The Influence of Winding Short-Circuit Mode in Short-Circuit Test on Core Magnetic Density Distributing

Wenfeng Zhang\textsuperscript{1, a}, Chunyao Lin\textsuperscript{1, b}, Junting Luo\textsuperscript{2, *}, Xian Yang\textsuperscript{1, c}, Wenxing Sun\textsuperscript{1, d}, Yunhan Sun\textsuperscript{2, e}, Qingmin Meng\textsuperscript{2, f}

\textsuperscript{1}China Southern Grid Guangdong Power Grid Co., Ltd Electric Power Research Institute, Guangzhou, Guangdong 510080, China
\textsuperscript{2}Shenyang Transformer Research Institute, Shenyang, Liaoning 110122, China

*Corresponding author e-mail: 2008beijing422@163.com, \textsuperscript{a}362473329@qq.com, \textsuperscript{b}13802933442@139.com, \textsuperscript{c}yxhust@163.com, \textsuperscript{d}swx_hust@163.com, \textsuperscript{e}yunhan.sun@outlook.com, \textsuperscript{f}m-qm@163.com

Abstract. Taking two power transformers as examples, the core magnetic density in different winding short-circuit modesties calculated and analysed with finite element method software. The necessity of transformer short-circuit test required in the standard is explained. The software analysis model is set up based on different short-circuit test modes. Analysis results include the distribution of the core magnetic density and the value of the current in the winding. Finally, the analysis conclusion is given.

1. Introduction

When conducting transformer short-circuit test, short-circuit different windings will cause different core magnetic density distribution. The article 4.2.5.1 of the IEC standard 60076-5: 2006 and the Chinese national standard GB1094.5-2008 “Power Transformers, Part 5: Ability to Withstand Short-Circuit”\textsuperscript{[1]2} both require that “If the pre-set short circuit is used for a transformer with single-concentric windings, the supply should preferably be connected to the winding furthest from the core. The winding closer to the core is to be short-circuited in order to avoid saturation of the magnetic core which could lead to an excessive magnetizing current superimposed on the short-circuit current during the first few cycles.” From the requirement we noted three points. First, the condition of the short circuit is pre-set short circuit; Second, whether to short-circuit the winding closer to the core (the inner winding) or far from the core (the outer winding) will impact the core magnetic density distribution; Third, exciting the inner winding while short-circuit the outer winding will lead to an excessive magnetizing current.

In existed articles and papers, the phenomenon of saturation of the magnetic core caused by excessive magnetizing current is usually related to no-load inrush current but is seldom attributed to short-circuit test inrush current \textsuperscript[3]. For the latter factor, the research of its transients during the changing process will show the realistic running state \textsuperscript[4], and the steady state analysis is the basement of the research. Therefore, this article will preliminarily research into the core magnetic density distribution at the steady state of pre-set short circuit, hoping to help the deeper research on the transients of these series of problems. According to the testing requirement above, in this article we preliminarily calculate the steady state core magnetic density distribution in four different short-circuit modes with the help of...
electric and magnetic analysis software, and then analyze and explain the necessity of the standard requirement.

2. Theoretical Foundation and Short-Circuit Test Modes

2.1. Theoretical Foundation

To get the maximum peak value of asymmetrical short-circuit current in transformer short-circuit test with a pre-set short circuit, it is required that the switching-on should occur at the moment the voltage applied passes through zero [5], which is the same as the switching-on condition for maximum inrush current caused by no-load switching-on operation. At this moment, the transient magnetic flux phenomenon will occur, which is similar to the situation in no-load switching-on process. If the transient flux reaches or approaches the value in no-load switching-on process, then it will cause the short-circuit inrush current, just as in no-load switching-on process. In principle, after switching on when the voltage applied passes through zero, there will be steady state magnetic flux, transient magnetic flux, and remanence, which will then cause inrush current [5] [6]. Similarly, when applied voltage passes through zero, whether the short-circuit test switching-on operation will bring inrush current depends on whether the steady state magnetic flux in the core reaches or approaches rated main magnetic flux. If yes, the inrush current will occur; otherwise there will be no or very small inrush current [7].

Regarding the steady state magnetic flux during short circuit switching-on operation, combining the national standard and the analysis in existed articles and papers, we could deduce the following:

a. During a short circuit under rated voltage or during a short-circuit test, the magnetic flux leakage in the inner and outer windings is big, the value of which is approximate to the magnetic density in the core at the moment [8].

b. When the outer winding is at excitation, the direction of the magnetic flux in the core is the same as that in the outer winding and is opposed to that in the inner winding. For the core limb, the two main components of the composite magnetic flux are part of the flux of the inner winding, and the flux of the core (same direction as that of the outer winding), which are in opposite direction and work against each other.

c. When the inner winding is at excitation, the direction of the magnetic flux in the core is the same as that in the inner winding and is opposed to that in the outer winding. For the core limb, the two main

Figure 1. Magnetic flux distribution in transformer short-circuit tests
components of the composite magnetic flux are part of the flux of the inner winding, and the flux of the core (same direction as that of the inner winding), which are in the same direction and superpose with each other.

The details of the above deductions could refer to Figure 1. In this article we also use electric and magnetic analysis software to calculate and analyze the core magnetic flux distribution stated in the deductions.

2.2. Short-Circuit Test Modes

To conveniently compare the influence to the core magnetic density of different short-circuit modes, in this article we set up the model in electric and magnetic analysis software and simulate single phase excitation situation, forming 4 typical winding short-circuit test modes [9] [10]:

a. When outer winding is at excitation, 3 phases of inner winding are short-circuited (short-circuit mode 1)

b. When inner winding is at excitation, 3 phases of outer winding are short circuited (short-circuit mode 2)

c. When outer winding is at excitation, single phase of inner winding is short circuited (short-circuit mode 3)

d. When inner winding is at excitation, single phase of outer winding is short circuited (short-circuit mode 4)

The connection diagrams of above short-circuit test modes are given in Figure 2.

![Short-Circuit Test Connection Diagrams](image)

**Figure 2.** Short-Circuit Test Connection Diagrams

3. Software Analysis

3.1. Main Parameters of the Example Products

We choose 2 products as examples. Example 1 is a 3-phase 3-column core structure 110kV level product, while example 2 is a 3-phase 5-column core structure 220kV level product.

a. Main parameters of the 3-phase 3-column product

1. Product Model Number: SWFZ11-40000/110
2. Core Data: \( \phi D = \phi 600 \), \( M_0 = 1,205 \), \( H_W = 1,405 \).
3. Winding Data:
   - LV (Inner Winding): Voltage =10,500V, Turns=105, Reactance Height=1,220.
HV (Outer Winding): Voltage = 63,510V, Turns = 635, Reactance Height = 1,220.

b. Main parameters of the 3-phase 5-column product
   ① Product Model Number: SSZ12-240000/220.
   ② Core Data: φD = φ1, 000, Yoke Width = 520, M₀/M₀' = 2, 120/1, 340, HW = 2, 215.
   ③ Winding Data:
      HV (Inner Winding): Voltage = 132,790V, Turns = 481, Reactance Height = 1, 825.
      MV (Outer Winding): Voltage = 69,860V, Turns = 253, Reactance Height = 1, 825.

3.2. Model Set-up
According to the structure characteristics of the example products, the 3D calculation models of the two products have been set up in electric and magnetic field calculation software MagNet, which are shown in Figure 3.

![Figure 3. Diagrams of Calculation Model](image)

The set-ups and assumptions of calculation condition and method during software analysis are listed as follows [11]-[14]:
   a. Based on the symmetrical structure of the example products, we conduct the analysis and calculation on 1/2 part of the product, which is symmetrical in front and back.
   b. Set up the winding characteristics based on turns and current input, and assume the winding current is evenly distributed.
   c. Do not consider the influence of pulling plate, clamping mechanism, tank, etc. to the core magnetic density distribution.
   d. Do not consider the influence of the remanence in the core.
   e. Analyze the steady state magnetic flux in the core during pre-set short-circuit.
   f. Analyze and calculate the 3D field which is under voltage excitation [15] [16].

4. 3D Field Calculation Result and Analysis

4.1. Current Distribution of each winding
Take voltage as excitation source, we calculate the current distribution under different short-circuit modes. The results are given in Table 1.

From Table 1 we could see that:
   a. Under 3-phase short circuit condition, no matter it is the inner winding or the outer winding is at excitation (phase A excitation), the phase A winding current is approximate to normal short-circuit current, and there is small current passing through phase B and C windings. For 3-phase 3-column structure, the current passing through phase B and C cannot be ignored, while for 3-phase 5-column structure, the current passing phase B and C is very small.
   b. Under single phase short circuit condition, no matter it is the inner winding or the outer winding is at excitation (phase A excitation), the phase A winding current is normal short-circuit current, and there is no current in phase B and C windings due to an open circuit.
Table 1. Current value of each winding under different short-circuit modes, A

| Winding Current | 3-Phase 3-Column | 3-Phase 5-Column |
|-----------------|------------------|------------------|
|                 | Short-Circuit    | Short-Circuit    | Short-Circuit    | Short-Circuit    |
|                 | Mode 1           | Mode 2           | Mode 3           | Mode 4           |
| Inner Winding   |                  |                  |                  |                  |
| $I_a$           | 12,074.8         | 12,110.1         | 12,106.8         | 12,108.5         |
| $I_b$           | 389.9            | 0                | 0                | 0                |
| $I_c$           | 389.9            | 0                | 0                | 0                |
| Outer Winding   |                  |                  |                  |                  |
| $I_a$           | 2,061.1          | 1,996            | 2,001.9          | 2,002.2          |
| $I_b$           | 0                | 6.435            | 0                | 0                |
| $I_c$           | 0                | 6.435            | 0                | 0                |

4.2. Core Magnetic Density Distribution

The 3D core magnetic field distribution of the example transformers and the magnetic density value of typical part under different short-circuit modes are given in Figure 4 and Figure 5. Figure 4 shows the data of 3-phase 3-column product, and Figure 5 shows the data of 3-phase 5-column product.

**Figure 4.** Magnetic density distribution of 3-phase 3-column product
We pick up the magnetic density value of typical core position according to above core magnetic density contour under different short circuit modes, as shown in Table 2.

**Table 2.** Typical core position magnetic density under different short circuit modes, T

| Core Magnetic Density | 3-Phase 3-Column | 3-Phase 5-Column |
|-----------------------|------------------|------------------|
|                       | Short-Circuit Mode 1 | Short-Circuit Mode 2 | Short-Circuit Mode 3 | Short-Circuit Mode 4 |
|                       | Short-Circuit Mode 1 | Short-Circuit Mode 2 | Short-Circuit Mode 3 | Short-Circuit Mode 4 |
| $B_1$                 | 0.29 1.85 0.351 1.85 | 0.316 1.94 0.316 1.94 |
| $B_2$                 | 0.86 0.23 1.396 0.266 | 0.641 0.356 1.276 0.33 |
| $B_3$                 | 0.043 0.019 1.068 0.09 | 0.014 0.007 0.616 0.041 |
| $B_4$                 | — — — — 2.08 0.089 1.506 0.045 |

Note: $B_1$ – Phase a Core Column Magnetic Density.
$B_2$ – Yoke Magnetic Density between phase A and B.
$B_3$ – Phase B Core Column Magnetic Density.
$B_4$ – Side Yoke Magnetic Density.

From Figure 4, Figure 5 and Table 2 we could see that:

a. Under 3-phase short circuit condition, when the outer winding is at excitation, the magnetic density in core column of phase A is small. The magnetic density in the yoke is slightly bigger than that in the core column. When the inner winding is at excitation, the magnetic density in core column of phase A
is big, the magnetic density in the yoke is rather smaller than that in the core column. From the contour we could see that the magnetic density in core column of phase B and C is rather small.

b. Under single phase short circuit condition, when the outer winding is at excitation, the magnetic density value in core column of phase A is similar to that under 3-phase short circuit condition, which is quite small. The magnetic density in the yoke is much bigger than that in the core column, and is bigger than that under 3-phase short circuit condition. When the inner winding is at excitation, the magnetic density in core column of phase A is big, the magnetic density in the yoke is rather smaller than that in the core column. From the contour we could see that the magnetic density in some positions of the core column of phase B and C is rather small, while in some other positions is quite big.

c. Take the magnetic density in the core column as example, after analyzing the magnetic density changing under different circumstances we could see that, when the outer winding is at excitation, the core column where locates the excitation winding has a small magnetic density. When the inner winding is at excitation, the core column where locates the excitation winding has a rather big magnetic density, which is approximate to the main magnetic density value.

d. The magnetic density of several special positions:
   ① For 3-phase 3-column product, when the outer winding is at excitation, and single phase is short-circuited (short circuit mode 3), the yoke magnetic density between phase A and B and the magnetic density in core column of phase B is rather big.
   ② For 3-phase 5-column product, when the outer winding is at excitation, and 3 phases are short-circuited (short circuit mode 1), the side yoke magnetic density in phase A is big.
   ③ For 3-phase 5-column product, when the outer winding is at excitation, and single phase is short-circuited (short circuit mode 3), the yoke between phase A and B and the side yoke of phase A has quite big magnetic density.

5. Summary
Using general electric and magnetic analysis software, this article analyzes the core magnetic density distribution under different short circuit modes by simulating four kinds of short-circuit tests, and explains the necessity of the requirement stated in Article 4.2.5.1 of Chinese national standard GB1094.5-2008 “Power Transformers – Part 5: Ability to Withstand Short-Circuit”.

a. The software analysis shows that, when 3-phase 3-column core structure is under a single-phase excitation and 3-phase short circuit condition, there is current passing the phase B and C winding due to the change of the magnetic field, which cannot be neglected, and thus does not satisfy the short-circuit test requirement. Moreover, the single-phase excitation, single phase short circuit will impact the impedance of the transformer, therefore in general cases, single phase excitation will not be used for 3-phase 3-column core structure products.

b. When 3-phase 5 column core structure is under a single-phase excitation and 3-phase short circuit condition, there is also current passing phase B and C winding due to magnetic field change. However, because of the side yoke, this current is usually rather small, and does not affect the short-circuit test. Therefore, generally, for 3-phase 5-column core structure products, the short-circuit test method of single-phase excitation, single-phase short circuit will be chosen. When affected by the connection type of the transformer, the short-circuit test method of single-phase excitation, 3-phase short circuit could also be used.

c. The software analysis shows that, when the outer winding is at excitation and the inner winding is short-circuited, the core column magnetic density is rather small; when the inner winding is at excitation and the outer winding is short-circuited, the core column magnetic density is approximate to the steady state value of main magnetic density in the core, the condition of which is the same as that when no-load switching-on operation produces the maximum inrush current, so that it will cause inrush current and saturate the core. For this reason, the standard requires that when conducting short-circuit test, the voltage should be applied to the winding which is far from the core (outer winding), and the winding which is close to the core (inner winding) should be short-circuited.
d. In reality, the transformer short-circuit test is a transient running state, the inrush current at the moment of short-circuit switch-on is rather big, and is a nonlinear wave. But this article is considering a steady state core magnetic density value under a sinusoidal current wave. The transient running state of short circuit needs deeper research and analysis.

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