial(A_Z)}{\partial_t}-J_s \\ L_1 : A_Z=0 \end{cases} \quad (2)$$

Where L_1 is tangential boundary; μ is permeability(H/m); σ is conductivity(S/m); ***J*** is current density of winding(A/m^2)[4-5].

Based on the regularity of LVW current distribution, LVW could be simplified and divided into 11 ampere-turn regions by its parallel branches merged. Because LVW structure along height are symmetrical, the ratios of branch number of each region to total one from the winding end to center are 3.125%,3.125%,3.125%,6.25%,6.25%,28.125%. The ratios of each region current to average value of all branches are 150%,96.7%,82%92%,96%,100%.
According to the difference of the turns and oil duct size, HVW is divided into three ampere-turns regions, their ratios being 3.125%,93.75% and 3.125% respectively. It is assumed in order to simplify analysis that current in each region is evenly distributed and total ampere-turns of both HVW and LVW is zero, in addition, leads current is ignored. The simplified calculation model is shown in figure 4, its boundaries being all Dirichlet type condition and to a certain distance away from the windings.

III.2. *Leakage magnetic field distribution*

Using the simplified model and 2D finite element engineering calculation software, the leakage magnetic field and the other related performance parameters of windings for special transformer are analyzed and verified. The distribution of leakage magnetic field and magnetic flux density of windings is shown in figure 5 and figure 6 respectively. LVW magnetic flux density of typical position got by 2D and 3D method are shown in table 2[6].

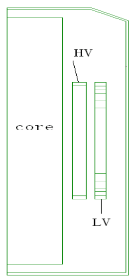


Fig. 4. The simplified calculation model.

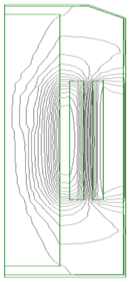
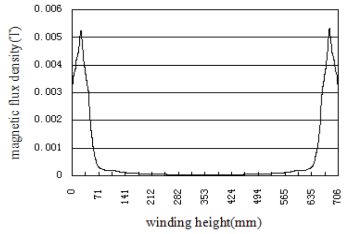
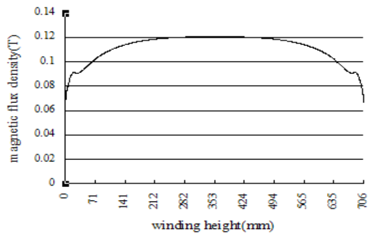


Fig. 5. The leakage magnetic field distribution.



(a) radial component



(b) axial component

Fig. 6. The distribution of magnetic flux density along LVW inner side height

It can be seen by Fig. 5 and Fig. 6 that winding leakage magnetic field distribution are reasonable and its distribution along winding height are nearly symmetric. The radial magnetic flux density of winding ends is larger than that of the other.

It can be known from the table 2 that the relative error of magnetic flux density in typical location is within 3%. Thus, the reasonability of 2D engineering method is verified.

Table 2. The radial magnetic flux density comparison of LVW typical location

Winding height(mm)	2D calculation values (T)	3D calculation values(T)	Error(%)
0	0.037	0.0365	1.92
35	0.052	0.0525	-1.00
680	-0.053	-0.052	-2.31
706	-0.030	-0.030	-0.33

III.3. *The verification of short-circuit impedance*

It can be known from the Table 3 that the calculated result is agreement with the measured values and the relative error is within 3%,which meet the technical demand of the special transformer.

Table 3. The comparison of short-circuit impedance

Calculation(%)	Measurement(%)	Error(%)
6.75	6.92	-2.46

III.4. *The calculation and analysis of short-circuit mechanical force*

The mechanical force and mechanical stress in HVW and LVW are obtained respectively by using 2D finite element engineering analysis software. They are shown in table 4 and Fig.7.

It can be seen from table 4 that the axial mechanical force along winding height is approximately symmetrical and is in the opposite direction. The axial mechanical force in region 1 of LVW is the largest, about 40 kN.

In addition, the critical pressure of HVW is 119.4N/mm which could be got from the formula (3).

$$P_{cr} = \frac{EZ}{R^3}\left\{\left(\frac{n}{2}\right)^2 - 1\right\} \tag{3}$$

Where E is the elastic modulus of copper conductors(N/mm^2);Z is the second moment of conductor cross section(mm^4); n is stay number; R is average radius(mm).

Table 4. The axial mechanical force of each winding region

Region	Low voltage(kN)	High voltage(kN)
1	-39.56	-28.93
2	-1.09	-1.22
3	0.58	28.80
4	-1.19	
5	-1.72	
6	0.48	
7	1.85	
8	1.56	
9	-0.03	
10	1.36	
11	36.14	

It can be known according to the calculation results of radial force that the largest radial force in HVW is 21.72N/mm, which is less than the critical pressure. Therefore, the radial stability of inner winding meet design requirement for special transformer.

The results show that the mechanical stress of HVW is less than the allowable stress value, thus, HVW meet the requirement of mechanical strength. The mechanical stress distribution of the LVW along its height are shown in the figure 8.

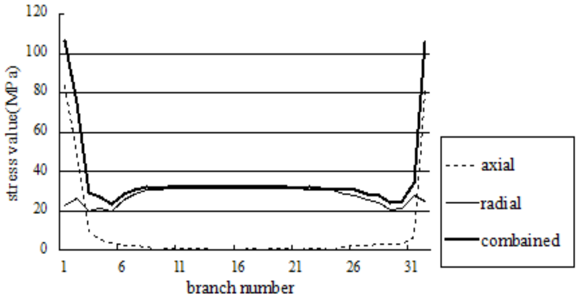


Fig. 7. The distribution of mechanical stress along branches of LVW.

Because the radial magnetic flux density of the LVW ends is larger and the branch current of winding ends is larger than that of other branches, the maximum axial mechanical stress is about 84 MPa in the branch 1 and branch 32. The combined mechanical stress of branch 1 and branch 32 is about 106 MPa. The used wire size of LVW is ordinary paper flat copper wire, and the allowable mechanical stress is 120 MPa. Therefore, LVW meet the requirement of mechanical strength in short-circuit condition.

It is shown by the above calculation that the computational efficiency of engineering method is increased by about twenty times, compare with 3D calculation.

IV.Conclusions

The 3D calculation model and the corresponding equivalent circuits for special transformer are established by FCCM. And LVW parallel branch current, winding leakage magnetic field distribution and short-circuit impedance are calculated and verified. Then the regularity of current distribution is applied to engineering calculation of special transformer. The winding leakage magnetic field and related performance parameters are calculated by using 2D FEM. By comparing 2D calculation results with the measured values or 3D calculation results for the typical products, it can be shown that the calculation results of winding leakage magnetic field, impedance and short-circuit mechanical force meet the requirements of product performance. Thus, the engineering practical and efficient calculation approach for special transformers is provided.

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