EFFICIENT COMPUTATION OF CIRCULATING CURRENTS IN ELECTRICAL MACHINES BASED ON EXISTING MODELS

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Abstract

In the design of high-speed electrical machines with parallel strand windings, circulating currents must be considered. This paper presents a method that utilizes existing Finite Element Analysis (FEA) models, combined with additional static FEA, to solve the voltage equation. The results show that this approach achieves sufficient accuracy while significantly reducing computation time compared to transient FEA with fully modelled strands.

1 Introduction

In the design process of electrical machines, the importance of AC copper losses has increased, e.g. due to the trend for high-speed machines but also for machines with high power density. For windings with parallel strands, it is essential to consider the circulating current losses caused by unevenly distributed currents. Meanwhile, it is common to calculate these circulating currents with FEA [1], analytically [2] or in a combination of both [3]. The main challenge in the methods is finding a balance between precision and computational efficiency. Typically, these computation methods have a closed workflow. The approach presented in this paper utilizes existing simulation models and results. This approach contributes to computational efficiency in calculating circulating currents and the sustainable use of data. In addition, the proposed method is applicable to both concentrated and distributed windings.

2 Given Toolchain

The goal is to implement the computation of the circulating currents into a given toolchain. The toolchain is based on the FEA-Software *FEMAG, Python* and other script languages. It is highly automated and customized for the motor design of fan and compressor applications. As usual, in the first step the parametrized model is built. Then standard quasi-static no-load and load calculations are conducted, and windings are modelled as a coarsely meshed surface without detailed strands (Fig. 1). The post-processing or additional FEA depends on the optimization target variable, e.g. efficiency.

This paper examines the test case of an inner rotor synchronous machine with surface magnets (PMSM) and distributed windings. However, the presented method is also suitable for outer rotor PMSMs with concentrated windings.

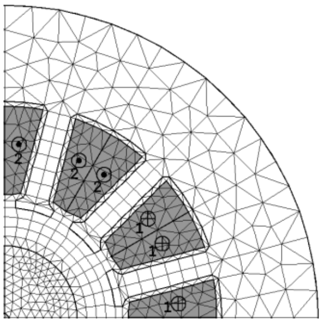

Fig. 1: Partial view of the standard mesh for the inner rotor motor example. The winding areas (Phase 1 and Phase 2) are highlighted in grey.

3 Circulating Current Computation

To simplify and enhance computational efficiency, circulating currents for a single slot are considered. Furthermore, the method has the following assumptions:

- 3D effects are neglected but could be considered as parameters in further work.
- Material properties are linear, no saturation, which is acceptable for high-speed machines.
- Skin and proximity effect are ignored as strands are thinner than skin depth.
- Vector potential is approximately constant over the strand area (based on the point-strand method in [1]).

The voltage equation (1) for one slot with N strands can be written in frequency domain:

$$\vec{U} = R\vec{I} + j\omega L\vec{I} + j\omega\vec{\Psi}_{PM} \qquad (1)$$

where $\vec{U}$ are the voltages, $\vec{I}$ the strand currents, R is the N×N resistances matrix, L the N×N inductances matrix and $\vec{\Psi}_{PM}$ the flux linkage from the permanent magnets. R has already been calculated under DC conditions using the given toolchain. The strand positions significantly affect both the inductance matrix L and the flux linkage Ψ_{PM}. For distributed windings, the random strand positions can be modelled using either a simple but computationally expensive place and check algorithm or a physical model. Refining these is beyond the scope of this digest. Once the strand positions are determined,

$\vec{\Psi}_{PM}$ can be calculated by interpolating the vector potential from the no-load results, comparable to [3]. For a semi-closed slot, $\vec{\Psi}_{PM}$ can be neglected as it is nearly constant for all strands, effectively cancelling out. If not, the imprecision due to small numbers must be considered. This also applies to the flux linked with the other phases if they are not in the regarded slot.

To determine the single strands self- and mutual inductances, the existing mesh and model data are used. The mesh is modified by inserting a node at each of the previously calculated strand positions and re-meshing the coil area (Fig. 2). Using the resulting mesh, further FEA is performed with the *Python* package *scikit-fem* [4]. The magnetization and the currents in the other phases are turned off. For 1…k…N strands, N static analyses are carried out with k-th strand current $I_{N=k} \neq 0$ and $I_{N \neq k}=0$. The self- and mutual inductances are calculated with the resulting vector potential A_i at the i-th strand and length l for each strand with equation (2).

$$L_{k,i} = \frac{A_i l}{I_k}, \;\; k,i = 1 \ldots N \qquad (2)$$

The initial circuit configuration is set with the positioning algorithm. Yet, it can be altered through permutation. With equation (1) and the Kirchhoff´s law the circulating currents are calculated by solving the resulting system of equations. The system for two parallel paths A and B is shown in equation (3), where $Z_{A,B}$ are the summarised frequency depended impedances, v is the voltage induced by time-variation of $\vec{\Psi}_{PM}$ and I_{in} is the total current. For every new path another equation must be added.

$$\begin{bmatrix} Z_A & Z_B \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} i_A \\ i_B \end{bmatrix} = \begin{bmatrix} v \\ I_{in} \end{bmatrix} \qquad (3)$$

By applying the principle of permutation, additional FEA can be avoided. Depending on the geometry and filling factor, a combination of new positions and permutations should be considered.

4 Results

Table 1 contains the resulting strand currents for an inner rotor machine with two parallel strands, a total current I_{in} = 30 A and the frequency f = 3000 Hz. The frequency corresponds to the fundamental frequency of a

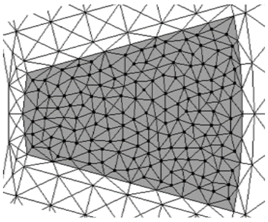

Fig. 2: Re-meshed winding area (highlighted in grey) for the distributed winding with N=140 strands

	Amplitude	Phase
Transient FEA with eddy currents	I_A = 12.19 A I_B = 19.92 A	φ_A = -26.96° φ_B = 16.11°
Presented method	I_A = 11.95 A I_B = 19.84 A	φ_A = -25.07° φ_B = 14.79°

Table 1: Comparison of amplitude and phase from FEA and the presented method at f = 3000 Hz, $\vec{\Psi}_{PM}$ neglected.

high-speed drive with distributed windings (one pole pair) at a speed of 180 krpm. The presented method is compared to a transient FEA which is performed in JMAG. In the FEA the single strands are modelled with their real geometry and eddy currents are considered.

The relative deviations are below 10% for the phases and below 5% for the amplitudes. Further 2D FEA in JMAG indicate that the deviation is due to the assumption of a constant vector potential over the strand area, not the neglect of eddy currents. In practise, the actual current waveform must be considered. This involves decomposing the signal using Fourier transformation and solving the system of equations (3) for each harmonic. It is crucial that the method remains effective at higher frequencies. The amplitude error stays around 5% at 10 kHz, while the phase error increases to about 20%, likely due to the assumption of a constant vector potential. For the full model considering $\vec{\Psi}_{PM}$ the computation time for the FEA (5000 steps) is 460 s, while the presented method (considering $\vec{\Psi}_{PM}$) takes 4 s. Both calculations were performed on the same system with an Intel Xeon Gold 6248R CPU (4 processors) and 32 GB RAM.

Conclusion

The method proposed in this digest allows the calculation of circulating currents in a given toolchain for different topologies. Due to its assumptions, it is computationally efficient with sufficient accuracy compared to the transient FEA with detailed modelled strands.

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