Development of a Common-Core Autotransformer with Constant and Variable Magnetic Flux (Postprint)

Authors: Li Cheng, Xu Tianqi, Li Yan

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Abstract

To address the challenges of low benefit coefficient and design difficulty for interconnecting autotransformers in power grids with similar voltage levels, this paper proposes a novel autotransformer design featuring constant and variable flux sharing a common core. Through 3D electromagnetic field simulations under various operating conditions, key parameters including the main core flux distribution and winding voltages during no-load operation, as well as winding currents and short-circuit impedance under short-circuit conditions, were determined for the autotransformer with this common-core structure. The simulation and estimation results show good consistency, demonstrating the feasibility of this structure. Transformers employing this innovative structure can effectively reduce main material costs, lower no-load losses, and decrease transportation weight. Furthermore, the simplified product structure facilitates manufacturing and processing, thereby enhancing operational safety and reliability.

Full Text

A Novel Design of Auto-Transformer with Common Core for Constant Flux and Variable Flux

Li Cheng[1], Xu Tianqi[2], Li Yan[2]
(1. Baoding Tianwei Baobian Electric Co., Ltd., Baoding 071056, China
2. Yunnan Minzu University, Kunming 650500, China)

Abstract

When power grids with close voltage levels are interconnected, the design of tie auto-transformers becomes difficult due to the low effectiveness coefficient. This paper proposes a novel design of auto-transformer with a common core for constant flux and variable flux. Through three-dimensional electromagnetic field simulation and calculation, the no-load main flux distribution, winding voltages, as well as important parameters such as winding short-circuit currents and short-circuit impedance of the transformer are analyzed and calculated. The simulation results basically coincide with the estimated results, which illustrates the feasibility of the new structure. By adopting this transformer with the new structure, the primary material cost, no-load loss, and transport weight can be effectively reduced. Furthermore, with a simplified structure, the transformer can be manufactured with greater ease, and the operational reliability would be enhanced consequently.

Keywords: Constant flux, variable flux, auto-transformer

1 Introduction

In some countries and regions with highly liberalized electricity markets, grid planning tends to be uncoordinated, sometimes requiring interconnection between grids with similar or even equivalent voltage levels. This leads to very low effectiveness coefficients for tie auto-transformers [1]. For such auto-transformers, traditional design methods create insurmountable problems. To address these issues, literature [2] adopted a dual-body structure design: one body maintains constant flux, exciting the boost winding (BV), tap winding (TV), and common winding (MV) through the low-voltage winding (LV). The BV and TV, after series connection, supply power to the excitation winding (EV) on the other variable-flux body. By adjusting the turns of TV, the per-turn potential of EV is changed, which in turn excites the series winding (HV). This achieves the purpose of on-load voltage regulation in the series winding by changing the per-turn potential. However, this dual-body, dual-core structure is complex, exhibits high no-load losses, and results in large transport weight and dimensions. Figure 1 [Figure 1: see original paper] shows a product lifting its dual bodies during installation.

Currently, all such products in domestic and international power transmission lines (including 500kV and 400kV grid interconnection lines that have emerged in Hong Kong and Guangdong in recent years) adopt this dual-body, dual-core structure. If a single-core structure could be used instead, it would significantly reduce the transformer’ s no-load losses and silicon steel consumption while decreasing transport volume and weight, yielding superior technical and economic performance. However, no research has been reported on this approach.

For a foreign project requiring an auto-transformer tie, the high-to-medium voltage ratio (kV) is quite close, with an effectiveness coefficient of only 0.2. To overcome the 500kV on-load tap changing problem, variable flux induction voltage regulation is employed. Typically, such transformers use a dual-core structure. The following sections verify through magnetic field simulation whether a single-core structure with two main limbs can be adopted, where one main limb operates at constant flux and the other at variable flux.

Product Specifications:
(1) Model: ODFPSZ–250000/500
(2) Rated voltage: 500 ±10×1.0%/ (kV)
(3) Connection group: YNa0d11 (three-phase group)
(4) Core type: Double-main-limb three-frame structure, with side limbs and yokes having 50% cross-section of main limbs
(5) Wiring diagram shown in Figure 2 [Figure 2: see original paper]
(6) Core and winding arrangement shown in Figure 3 [Figure 3: see original paper]

Winding arrangement:
- Main Limb I: Core -EV winding -HV winding -BV winding -MV winding
- Main Limb II: Core -LV winding -TV winding -BV winding -MV winding

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2 Product Basic Parameters

The basic parameters of the product are as described above, with the winding arrangement and core structure forming the basis for subsequent simulation analysis.

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4 Simulation Modeling

Two modeling methods are available in MagNet: first, using its built-in 3D geometric modeling function to directly build the model, which is inconvenient for complex models, time-consuming, and difficult to modify; second, building the 3D model in other parametric drawing software and then importing it into MagNet. This latter method combines powerful 3D parametric driving capabilities, enabling model modification through simple input of structural parameters, making it highly suitable for 3D model construction [3]. Based on the product' s structural characteristics, this paper adopts Pro/E to establish a three-dimensional half-model and imports it into MagNet.

Boundary conditions are set as tangential natural boundaries and normal symmetric boundaries at distances far from the core and windings, while material properties are selected directly from MagNet's extensive built-in material library. The completed model is shown in Figure 4 [Figure 4: see original paper].

MagNet' s field solver provides 3D static, time-harmonic, and transient field solutions. For large power transformers, the electromagnetic field to be solved is a quasi-static field varying under power-frequency sinusoidal excitation, which is best handled using the time-harmonic field approach. This treatment is completely analogous to the phasor method in circuit analysis, with results displayable as RMS, maximum, or average values [4]. Note that when selecting the time-harmonic field solver, the nonlinearity of ferromagnetic materials need not be considered, i.e., the relative permeability _Fe of the core is set as a constant [5].

5 Simulation Analysis

The magnetic field simulation employs MagNet software from Infolytica. Finite element method is used for magnetic field simulation calculations.

Three simulation conditions are examined:
1. HV-MV operation, HV winding maximum tap
2. HV-MV operation, HV winding rated tap
3. HV-MV operation, HV winding minimum tap

For all three conditions, the following are calculated:
Core flux distribution under no-load conditions
Winding currents and short-circuit impedance under short-circuit conditions

5.1 Simulation Condition 1: HV-MV Operation, HV Winding Maximum Tap

5.1.1 No-Load Simulation The MV winding of Main Limb II is excited with a voltage source: $V1 = \times \div 2 = 163,299.3V$. The TV winding and BV winding are connected in series and then paralleled with the EV winding. The equivalent circuit for operation is shown in Figure 5 [Figure 5: see original paper].

Comparison between simulated and estimated phase voltage results for each winding is presented in Table 1 .

Magnetic field simulation of the core is shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper].

Comparison between simulated and estimated magnetic flux density results in the main limbs is presented in Table 2 .

5.1.2 Short-Circuit Simulation The MV winding of Main Limb II is short-circuited, and the HV winding is excited with a current source: $I1 = 787.3\times 2 = 1,113.4A$. The TV winding and BV winding are connected in series and then paralleled with the EV winding. The equivalent circuit for operation is shown in Figure 8 [Figure 8: see original paper].

Comparison between simulated and estimated phase current results for each winding is presented in Table 3 .

The magnetic field energy is calculated as: $WS = 60,059.2$ J
Equivalent inductance: $LK = 2WS/I^{2}\_max = 193.8$ mH

Short-circuit reactance: XK = 2 fLK = 60.9 Ω
Impedance voltage: UK% = I_maxXK/U_max×100% = 15.09%

Based on the calculated impedance voltage value, the MV winding of Main Limb II is short-circuited and excited with a voltage source: V1 = ! 2 × 15.09%÷2 = 33,882.6V. The equivalent circuit for operation is shown in Figure 9 [Figure 9: see original paper].

Comparison between simulated and estimated phase current results is presented in Table 4 . The magnetic field energy is 60,013.4J, which basically matches the previous current source excitation results.

5.2 Simulation Condition 2: HV-MV Operation, HV Winding Rated Tap

5.2.1 No-Load Simulation The MV winding of Main Limb II is excited with a voltage source: V1 = ! 2 ÷2 = 163,299.3V. The TV winding is disconnected, and the BV winding is paralleled with the EV winding. The equivalent circuit for operation is shown in Figure 10 [Figure 10: see original paper].

Comparison between simulated and estimated phase-ground voltage results is presented in Table 5 .

Magnetic field simulation of the core is shown in Figures 11 [Figure 11: see original paper] and 12 [Figure 12: see original paper].

Comparison between simulated and estimated magnetic flux density results in the main limbs is presented in Table 6 .

5.2.2 Short-Circuit Simulation The MV winding of Main Limb II is short-circuited, and the HV winding is excited with a current source: I1 = 866.0× 2 = 1,224.7A. The TV winding is disconnected, and the BV winding is paralleled with the EV winding. The equivalent circuit for operation is shown in Figure 13 [Figure 13: see original paper].

Comparison between simulated and estimated phase current results is presented in Table 7 .

The magnetic field energy is calculated as: WS = 49,146.4 J
Equivalent inductance: LK = 2WS/I²_N = 131.1 mH
Short-circuit reactance: XK = 2 f LK = 41.2 Ω
Impedance voltage: UK% = I_NXK/U_N×100% = 12.35%

Based on the calculated impedance voltage value, the MV winding of Main Limb II is short-circuited and excited with a voltage source: V1 = ! 2 × 12.35%÷2 = 25,209.3V. The equivalent circuit for operation is shown in Figure 14 [Figure 14: see original paper].

Comparison between simulated and estimated phase current results is presented in Table 8 . The magnetic field energy is 49,123.2 J, which basically matches the previous current source excitation results.

5.3 Simulation Condition 3: HV-MV Operation, HV Winding Minimum Tap

5.3.1 No-Load Simulation The MV winding of Main Limb II is excited with a voltage source: V1 = × ÷2 = 163,299.3V. The TV winding and BV winding are connected in reverse series (or the TV winding direction is reversed) and then paralleled with the EV winding. The equivalent circuit for operation is shown in Figure 15 [Figure 15: see original paper].

Comparison between simulated and estimated phase voltage results is presented in Table 9 .

Magnetic field simulation of the core is shown in Figures 16 [Figure 16: see original paper] and 17 [Figure 17: see original paper].

Comparison between simulated and estimated magnetic flux density results in the main limbs is presented in Table 10 .

5.3.2 Short-Circuit Simulation The MV winding of Main Limb II is short-circuited, and the HV winding is excited with a current source: I1 = 962.3× 2 = 1,360.9A. The TV winding and BV winding are connected in reverse series (or the TV winding direction is reversed) and then paralleled with the EV winding. The equivalent circuit for operation is shown in Figure 18 [Figure 18: see original paper].

Comparison between simulated and estimated phase current results is presented in Table 11 .

The magnetic field energy is calculated as: WS = 47,971.8 J
Equivalent inductance: LK = 2WS/I^2_min = 127.9 mH
Short-circuit reactance: XK = 2 f LK = 40.2 Ω
Impedance voltage: UK% = I_minXK/U_min×100% = 12.06%

Based on the calculated impedance voltage value, the MV winding of Main Limb II is short-circuited and excited with a voltage source: V1 = ! 2 × 12.06%÷2 = 22,155.6V. The equivalent circuit for operation is shown in Figure 19 [Figure 19: see original paper].

Comparison between simulated and estimated phase current results is presented in Table 12 . The magnetic field energy is 48,001 J, which basically matches the previous current source excitation results.

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6 Scheme Comparison

A simple comparison between the single-core scheme with double main limbs and the dual-core scheme with two single main limbs is presented in Table 13 .

The comparison reveals that the single-core scheme saves approximately 500,000 yuan in primary material costs alone compared to the dual-core scheme. Additionally, the single-core scheme reduces no-load losses by 12.7 kW and transport weight by 20.6 tons. Since the single-core scheme simplifies the product’ s lead structure compared to the dual-core scheme, manufacturing is easier and safety reliability is improved.

7 Conclusion

Through magnetic field simulation calculations under the three operating conditions, the feasibility of the auto-transformer with common core for constant flux and variable flux has been verified. The simulation results for main core flux distribution, winding voltages under no-load conditions, and winding currents and short-circuit impedance under short-circuit conditions basically coincide with estimated results. Using existing double-limb three-frame cores and test windings from other product types in the factory, combined into a similar structure for experimental verification, also matches the simulation calculations. Therefore, the scheme adopting this structure is completely feasible.

The comparison shows that the single-core scheme saves approximately 21% in primary material costs alone compared to the dual-core scheme, reduces no-load losses by about 22%, and decreases transport weight by approximately 14%. From a manufacturing perspective, the single-core scheme has a relatively simple structure that facilitates production. From an operational perspective, the simplified structure provides enhanced safety reliability. In summary, the scheme employing the common core for constant flux and variable flux offers optimal technical and economic performance.

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Note: Figure translations are in progress. See original paper for figures.