

Electromagnetic analysis and optimization of copper bar in foil winding transformer

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Abstract. In this paper, a novel overlapping approach between the copper foil windings and copper bar is presented. The electromagnetic field is computed and analyzed using three-dimensional (3-D) finite element method based on an actual SCB transformer with amorphous foil winding. The current density cloud of foil winding and copper bar is obtained using the magnetic vector potential method to visually observe the existence of skin effect. Then the current density of novel overlapping mode is computed and compared with the traditional one. The results show that the novel overlapping mode not only reduce maximum current density of foil winding, but also save material. The study of this paper is significant for practical manufacture and production.

Introduction

With the improvement of the national energy policy, the strengthening of people's environmental awareness, and continuously increase of performance-price ratio for amorphous distribution transformers, as a result, amorphous alloy transformers have been more widely used [1]. Therefore, the research on relevant theoretical is becoming increasingly significant. Due to the special structure of amorphous alloy transformer, low voltage winding usually made of foil winding, copper bar orthogonal overlaps with copper winding. With both the overlapping way and winding skin effect, the current density distribution of copper bar is uneven. This phenomenon is calculated and analyzed, and according to the analysis guide the transformer structural optimization.

The study involved skin effect of foil winding, the traditional analytical calculation cannot meet the need. With the development of finite element numerical method [2], the description of foil winding current distribution has been studied, such as two-dimensional (2-D) analysis of the current density distribution of the single copper foil [3]. As the working current of low-voltage foil winding existed unevenly distributed eddy current and do not know the current magnitude, using the finite element method requires to know previously the winding current distribution [4]. It has great practical significance for dry-type foil winding transformers modeling by three-dimensional eddy current field research [5]. Skin effect of windings using 3-D modeling ,as in [6] gives the average flows scheme, adding ferromagnetic ring plate at end of windings so that the end of the foil winding radial flux density decrease and average. The average current effect is obvious, but it cannot be applied in a single layer on the lap of copper foil and copper bar at the 3-D field distribution problem.

Therefore, this paper uses a SCB transformer as a prototype model by 3-D frequency-domain finite element method to analyze skin effect distribution of foil winding and the copper bar current density distribution. Some distribution rules are obtained and then some reasonable suggestions are given for the optimization of the copper bar structural.

Simulation Model

In this paper, the model is amorphous alloy transformer which the type is SCB for the study, some basic parameters are shown in Table I.

Table 1 BASIC PARAMETERS OF THE TRANSFORMER

	Types of wire	Rated voltages	Rated current	Types of connection
High Voltage	Band wires	10kV	21A	△
Low Voltage	Foil	400V	909A	Y

The leakage magnetic field and eddy current distribution in windings are calculated based on finite element method, the rated current is applied directly for the excitation of the calculation mode to simulate the transformer normal operation [7]. The major issue is the current density distribution of low-voltage foil winding and copper bar. The wound core impact to the excitation current, eddy current generated by low-voltage winding flux leakage and skin effect of single foil windings are considered. The eddy current influence of core, structure components and high-voltage winding is ignored.

Therefore, the computation model includes core, high voltage winding, low voltage winding. And the low voltage winding is established layered according to the number of turns. Fig.1 shows the physical model and simulation model of transformer.

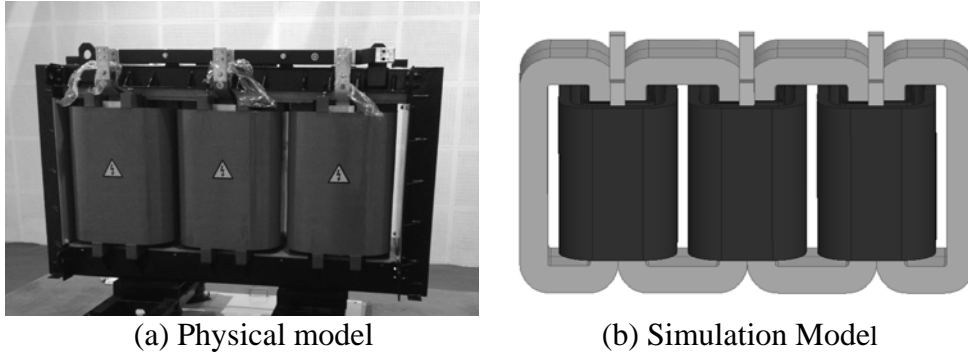


Fig.1 The schematic of transformer modeling

As the calculate area contains eddy current area, the professional software using scalar magnetic potential method named T - Ω for solving the problem. The following control of the equation as follows.

$$\nabla \times \left[\left(\sigma + \varepsilon \frac{\partial}{\partial t} \right)^{-1} \nabla \times \mathbf{T} \right] + \mu \frac{\partial}{\partial t} [\mathbf{T} - \nabla \Omega] = 0 \quad (1)$$

$$-\nabla \left(\sigma + \varepsilon \frac{\partial}{\partial t} \right)^{-1} \nabla \cdot \mathbf{T}$$

Introducing the penalty function,

$$\nabla \times \left[\left(\sigma + \varepsilon \frac{\partial}{\partial t} \right)^{-1} \nabla \times \mathbf{T} \right] - \nabla \left(\sigma + \varepsilon \frac{\partial}{\partial t} \right)^{-1} \nabla \cdot \mathbf{T} + \mu \frac{\partial}{\partial t} [\mathbf{T} - \nabla \Omega] = 0 \quad (2)$$

$$\text{In addition, } \nabla \cdot \mathbf{B} = 0, \nabla \cdot [\mu(\mathbf{T} - \nabla \Omega)] = 0 \quad (3)$$

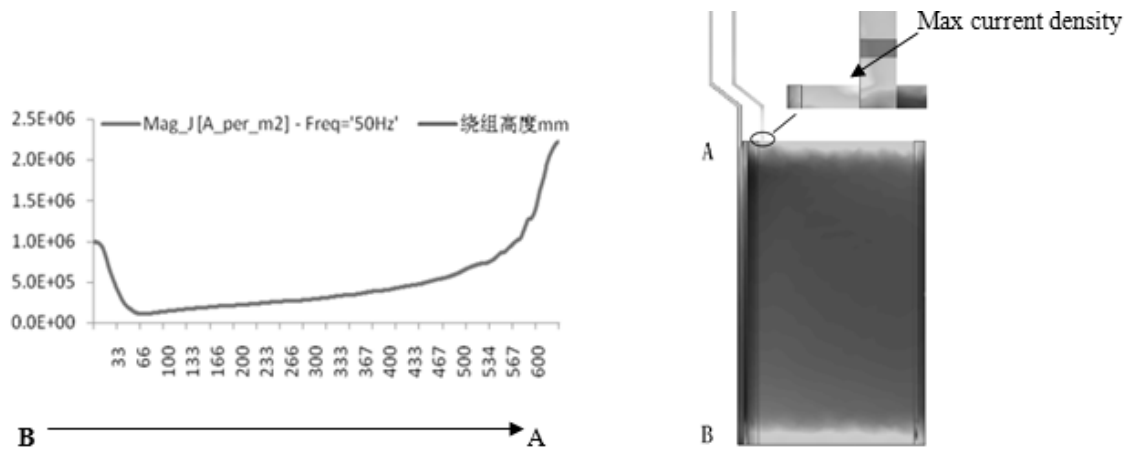
Wherein, \mathbf{T} is the vector electric potential, Ω is scalar magnetic potential, σ is conductivity, ε is permittivity, μ is magnetic permeability.

In the calculation process, assume the current density distribution of high voltage winding is even, the magnetized characteristic of wound core used the basic magnetized curve description, the hysteresis characteristic is ignored.

The results of the analysis

Because of focusing on low-voltage eddy current field, so do not build carefully a high-voltage winding. The current flowing into the low-voltage winding is from the outermost copper bar. In order to calculate accurately the current density distribution of copper bar, the current density distribution of single layer copper foil must be calculated. In consideration of the skin effect, the current density distribution of low-voltage winding is shown in Fig.2. The current density distribution of foil windings in the axial direction is uneven. The current density distribution along axial from points B to A is shown in Fig.2 (a), the maximum current density is 2.4A/mm² show in

elliptical area in Fig.2(b). But the design value of the average current density of the foil is $0.84\text{A}/\text{mm}^2$, the lower design value is used to avoid high eddy current loss due to skin effect.

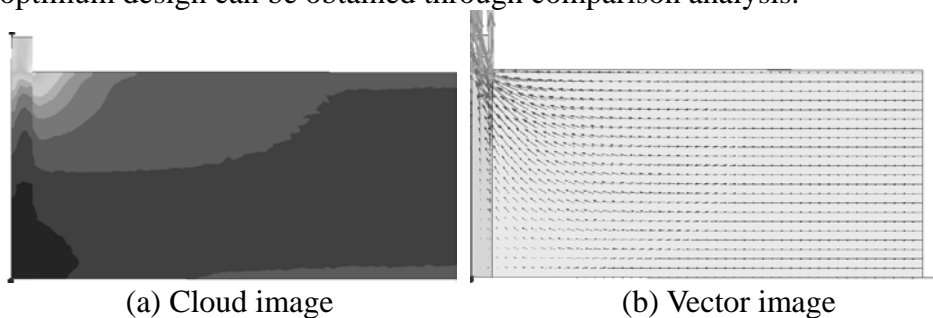


(a) Winding current density radial distribution (b) Winding current density cloud

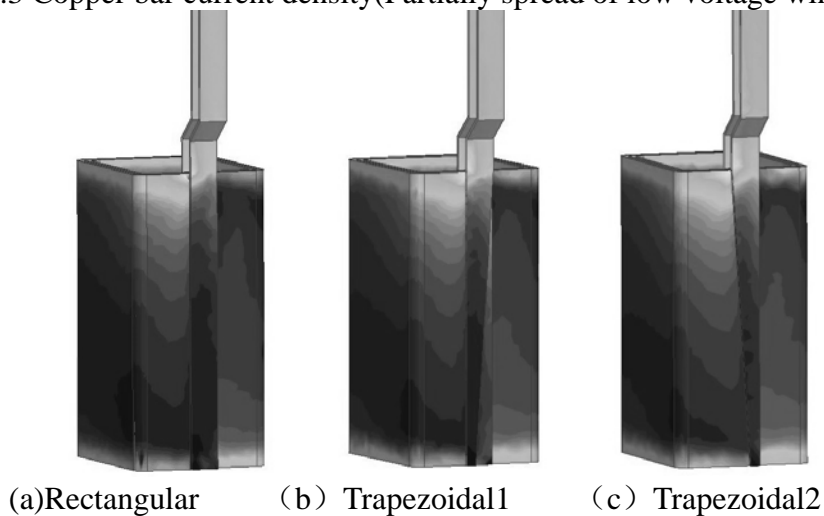
Fig.2 The current density of low voltage foil winding

Structure Optimization

In engineering design, the most convenient and simplest way is the shape optimization. Using this method can guarantee both the designed quality and efficiency, it also can simplify the production process and maximize profits. The two different shapes copper bar are proposed in this paper, so the optimum design can be obtained through comparison analysis.



(a) Cloud image (b) Vector image
Fig.3 Copper bar current density (Partially spread of low voltage winds)



(a) Rectangular (b) Trapezoidal1 (c) Trapezoidal2
Fig.4 Three kinds of copper bar placement

The first option is a rectangular copper bar. The model of the copper foil simplified after the expanded of the winding, skin effect of single copper foil winding is more intuitive, as shown in Fig.3. It can be seen that the current density distribution of the copper bar is very uneven. The current density in bottom part is significantly lower than the upper end of the copper foil. The left

side of current density is lower than the right side at the copper bar. The hole cloud image is show Fig.4(a). According to the flow direction and distribution of current, the copper bar can be optimized.

The second option is a trapezoidal copper bar. Due to the utilization of the rectangular copper bar is not high, according to the trend of current density vector image, it will simplify from rectangular copper bar to trapezoidal. But there are two placement methods show as Fig.4(b) and Fig.4(c) , it has some differences in maximum current density. However, the maximum current density presents at the upper end of the copper foil which inflows in the intersection. From table 2, the maximum current density is Fig4(a) and Fig4(c) is the smallest. But the volume of copper bar is reduced by about 1/5 in Fig4(c), so it is the best lap way. The trapezoidal copper bar can not only save cost but also reduce the maximum current density. This also coincides with the distribution and flow direction of current density.

Table2 Comparison of three kinds of copper bar placement

Shape of copper bar	Max current density(A/mm ²)	Copper bar Volume (mm ³)
(a)Rectangular	4.5	468960
(b)Trapezoidal ¹	4.1	368160
(c)Trapezoidal ²	3.8	368160

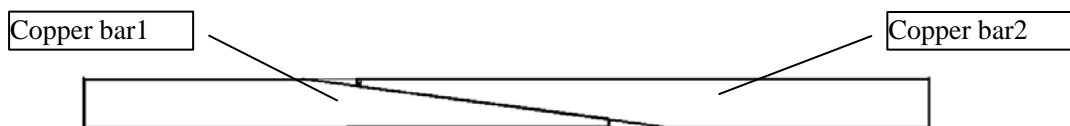


Fig.5 processing schematic of low copper bar

The trapezoidal, it also avoids point discharge situation and the machining process technology is easy to implement, the schematic diagram of the production process shown in Fig.5. And more importantly the trapezoidal copper bar is able to save about 1/5 copper bar material. It is very significant for the company.

Summary

In this paper, it is a detailed study that the current density distribution of between foil and copper bar, and make a bold simplify for copper bar. The simulation results show that the simplification of the calculation model is reasonable, because of there is little effect on current density for the novel overlapping mode and the traditional one. And 1/5 of the copper bar materials are saved, significantly increased economic efficiency.

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