

A Framework to Model Skewing of Synchronous Machine for Digital Twin Applications

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This paper presents a novel framework for modeling rotor skewing in synchronous machines, specifically Permanent Magnet Synchronous Motors (PMSM) and Synchronous Reluctance Motors (SYNRM), suitable for digital twin applications. The method employs a multi-slice approach to approximate the 3D skewing phenomenon, iteratively determining the optimal line current and rotor angle for each slice to achieve target voltage and shaft power. A key feature of this framework is its ability to handle the cross-dependencies between rotor angle, line current, voltage, and power through an adaptive step-size optimization algorithm based on Nelder-Mead. This ensures accurate and stable convergence to the desired operating point, enabling precise simulation of skewed rotor performance, particularly the reduction of torque harmonics. The proposed framework facilitates the development of high-fidelity digital twins for synchronous machines, enabling advanced analysis and optimization of their design and operation.

Index Terms— Digital twin, finite element analysis, multi-slice model, optimization, skewing, synchronous machines.

I. INTRODUCTION

SKIEWING is a widely adopted technique in synchronous machine design to mitigate torque ripple and reduce noise and vibration. While effective, it introduces significant complexity into electromagnetic analysis due to its inherent three-dimensional nature. Traditional 3D finite element analysis (FEA) can be computationally prohibitive for routine design and optimization tasks. Multi-slice models offer a promising alternative by decomposing the machine into individual slices, simplifying the analysis. However, challenges remain, including computationally expensive coupling between slices through electrical circuits [1], potential convergence issues, and the accurate determination of operating conditions for each slice. Existing approaches, such as those relying on flux maps, may not be suitable for real-time digital twin applications [2]. Accurate determination of the current vector is crucial for achieving the desired operating point (power and voltage) in skewed machines. Employing a current source model simplifies the analysis by enforcing consistent current distribution across all slices, facilitating the accurate representation of machine behavior under skewed conditions.

This paper introduces a computationally efficient framework to model skewing for digital twin applications, providing a faster alternative to the existing methods. This work builds upon existing techniques for modeling skewing but introduces a novel iterative approach which ensures more precise and stable convergence compared to previous methods.

II. FRAMEWORK FOR MULTI-SLICE SKEWING MODEL

This section outlines the proposed framework for modeling rotor skewing in synchronous machines. The framework employs a multi-slice approach to approximate the 3D skewing phenomenon, dividing the rotor into multiple 2D slices along the axial length. Each slice represents a different angular position determined by the total skew angle. The modeling process comprises three main stages:

- a. A time-stepping 2D finite element analysis (FEA) of the machine with a non-skewed rotor is performed

using a voltage source model. This simulation provides the initial time-varying stator current waveform and rotor angle, which are crucial inputs for the subsequent slice-wise optimization.

- b. This stage forms the core of the framework. Each rotor slice is analyzed using a series of magnetostatic FEA simulations with a current source model. An iterative optimization algorithm, based on the Nelder-Mead method, determines the optimal line current magnitude and the reference rotor angle for the multi-slice model to collectively satisfy the target voltage and shaft power. More details are provided in Section III.
- c. A final time-stepping 2D FEA simulation is performed for each slice using the optimized line current and rotor angle obtained in the previous stage, again employing a current source model. This provides detailed time-series data of the machine's electromagnetic performance under skewed conditions.

III. ROTOR ANGLE AND CURRENT AMPLITUDE SEARCH USING NELDER-MEAD OPTIMISATION

This section details the core optimization process (Section II). The Nelder-Mead simplex method is employed for its robustness in handling non-linear problems and its ability to converge without derivative information. While alternative methods like Particle Swarm Optimization (PSO) were considered, they exhibited significantly slower convergence for this specific problem due to the high sensitivity of the objective function to small variations in both rotor angle and current.

A. Initialisation

For each slice, the initial line current and initial rotor angle is derived from the non-skewed simulation (Section II). The initial rotor angle for each slice is set based on its axial position and the total skew angle, with a 30° electrical angle adjustment for Star or Delta connection, ensuring a progressive angular shift across slices. It is essential to maintain identical winding currents across all slices, reflecting the physical constraint of a shared winding in the actual machine. This is precisely why a

current source model is employed for the slice-wise optimization.

B. Nelder Mead Optimisation with Current Source Model

The Nelder-Mead algorithm iteratively refines the line current magnitude and the reference rotor angle. The reference rotor angle, determined for the first slice, establishes the angular position for all subsequent slices, with their respective rotor angles calculated based on the defined skewing angle and their axial position. The objective is to minimize the error between the averaged slice voltages and shaft powers and their respective target values.

Crucially, the algorithm addresses the inherent cross-dependencies between the variables. Changes in the rotor angle significantly affect both the voltage and the power output. Similarly, modifying the line current impacts not only the power but also the voltage due to changes in the magnetic flux distribution. The Nelder-Mead method, through its simplex-based operations, implicitly manages these interdependencies. It evaluates the objective function (a combination of voltage and power errors) at each vertex of the simplex (representing different combinations of line current and rotor angle for a slice). By iteratively transforming the simplex, the algorithm searches for the optimal combination that minimizes the aggregate error in both voltage and power, effectively navigating the complex interplay between the variables.

C. Convergence

The iterative process continues until either the relative errors for both voltage and power fall below a predefined tolerance or the changes in line current and rotor angle between consecutive iterations become negligibly small. Further details on the intricacies of the optimization strategy, including the adaptive step-size adjustments and convergence criteria, will be elaborated in the full paper. This method ensures that the optimization process effectively navigates the complex interplay between variables to arrive at a solution that accurately reflects the desired performance of the skewed machine.

IV. RESULTS

The multi-slice skewing model was implemented and tested on a variety of PMSM and SYNRM designs. The framework accurately captures the reduction in torque ripple achieved through skewing. Here we apply the presented framework on an example case of a 55kW V-Type PMSM whose nominal voltage and frequency are 370V and 43Hz respectively. The 2D simulations with skewed model use in-house finite element software. The flux density of the 2D model is presented in Fig. 1. The torque of the skewed and unskewed case is presented in the Fig. 2. Furthermore, the average torque for the unskewed case was 1242 Nm, while the average torque in the skewed case was 1238 Nm, resulting in a torque computation error of only 0.4% at the nominal operating point. The average voltage output from the sliced model was 373 V, indicating an error of 0.8% from the expected nominal voltage. These results demonstrate that the proposed framework effectively and

autonomously determines the appropriate operational points for each slice, ensuring accurate averaged power and voltage matching with the expected nominal values. This is achieved without the need for manual trial-and-error procedures, which is crucial for the accurate and fast simulation of multi-slice skewed electrical machines.

V. CONCLUSION

The presented framework provides an efficient and accurate method for modeling rotor skewing in synchronous machines for digital twin applications. The multi-slice approach, combined with the novel iterative algorithm for determining line current and rotor angle, enables the simulation of skewed rotor performance with reduced computational cost.

The adaptive step-size adjustments and cross-dependency handling ensure stable convergence and accurate results. This framework is a valuable tool for the design and optimization of synchronous machines, particularly in the context of digital twins, where real-time performance monitoring and prediction are crucial. Future work will focus on further validating the framework against experimental data and extending its capabilities to include other operational outputs like core losses.

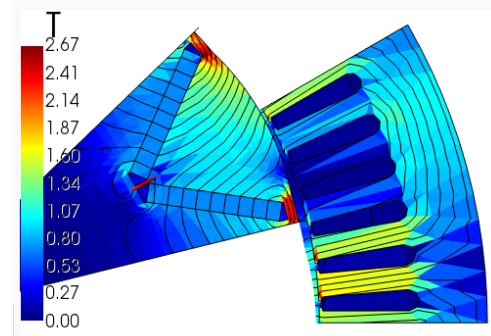


Fig. 1. Magnetization as a function of applied field.

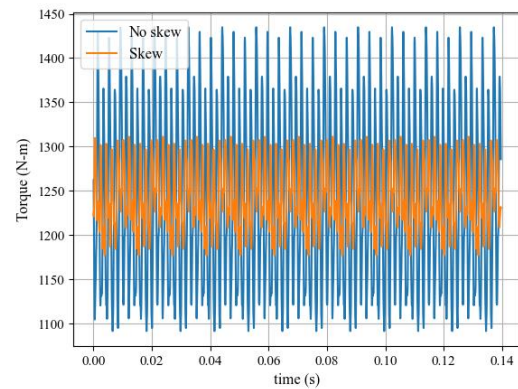


Fig. 2. Torque characteristics comparison of skewed and non-skewed rotor

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