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AC RESISTANCE IN MEDIUM FREQUENCY TRANSFORMERS WITH FOIL WINDINGS: A COMPUTATIONAL STUDY

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Abstract

The challenges and flexibilities of calculating AC foil winding losses using known numerical techniques are addressed. The performance of quick 1D models is compared with the exhaustive 2D and 3D models covering the geometries with increased isolation distances. The dependency of AC resistance on isolation distances and the operating frequency is investigated. In 2D geometries, the magnetic field distribution variation inside and outside the core window is carried out. The viability of using double 2D FEM method as an alternative for 3D FEM is explored for a wide range of geometric specifications. The accuracy of AC resistance calculations is validated experimentally with a laboratory prototype.

1 Introduction

The increased penetration of distributed energy resources in electrical grids and the increased operating power and voltage level of novel semi-conductor devices have lead to a design of Solid State Transformers (SSTs) as a governing technology in Medium Voltage (MV) applications. Medium Frequency Transformers (MFT) are combined with power electronic converters. MFTs are used to achieve voltage level regulation, galvanic isolation, and impedance balance. A higher operating frequency in MFTs causes up to an 80% reduction in volume compared to their low-frequency predecessors [1]. This reduction in size contributes to increased volumetric and gravimetric power density levels. However, increased power density combined with increased frequency-dependent losses brings challenges in the design process of MFTs. The main loss component in most SSTs is caused by MFT, as shown in Fig. 2, since the increased frequency-dependent losses are directly dependent on the conductivity of the MFT winding material. While the frequency-dependent losses are raised, the heat dissipation surfaces are reduced due to the decrease in volume. Consequently, high considerations are required to implement reliable thermal management in the design and modelling steps of MFTs.

In a nutshell, achieving an efficient, optimized, and rigorous SST design lies in the implementation of an accurate estimation of winding losses and managing the heat dissipation brought by these losses in MFTs. Additionally, to limit the induced eddy effect on the windings, the thickness of the conductors are reduced below the skin depth of the winding material. Accordingly, modelling these ultra-thin conductors with the presence of high current concentration on the edges becomes a precision demanding task. While the computation of AC winding losses is challenging due to the geometric aspect ratio of the conductors and highly condensed magnetic field in the winding area of the MFTs, the effort by researchers has been dedicated to achieving both accuracy and computational efficiency.
This paper addresses a broad investigation of the loss estimation methods of foil conductors within MFT windings, focusing on the 1D, 2D, and 3D Finite Element Methods (FEM). These methods are evaluated based on the accuracy versus complexity trade-off. In addition, an alternative for 3D FEM is proposed as the combination of two 2D FEM simulations to achieve accuracy besides lower computations.

2 1D Analytical Approaches

One-dimensional estimation of AC losses inside foil windings of a transformer was implemented first by Dowell in [3]. Later, enormous research was done to examine and improve the reliability of his method [4]–[6]. Dowell's approach starts with the assumption of one-dimensional magnetic field distribution inside the winding window of the transformer, shown in Fig. 3.

![Fig. 3 Illustrative explanation of Dowell's method](image)

This assumption is enabled by approximating the height of the windings, \( h_w \), equal to the height of the winding window and infinite permeable core material. Thus, the 1D Helmholtz equation, \( \partial H_y(x) / \partial x = J_z(x) \), can be solved by implementing Ampere's law to the left and right boundaries of the windings, leading to a close form equation for the AC resistance factor [5].

However, the rise in the voltage ratings of transformers has introduced deviations to this approach. As shown in Fig. 4, clearance distances are included in the geometric limitations of MFT designs. These clearance distances are dependent on the isolation voltage the transformer and the electric field strength of the isolation material surrounding the windings [7]. Additional clearance distances in the winding window cause the two-dimensional distribution of magnetic field. The magnetic flux density distribution in two geometries with and without clearance distances is plotted in Fig. 5. This 2D field distribution causes a concentration of current density on the corners of conductors, identified as the "corner effect." A detailed study on the corner effect in MFTs has been done in [8].

![Fig. 4 MFT structure geometry, a) the cross-section of windings inside the window area, b) the cross-section of windings outside the window area, c) top view](image)

Countless studies have been done to improve the accuracy of the 1D method, either by introducing a geometric-based correction factor to Dowell's equation [8], [9] or implementing a simulation-based empirical model [10]. However, these studies are strongly coupled for limited geometric specifications and the accuracy vary with respect to various isolation requirements.

3 2D Finite Element Approach

The deviation of 2D field distribution from 1D assumptions inside the winding window of MFTs has initiated 2D FEM computations in modeling winding losses. Compared to the 1D analytical approach, this method requires higher computational resources, meshing procedures, and post-processing. Even though this brings complexity to the problem, the high accuracy and the flexibility of FEM in computing the field and current density distribution in arbitrary geometries and the improved access to computational resources make FEM a preferred choice. In medium-frequency applications, precise pre-processing steps are required to achieve a reliable solution. Extra-thin conducting materials...
demand high discretization in the direction of the skin depth. A mesh convergence analysis should be included in the simulations to bring accuracy without having excess discretization to accomplish a well-grounded solution.

In Fig. 6, a comparison of the calculated resistance factor using 1D analytical methods of Dowell [3], modified Dowell [4], Ferreira, and 2D FEM is presented. The solutions with no clearance distances from all methods overlap perfectly. However, results show the deviation of the 1D approaches with the increase of clearance distance D. While this deviation converges to a specific value in each frequency step, it is more significant in higher frequencies. This deviation can be referred to the divergence of the magnetic field distribution with the presence of clearance distances, shown in Fig. 5. The geometric and material property specifications of the studied model are given in Table 1.

![Fig. 6 The resistance factor calculated with the 1D analytical method and 2D FEM for various clearance distances](image)

Table 1 Specifications of the Under Study Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foil Thickness</td>
<td>d_o</td>
<td>0.2 (mm)</td>
</tr>
<tr>
<td>Foil Height</td>
<td>h_o</td>
<td>50 (mm)</td>
</tr>
<tr>
<td>No. of Turns</td>
<td>N1; N2</td>
<td>14:14</td>
</tr>
<tr>
<td>Foil Conductivity</td>
<td>σ_w</td>
<td>5.998 x10^7 (S/m)</td>
</tr>
<tr>
<td>Clearance Distance</td>
<td>D</td>
<td>0 ~ 50 (mm)</td>
</tr>
</tbody>
</table>

4 3D Finite Element Approach

While the implementation of 2D FEM has fixed the deviations due to the clearance distances in the winding window inside the core, it is wise to investigate the 3D distribution of the magnetic field along the windings. As shown in Fig. 4, the MFT windings have a 3D geometry. The majority of the winding length is outside the core window, yielding some deviation in the magnetic field and current density distributions of the windings. In Fig. 7, the numeric difference of the current density distribution in the foil conductors of an MFT winding for surfaces inside the core window and outside the window for different clearance distances is graphed.

![Fig. 7 Discrepancy of the current density in foil conductors between inside and outside of winding window cross-sections,](image)

- a) D = 10 (mm), b) D = 30 (mm), c) D = 50 (mm), f = 20 (kHz), d_o = 0.5 (mm)

It can be remarked that the deviation between two surfaces is dependent directly on the clearance distances. With the increase in clearance distances, the variation has dropped significantly. Thus, the need for a model that considers the 3D field distribution is inevitable to have better accuracy. However, the computational requirements of a 3D FEM model is multiple times higher than a 2D FEM. Applying a reliable mesh to the extra-thin windings with 3D geometry is challenging.

Additionally, establishing the problem formulation and boundary conditions to fulfill the requirements of achieving a consistent solution in 3D are added to the discretization complexity. Consequently, solving such an extended problem with increased number of degrees of freedom is time-consuming and needs high computational capabilities. The size of a system of equations for the geometry in Fig. 7 with 2D and 3D FEM formulations are 3x10^6 and 1.2x10^4 degrees of freedom respectively.

5 Double 2D FEM

To overcome the difficulties and reduce the efforts needed to model the electromagnetic behavior of a magnetic component with a 3D geometry, using so called “Double 2D” FEM (D2D) for two different surfaces of the original geometry inside the window area, shown in Fig. 4 a), and outside the window area,
shown in Fig. 4 b), is recommended in [11] and [12]. The studies detail the procedure of applying the proposed method on low power components. However, a comprehensive comparison is required to investigate the viability and accuracy of this method for different geometries. In the MV application, with the presence of large isolation distances, while the field distribution has a dominant third component, the consideration toward using this method needs to be reformulated. For this reason, a parametric sensitivity analysis has been tackled.

Fig. 8 Resistance factor calculated with 3D FEM and D2D FEM
a) $D = 20$ mm, b) $D = 30$ mm, c) $D = 40$ mm, d) $D = 50$ mm

Fig. 8 illustrates the ac resistance factor, $F_{ac}$, for 3D and 2D FEM inside and outside the winding window. The D2D method uses the length-normalized results of these 2D simulations. As shown, in smaller clearance distances, the discrepancy between 2D and 3D is higher. This can be due to the inhomogeneous current density distribution between the two 2D surfaces along the conductor path. However, this discrepancy mitigates with the increase in the clearance distance.

Fig. 9 carries out this discrepancy for the calculated ac resistance of studied models using 3D and D2D FEM. While the highest difference is around 10% for the isolation distance of 20 mm, the discrepancy reduces to about 7 % with the increase of $D$. Considering the high amount of reduced calculations in D2D compared to 3D FEM; the proposed method can be inferred as an efficient alternative over 3D FEM. As mentioned above, creating a confident 3D model is challenging and the results obtained, especially subject to this high aspect ratios, are very prone to errors. On the other side, the experimental tests are also complex since the active part of the impedance has a very small contribution. The measurement experiments, results and the validation of the 3D model is elaborated in the next section.

Fig. 9 The value and the deviation of ac resistance calculated using D2D method from 3D FEM,
a) $D = 20$ mm, b) $D = 30$ mm, c) $D = 40$ mm, d) $D = 50$ mm

<table>
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<td>14:14</td>
</tr>
<tr>
<td>Foil Conductivity</td>
<td>$\sigma_w$</td>
<td>5.998 x10$^7$ (S/m)</td>
</tr>
<tr>
<td>Core</td>
<td>-</td>
<td>Ferrite U126/91/20</td>
</tr>
<tr>
<td>Primary mould width</td>
<td>-</td>
<td>80 (mm)</td>
</tr>
<tr>
<td>Secondary mould width</td>
<td>-</td>
<td>140 (mm)</td>
</tr>
</tbody>
</table>

Table 2 Specifications of Manufactured Laboratory Prototype
6 Experimental Verification of ac Resistance

To evaluate the validity of calculated ac resistances, a laboratory-scale foil-wound with the specifications given in Table 2 is manufactured.

The ac resistance measurements in medium frequency ranges are challenging due to the low power factor of the system. The accurate phase measurement needs to be done with careful consideration. Using standard measurement devices, a phase compensation should be done using a resonating capacitor to unify the system's power factor on the corresponding measurement frequency. This study implements the measurements using Newton's 4th PPA5500 precision power analyzer.

![Manufactured MFT prototype](image)

Table 3 Calculated and Measured dc Resistances of Primary and Secondary Windings of the Manufactured Prototype

<table>
<thead>
<tr>
<th>Rdc (mΩ)</th>
<th>Calculated</th>
<th>Measured</th>
<th>error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary winding</td>
<td>7.18</td>
<td>7.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Secondary winding</td>
<td>11.34</td>
<td>11.7</td>
<td>3</td>
</tr>
</tbody>
</table>

For the implementation of ac resistance measurements, the winding is short circuited and the secondary winding is excited with a sinusoidal waveform driven by a linear amplifier and a signal generator. The measured and calculated values of ac resistance of the prototype in the frequency range of 5-30 kHz is plotted in Fig. 11. While the comparison between the measured ac resistance and the 3D FEM simulation of windings shows high discrepancy, it is wise to investigate the ohmic loss in the connection foil busbars of the windings. A 3D FEM simulation is implemented to model the busbars connections, as shown in Fig. 13. The results show that the proximity loss on the connection busbars carries a high portion of the total ohmic loss in the windings. This can be interpreted by the magnetic field vectors illustrated in Fig. 12 and 13. The leakage flux in the duct between primary and secondary windings penetrates the connection busbars perpendicularly, causing loops of induced eddy current parallel to the long edge of the foil cross-section. The distribution of induced eddy currents inside busbars is shown in Fig. 13.
With the added busbars to the computations, the measured and simulated total ac resistance values agree with the most significant absolute error of 4% in 20 – 30 kHz.

8 Conclusion

A rigorous analysis of various MFT models for winding losses is presented in this paper. The deviation of 1D Dowell's method from 2D FEM is addressed. Consequently, the 3D magnetic field distribution is investigated for MFTs with large isolation distances using FEM. The 2D magnetic field and current density distribution inside and outside the core window are compared. The 3D finite element method is crucial in the modeling and designing MFTs. 3D FEM can achieve accuracy and flexibility for a wide range of geometries. However, for a 3D geometry, the implementation and process of a FEM simulation is complex and time-consuming.

A double 2D method as an alternative for 3D modeling of MFTs with increased clearance distances has been investigated. It has been shown that the D2D technique can improve the accuracy of computing the winding losses in MFT windings without influencing the complication of the problem, which is dissimilar to 3D. The additional ohmic loss in the connection busbars is modeled, and the accuracy of calculations is evaluated using a laboratory prototype. The connection busbars traversing the leakage flux lines impact the total ohmic loss in the studied MFT in the range of 20%.

5 Acknowledgements

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6 References


