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PEEC Based Fast 3D Litz Wire Model

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***Abstract*—Litz wires, which are utilized to suppress eddy current, often have complex structures. This paper presents a partial element equivalent circuit (PEEC)-based 3D model for Litz wires with round conductor. The model accounts for both transverse and longitudinal magnetic fields. The discretization of the Litz wire is based on cylindrical elements resulting in a reduced number of elements. Cylindrical element analysis is based on a 2D analytical method. The proposed model is compared with 3D FEM, which shows the model has good accuracy and fast computational speed. It is promising to facilitate Litz wires optimization.**

***Index Terms*—Copper losses, eddy current, proximity effect, skin effect.**

I. INTRODUCTION

Copper loss is a major factor that affects the efficiency of magnetic components. Eddy current loss becomes prominent in medium frequency applications. To reduce it, Litz wire is a common choice. Litz wire consists of dozens or hundreds insulated strands, which are twisted together in a complex structure. This reduces the proximity effect losses and ensures a balanced current distribution among the strands.

Accurate loss estimation is crucial for selecting optimal Litz wires. For simplicity, it is common to assume a uniform current in each strand and consider only strand level effect [1]. However, in real Litz wires, perfect twisting may not be achieved, making the bundle-level effects considerable [2]. Generally, numerical methods like 3D FEM are versatile, but the computationally demanding for Litz wires due to their complex structures [3]. To increase the computational speed, various methods have been developed. Homogenisation method [4] extracts effective complex permeability of Litz wire and accelerates FEM by reducing model's degree of freedom. 2.5D approximation [5] are developed to approximate 3D cases by several 2D simulations. PEEC is a promising numerical method, which approximates the field problem with an electrical equivalent circuit [6]. In [6], formulas from [7] are used to reduce discretization effort, which assumes a uniform magnetic field across the cross-section of strands and neglects the impact of eddy current on magnetic field at the same time.

This paper presents a 3D PEEC model for Litz wire with round strands. The proposed model adopts cylindrical elements, the same as [6]. The proposed model considers both longitudinal and transverse magnetic field. The transverse magnetic field is based on 2D analysis [8], which can consider the impact of eddy current. The proposed model provides possibility to analyse Litz wire in more details.

II. THEORY OF THE PROPOSED MODEL

A. Basic Equivalent Circuit

The model is formulated in frequency domain, and the voltage drop $-\nabla\varphi$ on a Litz wire is decided by the electric field E and magnetic vector potential A, as shown in (1). Fig.1 shows the equivalent circuit of a strand. R_{dc} is DC resistance related to the E. R_{eddy}, L_{s} and V_{mutual} are related to the A and represent the eddy current loss, self inductance and induced voltage due to external currents, respectively.

$$-\nabla\varphi = E + j\omega A \tag{1}$$

The primary goal is to analyse strands' interactions and represent these interactions in the impedance matrix Z, which is composed of DC resistance R_{dc}, impedance from transverse field Z_{ts} and longitudinal field Z_{lg}. Two assumptions are made for this analysis. The first one is that the current flows along the paths of strands. Next one is the independence between eddy currents caused by transverse and longitudinal magnetic field.

$$Z = R_{\text{dc}} + Z_{\text{ts}} + Z_{\text{lg}} \tag{2}$$

B. Transverse Magnetic Field

Transverse magnetic field H_{ts} is the main factor causing eddy current in Litz wires. In 2D analysis, for a round conductor the general solution of A is (3), when only consider 1st order harmonic [8]. The coefficient C is the vector potential contributed by other currents, D relates to the current I the conductor carrying, A_1', A_1'', B_1' and B_1'' relate to the 1st order harmonics. The relations between some coefficients are list

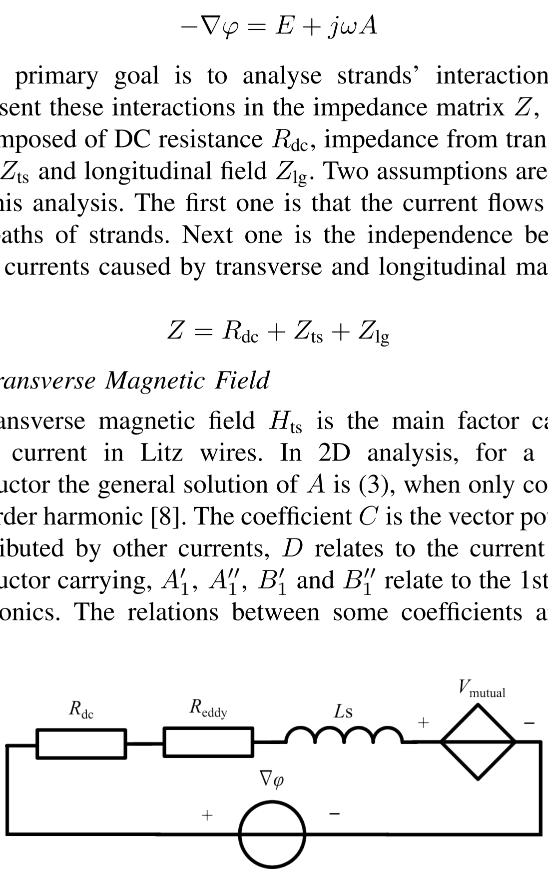

Fig. 1. Equivalent circuit of a strand

in (4), J is the first kind of Bessel function, the subscript is the order, κ relates to skin depth. It is also known that the skin effect is independent from the proximity effect in 2D and only related to radius a. So, the skin effect in Z_{ts} is calculated independently. Then, for the proximity effect, a matrix is constructed based on matching vector potential and field in x and y direction of each element. It is essential to note that conversion from 2D to 3D is done through Biot-Sarvart law. After solving the matrix, the each element's A's composition is obtained. Combining with skin effect part, the Z_{ts} is obtained.

$$\begin{aligned} A(x,y) = C + \frac{D}{2}\ln\left(x^2+y^2\right) + A_1'x + B_1'y \\ + A_1''\frac{x}{x^2+y^2} + B_1''\frac{y}{x^2+y^2} \end{aligned} \tag{3}$$

$$\begin{aligned} D = -\frac{\mu I}{2\pi} \quad A_1''|B_1'' = \frac{a^2 J_2(\kappa a)}{J_0(\kappa a)} A_1'|B_1' \\ \kappa^2 = -j\omega\sigma\mu \end{aligned} \tag{4}$$

If only account for a uniform transverse external field, the portion of the proximity effect can be obtained by (5). H_{ik} and H_{jk} are the transverse field applied on element k from strand i and j, respectively. Element k belongs to strand i. Subsequently an approximate Z_{ts} for low frequencies is obtained.

$$Z_{\text{ts\_p}ij} = -\frac{2\pi\kappa a J_1(\kappa a)}{\sigma J_0(\kappa a)} \sum_k H_{ik} H_{jk} \tag{5}$$

C. Longitudinal Magnetic Field

In general Litz wrie model, longitudinal magnetic field H_{lg} is neglected, because of trivial longitudinal magnetic fields, when the strands have a relatively long pitch. Here, the term associated with the longitudinal magnetic field is added to double-check the assumption. By solving a round conductor subjected to a uniform longitudinal field in 2D, the equation (6) is obtained by integrating the Poynting vector over the perimeter. The real part of S is the loss, and the imaginary part is the reactive power. If H_{lg} is calculated by a unit current, S equals the corresponding portion in the impedance Z_{lg}.

$$S = -\frac{2\pi\kappa a J_1(\kappa a)}{\sigma J_0(\kappa a)} H_{\text{lg}}^2 \tag{6}$$

III. CASE STUDY

In order to validate the model, two configurations were calculated. One configuration comprises of one level bundle with 11 strands, and the other comprises of two level bundles with 3×3 strands. Strand radius is 0.1mm. Pitch is 30mm and 10mm, respectively. Each strand sectioned into 20 pieces per pitch. The computational time is 0.28s for the first case and 0.20s for the second case, which took 34h and 40h in 3D FEM, respectively. The matrix for proximity effect is calculated with iterative method, with the initial point set as the uniform field case.

The results are shown in Fig. 2, and each '+' in the legend represents one iteration. In both cases, results considering uniform field are accurate in low frequency range. The result 'U+' performs better than 'Uniform' and has less relative error around 1MHz. The result 'U++' is also better than 'U+'. After two iterations, the results are closer to FEM result, which shows the matrix capture the impact of eddy current. In both cases, the curves with Z_{lg} does not show considerable difference from 'U++', which proves the impact of longitudinal field is trivial when pitch is long enough.

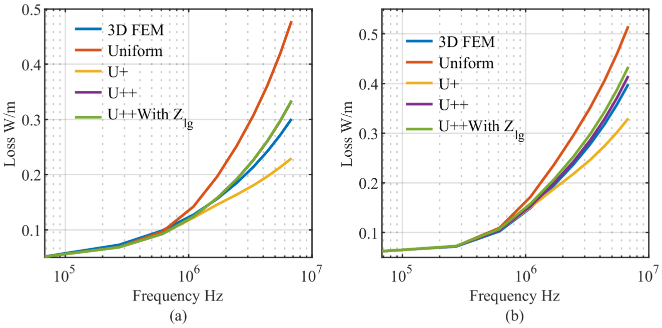

Fig. 2. Loss per unit length with 1A input current. Wire with 11 strands (a), with 3×3 strands (b)

IV. CONCLUSION

A PEEC based 3D Litz wire model is proposed. The proposed method employs cylindrical element and considers the longitudinal field and the impact of eddy current in transverse field. The model ensures accuracy and computational speed.

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