Magnetic Flux and Core Loss Finite Element Analysis of Electrical Steels Combinations in Lamination Core Steps of Single-Phase Distribution Transformers

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Abstract—This paper presents a finite element (FE) analysis of combinations of electrical steels in the lamination core steps of a real 6.3 MVA single-phase distribution transformer. The magnetic core of this transformer has a cruciform cross-section with lamination core steps. Two electrical steels are combined in the lamination core steps of transformer: a convectional grain oriented electrical steel (M-5) and laser-scribed electrical steel (23ZDKH90). 3-D FE simulations are performed to calculate the core losses (no-load losses) without and with combinations of electrical steels. B-H curves and iron loss curves of electrical steels are taken into account in the numerical simulations. The core loss calculated in FE simulation without combination of steels is compared with the core loss measured in no-load laboratory tests. Results obtained in this paper show that the combination of electrical steels in the lamination core steps can reduce 5% the core losses in single-phase distribution transformers with stacked magnetic cores.

Keywords—core loss; distribution transformer; electrical steel; no-load loss; finite element; lamination core step

I. INTRODUCTION

The combinations of electrical steels in magnetic cores of transformers are employed by manufacturers to reduce losses, temperature, and costs [1]-[16]. Actually in USA, Mexico, Greece, Germany, Italy, Japan, and Poland some transformer companies are combining electrical steels and high permeability alloys in magnetic cores of transformers.

Furthermore, in the last twenty years, the combinations of electrical steels and ferromagnetic materials have been studied and applied in instrument, power, and distribution transformers and new core transformer topologies have been proposed to combine electrical steels in distribution and power transformers [1]-[16]. Some authors have analyzed the combination of grain oriented electrical steels (GOESs) in magnetic cores of distribution and power transformers to reduce core losses, temperature, manufacturing costs, and material costs [2]-[4]. Other authors have analyzed combinations of GOESs in magnetic wound cores of distribution transformers to reduce losses [5]-[10]. Other authors have combined GOESs and non-grain oriented electrical steels (NGOESs) in instrument transformers, and other authors have combined GOESs and some high permeability alloys in toroidal magnetic cores for current transformers to reduce material costs and to improve their measurement properties [11]-[15]. Finally, some authors have combined GOESs and amorphous steels in magnetic cores of distribution transformers to reduce losses and material costs [16].

Furthermore, after reviewing the existing literature, the authors note that there is not information related with combinations of GOESs in the lamination core steps of distribution transformers. J.C. Granfield in 1949 proposed to combine GOESs and NGOESs in lamination core steps in stacked magnetic cores of transformers, inductors, and reactors, see Fig. 1 [1]. He proposed to use GOES laminations in the internal core steps and NGOES laminations in the outer core steps to reduce power losses [1]. In this paper the idea of J.C. Granfield is utilized but considering only GOESs with different magnetization and iron loss (W/kg) properties in the core steps of a distribution transformer.

Fig. 1. Granfield’s idea to combine grain oriented steel (hot rolled steel) and non-grain oriented steel (cold rolled steel) in lamination core steps of a magnetic core [1]. Extracted from patent US 2 465 798, 1949.

This paper presents a magnetic flux and core loss numerical analysis of combinations of electrical steels in a magnetic core of a real 6.3 MVA single-phase distribution transformer. The magnetic core of this transformer has a cruciform cross-section. A convectional GOES (M-5) and a laser-scribed electrical steel
(LSES) (23ZDKH90) are combined in the lamination core steps of transformer. 3-D finite element (FE) simulations are performed to compute the core losses and magnetic flux distributions in the transformer magnetic core with and without combinations of electrical steels. Furthermore, the core loss of transformer without combinations of electrical steels is measured in laboratory and compared with FE simulation. With this comparison, authors validate the FE simulations in this paper. The magnetization properties and iron loss properties of electrical steels are taken into account in the nonlinear FE simulations.

II. 3-D FINITE ELEMENT SIMULATIONS

The distribution transformer is modeled in three dimensions (3-D). ANSYS Maxwell software is utilized to compute the losses in the magnetic core with and without combination of electrical steels [17].

A quasi-static magnetic vector potential formulation is utilized to solve 3-D eddy current problems given by:

\[
\nabla \times \left( \frac{1}{\mu} (\nabla \times A) \right) = J_e - j\omega \sigma A
\]

where \( \mu \) is the permeability (H/m), \( A \) is the magnetic vector potential (Wb/m), \( J_e \) is the current density (A/m\(^2\)), \( \omega \) is the angular frequency (rad/s), and \( \sigma \) is the electrical conductivity (S/m). The finite element method (FEM) is utilized to solve equation (1) in the domain of transformer model.

A. Exciting Windings Modeling

For 6.3 MVA single-phase distribution transformer only the low voltage (LV) winding is used to magnetize the core of transformer, the high voltage (HV) winding is omitted in order to provide open circuit test conditions. The exciting winding is made of aluminum with a relative permeability of 1 and an electrical conductivity of \( 3.8 \times 10^7 \) S/m. The excitation winding has 18 turns. The power losses produced in the excitation winding are omitted. Fig. 2 shows the 3-D distribution transformer model and Table 1 shows the technical specifications of distribution transformer.

![Fig. 2. 3-D model of magnetic core of 6.3 MVA distribution transformer.](image)

### Table 1. Technical Characteristics of Distribution Transformer

<table>
<thead>
<tr>
<th>No. phases</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Impedance</td>
<td>7.83%</td>
</tr>
<tr>
<td>Transformer rating</td>
<td>6.3 MVA</td>
</tr>
<tr>
<td>High voltage (HV) winding</td>
<td>10.5 kV</td>
</tr>
<tr>
<td>Low voltage (LV) winding</td>
<td>710 V</td>
</tr>
</tbody>
</table>

B. Magnetic Core Modeling

The original and real magnetic core of the transformer is built using the step-lap overlap technique. In the 3-D FE simulations the ‘45” overlap core joints are not taken into account in this paper. To reduce the computational complexity inter-laminar layers are avoided and only the solid lamination steps are considered in the FE simulations.

The real magnetic core is made of laminations of M-5 electrical steel [18]. This is a conventional GOES utilized in the manufacturing of distribution transformers. The M-5 steel laminations have a thickness of 0.30 mm, a mass density of 7650 kg/m\(^3\), and an electrical conductivity of \( 1.96 \times 10^6 \) S/m. Furthermore, 23ZDKH90 steel is a GOES treated using the laser scribing method [19], [20]. The laser scribing process refines the magnetic domains, increases the magnetic permeability, and reduces the losses in the steel [20]. The 23ZDKH90 steel laminations have a thickness of 0.23 mm, a mass density of 7650 kg/m\(^3\), and an electrical conductivity of \( 2 \times 10^6 \) S/m [19]. In the distribution transformer the electrical steels M-5 and 23ZDKH90 are combined in the twenty lamination core steps of transformer. Fig. 3 shows a view of the lamination core steps of the cruciform cross-section of distribution transformer.

The experimental B-H curve and the specific iron loss curve of M-5 and 23ZDKH90 steel at 50 Hz are used in the FE simulations [18], [19]. These curves are obtained from the steel manufacturers using an Epstein frame. Fig. 4 shows the specific iron loss curves for M-5 and 23ZDKH90 steel at 50 Hz. The magnetic core of distribution transformer is designed to operate at 1.63 T.

C. Core Losses in Distribution Transformer

The core losses in the distribution transformer are computed by ANSYS Maxwell software utilizing a numerical dynamic core loss model (DCLM) [21]. Utilizing this core loss numerical model one avoids the use of very small finite elements in the magnetic core models of transformers or electrical machines [21]. A hysteresis loss coefficient \( (k_h) \) and an eddy current loss coefficient \( (k_e) \) are used to compute the total core losses in magnetic cores of transformers. DCLM uses the magnetic field distributions and the loss coefficients to compute the losses in the core of distribution transformer with and without combinations of steels. DCLM utilizes equivalent elliptical loops to simulate the hysteresis cycles in the core of transformer and electrical machines [21]. Utilizing these hysteresis loops ANSYS Maxwell can calculate the hysteresis losses in the core of distribution transformer [21]. Furthermore, \( k_e \) coefficient is given by [21]:

\[
\text{loss} = k_h B^2 + k_e I^2
\]
\[ k = \frac{\pi^2 \sigma_s d_s^2}{6} \]  

where \( d_s \) is the thickness of electrical steel laminations and \( \sigma_s \) is the electrical conductivity of electrical steel laminations.

The loss coefficients \( k_h \) and \( k_c \) for electrical steels in the magnetic core of the transformer are computed by ANSYS Maxwell software utilizing a regression method, the specific iron loss curves of electrical steels, and properties of electrical steels.

Table II shows the hysteresis and eddy loss coefficients for M-5 and 23ZDKH90 steel at 50 Hz computed by ANSYS Maxwell software.

<table>
<thead>
<tr>
<th>Loss Coefficient</th>
<th>M-5 (50 Hz)</th>
<th>23ZDKH90 (50 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_h )</td>
<td>51.92</td>
<td>43.26</td>
</tr>
<tr>
<td>( k_c )</td>
<td>0.29</td>
<td>0.17</td>
</tr>
</tbody>
</table>

D. Finite Element Mesh of Transformer

A total of 113,000 finite elements are used in the transformer model. Fig. 5 shows the FE mesh of the magnetic core of the distribution transformer.

E. Nonlinear Time-Harmonic Analyses

Nonlinear time-harmonic analyses are carried out to compute the core losses in the transformer core. An exciting current \( I_{ex} = 8.3 \) A at 50 Hz is injected in the LV winding to magnetize the magnetic core. The excitation current of this transformer is measured in laboratory during the no-load test and corresponds to 0.1\% of the nominal current of transformer.

F. Core Losses in Magnetic Core without Combination of Electrical Steels

Fig. 6 shows the magnetic flux density distributions for core of distribution transformer without combinations of electrical steels.

Table III shows the core loss computed and measured for distribution transformer without combinations of electrical steels. A difference of 3.48\% is calculated between the core
loss calculated in FE simulation and the core loss measured in no-load test.

### TABLE III.
CORE LOSS IN MAGNETIC CORE WITHOUT ELECTRICAL STEELS COMBINATIONS IN DISTRIBUTION TRANSFORMER

<table>
<thead>
<tr>
<th>Core Loss (FE analysis)</th>
<th>Core Loss (Measured)</th>
<th>Loss difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total core loss</td>
<td>4.15 kW</td>
<td>4.30 kW</td>
</tr>
</tbody>
</table>

G. Core Losses in Magnetic Core with Combinations of Electrical Steels

The combinations of electrical steels in lamination core steps of distribution transformer are shown in Fig. 7.

The larger volume of steel in the main and central core steps contributes higher amount of losses. Hence, LSES is preferred in the central steps and GOES is applied on the outer steps. Figs. 8 and 9 show the magnetic flux density and core loss distributions in the core steps of the distribution transformer for the different combinations of steels. From these figures one can see that the magnetic flux and core loss distributions change when one increases the amount of LSES in the core steps. The increment of LSES in the inner core steps and the reduction of GOES in the outer steps produce a reluctance change in the magnetic core. One part of the magnetic flux prefers to circulate in the inner core steps where the permeability is high and the losses (W/kg) are smaller and another part of the magnetic flux is forced to circulate in the outer core steps where the permeability is lower and the losses (W/kg) are a little higher. This imbalance of flux and losses produces a reduction of the total core loss in the magnetic core of distribution transformer.

Table IV shows the core losses calculated for the steel combinations in the magnetic core of distribution transformer. This table includes the loss difference between the steel combinations in magnetic core and the magnetic core without steel combinations. The authors calculated the average magnetic flux density ($B_{avg}$) in the cruciform cross-section for each combination of steels. A value $B_{avg} = 1.72$ T is calculated for the steel combinations. Moreover, a maximum flux density of 1.805 T is calculated in the combined core in the core steps with 23ZDKH90 steel.

### TABLE IV.
CORE LOSSES AND LOSS DIFFERENCE OF ELECTRICAL STEEL COMBINATIONS IN DISTRIBUTION TRANSFORMER

<table>
<thead>
<tr>
<th>Steel Combination</th>
<th>Core Loss (kW)</th>
<th>Loss difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>4.10</td>
<td>1.20%</td>
</tr>
<tr>
<td>A2</td>
<td>4.03</td>
<td>2.89%</td>
</tr>
<tr>
<td>A3</td>
<td>3.95</td>
<td>4.82%</td>
</tr>
</tbody>
</table>

Fig. 8. Magnetic flux density distributions in lamination core steps.

Fig. 9. Volumetric core loss distributions (W/m$^3$) in lamination core steps.

### III. CONCLUSIONS

The magnetic field distributions and core losses in a magnetic core of a real single-phase distribution transformer without and with combinations of electrical steels in the
lamination core steps are analyzed utilizing 3-D FE simulations.

Authors concluded that the core losses in a single-phase distribution transformer can be reduced a maximum of 5% combining GOES and LSES in the lamination core steps of transformer. Magnetic saturation problems were not found in the electrical steels combinations in the magnetic core of transformer.

The methodology presented in this paper can be applied to combine electrical steels in power, distribution, and instrument transformers with stacked magnetic cores.

Authors are going to perform laboratory tests of magnetic cores (prototypes) with different electrical steels combinations to measure and to analyze the core loss, temperature, and magnetic flux distributions in transformers.

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REFERENCES