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Refinement of Outer Rotor Permanent Magnet Flux Switching Machine for Downhole Application

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Abstract

Electric machinery in downhole oilfield environments endure severe high-pressure, high-temperature (HPHT) conditions. This study examines a 12-slot/22-pole outer rotor Permanent Magnet Flux Switching Machine (PMFSM) optimized for these applications. JMAG Designer software was employed to model and simulate diverse combinations. A deterministic optimization method was utilized to enhance the design parameters, including rotor geometry, permanent magnet size, and coil turn quantity. The optimized model demonstrated a 102.6% augmentation in torque (from 16.58 Nm to 33.57 Nm), a diminution in cogging torque (from 3.2 Nm to 1.76 Nm), and a 37.3% reduction in magnet weight. These improvements validate the suitability of outer rotor PMFSMs for efficient and reliable downhole operations.

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1. Introduction

Downhole applications in the oil and gas industry operate under extreme conditions of high pressure and high temperature (HPHT), requiring machines that are efficient, reliable, and robust. While induction motors (IMs) are commonly used, they suffer from high starting currents and low partial load efficiency. Permanent Magnet Flux Switching Machines (PMFSMs) offer better torque density and efficiency, but existing designs need refinement for downhole environments. This project focuses on optimizing an outer rotor PMFSM to address these challenges and improve performance.

The current standard for downhole applications, Induction Motors (IMs), faces significant challenges, including high starting currents, low starting torque, and reduced efficiency during partial load operations. These limitations hinder their performance in high-pressure and high-temperature (HPHT) environments. While Permanent Magnet (PM) machines offer superior torque density and efficiency, conventional designs are not suitable for downhole conditions due to high copper losses, excessive magnet usage, and thermal instability. There is a critical need for a more efficient and robust solution to overcome these issues in an extreme operating condition. Therefore, this paper aims to investigate the initial performances of outer rotor PMFSM for downhole applications based on various rotor pole topologies using JMAG Designer version 18.1.01z. Apart from that, this paper also aims to optimize finest topology based on rotor pole combination using deterministic optimization for obtaining optimum torque.

Motors used in downhole applications must withstand extreme heat, pressure, and tight installation spaces. Traditional motors like induction machines often face thermal and efficiency limitations. PMFSMs offer better torque density, reduced component count, and improved cooling due to their stator-based excitation. These advantages make them suitable for oil and gas drilling tools where consistent performance and durability are required. The concept of flux switching arises from changes in rotor position, which cause the armature flux to alternate between high and low states—a principle known as "flux exchanging." Machines based on this principle are called flux switching machines. Although the idea emerged in the 1940s, it gained more attention in the 1950s with early designs such as Laws' relay and was further developed into single-phase generators [1]. The term "flux exchanging" became more common in the late 1990s, coinciding with advancements in power electronics [2]. The use of tools like Computer-Aided Design (CAD) and Finite Element Analysis (FEA) later improved the modeling and optimization of Flux Switching Machines (FSMs), which have since been applied in various fields including home appliances, automotive systems, wind energy, and aerospace.

Although much of the literature focuses on PMFSM modeling and topologies, many studies also explore specific aspects of optimization. Key areas include reducing electromagnetic losses such as eddy current, iron, and proximity losses [3]. Some research considers flux weakening during design, back-EMF waveform optimization in radial and axial machines [4], and improving torque through parameters like split ratio, winding configuration, and slot opening [5]. The impact of individual design factors on torque has also been analyzed [6], though comprehensive optimization across all parameters is limited. Optimization techniques have advanced over the years and are generally categorized into deterministic and heuristic methods [7].

2. Methodology

This section describes the modeling, coil arrangement, and optimization procedures for the proposed outer rotor PMFSM using JMAG-Designer software.

2.1 Modeling Procedure Using JMAG

Fig. 1 illustrates a comprehensive process for designing and simulating an electric machine using JMAG-Designer version 18.1.01z. The flowchart guides readers through a step-by-step workflow, starting with setting design parameters and sketching key components like the stator, rotor, permanent magnets, and armature coil. The process emphasizes iteration, with evaluation points to ensure each design step is successful before moving forward. Once the design sketches are validated, materials, operational conditions, and electrical circuits are defined, followed by mesh setup for numerical simulation. The machine is then simulated, and the results are checked for validity, allowing for further refinement if needed. Table 1 complements this by providing a detailed table of design parameters—including geometric dimensions, winding details, and material weights—that are essential for accurately modeling and simulating the machine's performance. Together, these visuals depict an organized and iterative approach that balances precise design input with simulation feedback to achieve an optimized, validated electric machine design before physical implementation.

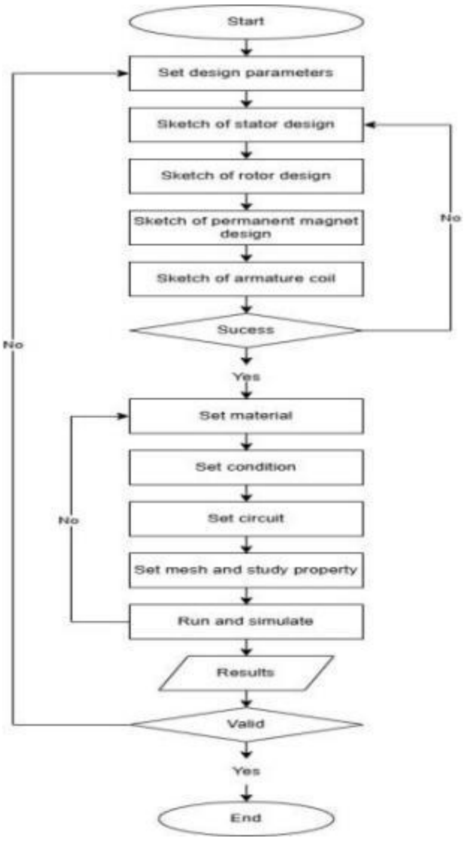


Fig. 1 *Workflow to model and investigate OR-PMFSM*

Table 1 *Modeling parameters of OR-PMFSM*

Items	Unit	Design parameters
Stator pole/slot numbers		12 slots
Rotor pole numbers		22 poles
Rotor inner radius	mm	40.5
Rotor outer radius	mm	40
Stator inner radius	mm	20
Stator outer radius	mm	40
Rotor pole width	mm	3.49
Rotor pole height	mm	5
PM width	mm	3.49
PM radial length	mm	20
Armature slot width	mm	10.41
Armature slot length	mm	17.26
Number of turns	turns	33
Armature slot area	mm^2	50.73
PM weight	kg	1.26
Air gap	mm	0.5

Fig. 2 shows the flowchart for armature coil arrangement analysis. A coil test was conducted under no-load conditions using 2D-FEA to confirm the machine's three-phase operation. Twelve armature coils were arranged such that they produced sinusoidal waveforms with 120° phase shifts. The results confirmed correct phase alignment for U, V, and W, enabling proper electromagnetic operation.

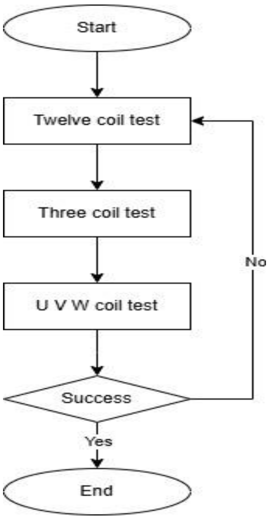


Fig. 2 *Flow chart for armature coil arrangement analysis*

2.2 Approach for Torque Optimization

Torque optimization was performed using a deterministic method and the procedure is shown in Fig. 3. Design parameters including rotor pole dimensions, magnet size, and coil turns were varied while keeping the overall machine size constant. The goal was to maximize average torque and reduce cogging torque.

Deterministic optimization was chosen in this project because it offers a straightforward and systematic approach to improving the machine's performance by adjusting design parameters step by step. Unlike heuristic or hybrid methods, which can be complex, time-consuming, and require extensive computational resources, deterministic methods are easier to implement and provide clear cause-and-effect relationships between design changes and performance outcomes. This makes them especially suitable for undergraduate-level research where the focus is on understanding and refining the design efficiently using available tools like JMAG Designer. Meanwhile, the flowchart for performance examination is shown in Fig. 4.

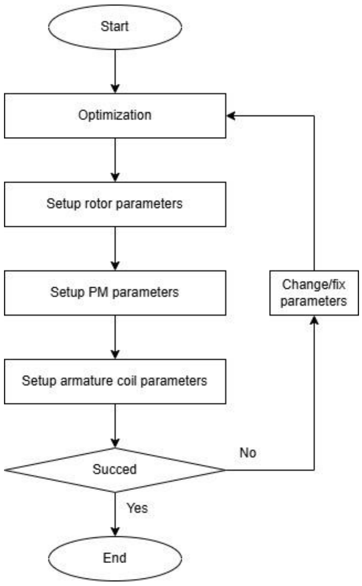


Fig. 3 *Deterministic optimization procedure*

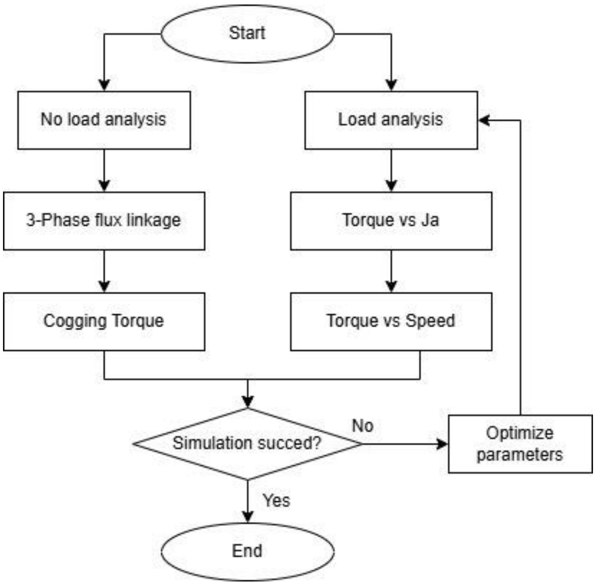


Fig. 4 *Flowchart for Performance Examination*

3. Results And Discussions

Fig. 5 shows the full design of the outer rotor permanent magnet flux switching motor (PMFSM) for downhole applications. Each stator slot contains two iron teeth with a rectangular permanent magnet placed between them, surrounded by armature windings. The stator yoke is segmented to help remove heat efficiently, as the main heat sources are located in the stator. The permanent magnets produce circular magnetic flux with alternating polarity. The rotor uses iron teeth as poles, and the number of rotor teeth equals the number of pole pairs, allowing for more pole pairs and higher torque at low speeds.

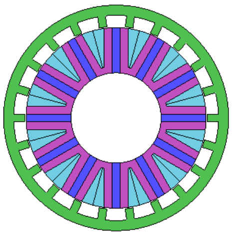


Fig. 5 *Complete schematic of outer rotor PMFSM*

3.1 No Load Test

The 12-slot/14-pole outer rotor PMFSM design shows a high flux linkage of 0.11 Wb, as seen in Fig. 6, indicating strong torque and power potential compared to other configurations. However, this performance is not consistent across all pole combinations. In contrast, cogging torque analysis in Fig. 7 shows that the 12-slot/22-pole design has the lowest cogging torque (3.2 Nm) due to its low highest common factor (HCF) and high least common multiple (LCM), which improve smoothness. Meanwhile, the 12-slot/14-pole setup has the highest cogging torque (8.85 Nm). Both configurations show six cogging cycles.

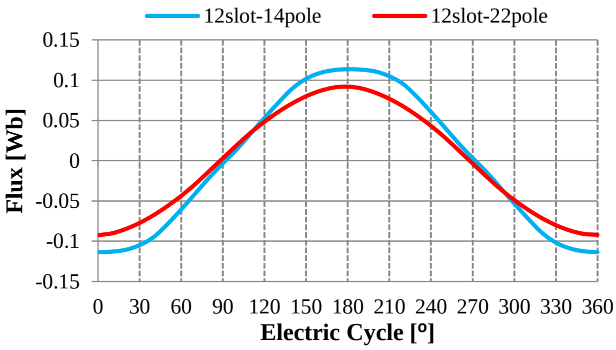


Fig. 6 *U-phase flux linkage*

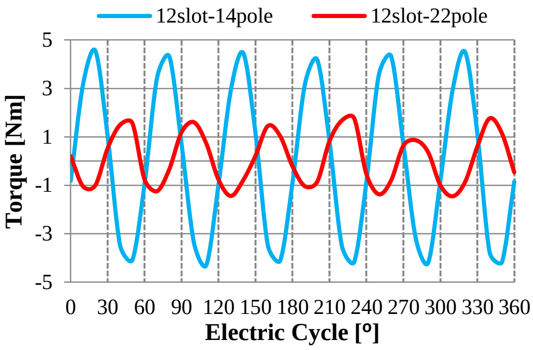
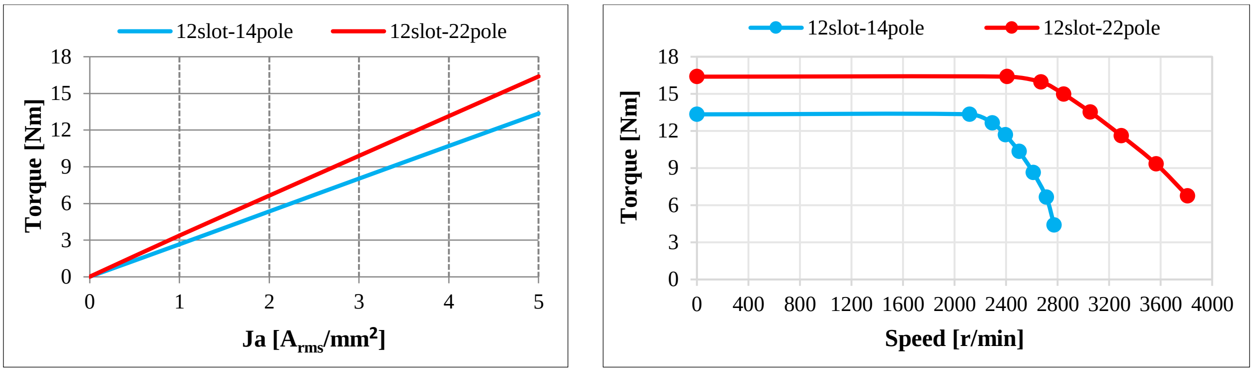


Fig. 7 *Cogging torque analysis*

3.2 Load Test

The performance of the outer rotor PMFSM was analyzed under different rotor pole configurations by varying the armature current density, which was limited to 5 Arms/mm^2 due to high downhole temperatures and lack of cooling. As shown in Fig. 8(a), torque increases linearly with current density, with all configurations reaching peak torque at the maximum current. The 12-slot/22-pole design delivered the highest torque of 16.58 Nm, followed by the 14-pole design at 13.42 Nm. Although both are below the 25 Nm target achieved by inner rotor PMFSMs, optimization could help reach this goal. Torque performance at different speeds, shown in Fig. 8(b), highlights the 22-pole configuration as the best performer, producing 16.39 Nm at its base speed of 2434.45 r/min, while the 14-pole setup peaks at 13.42 Nm at 2126.93 r/min. Beyond these base speeds, torque declines due to increased back-EMF and flux weakening.



(a) **(b)**

Fig. 8 *(a)Torque vs. J_a for outer rotor PMFSM and (b) Torque vs. Speed*

Fig. 9 presents power output trends, where the 22-pole motor again leads, generating 4.18 kW at peak torque before dropping to 2.72 kW at higher speeds from core losses. In comparison, the 14-pole motor peaks at 2.97 kW. Overall, the 22-pole design offers about 35% more power, making it better suited for high-torque, moderate-speed applications like downhole drilling.

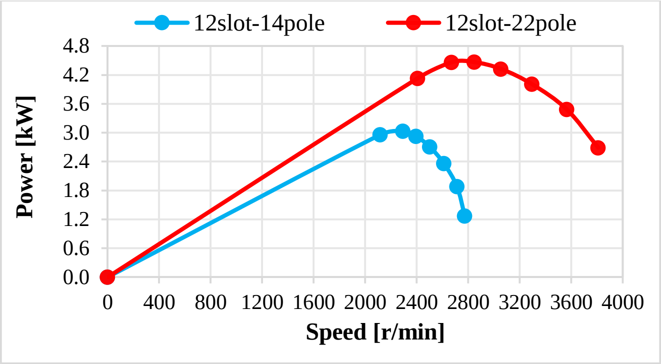
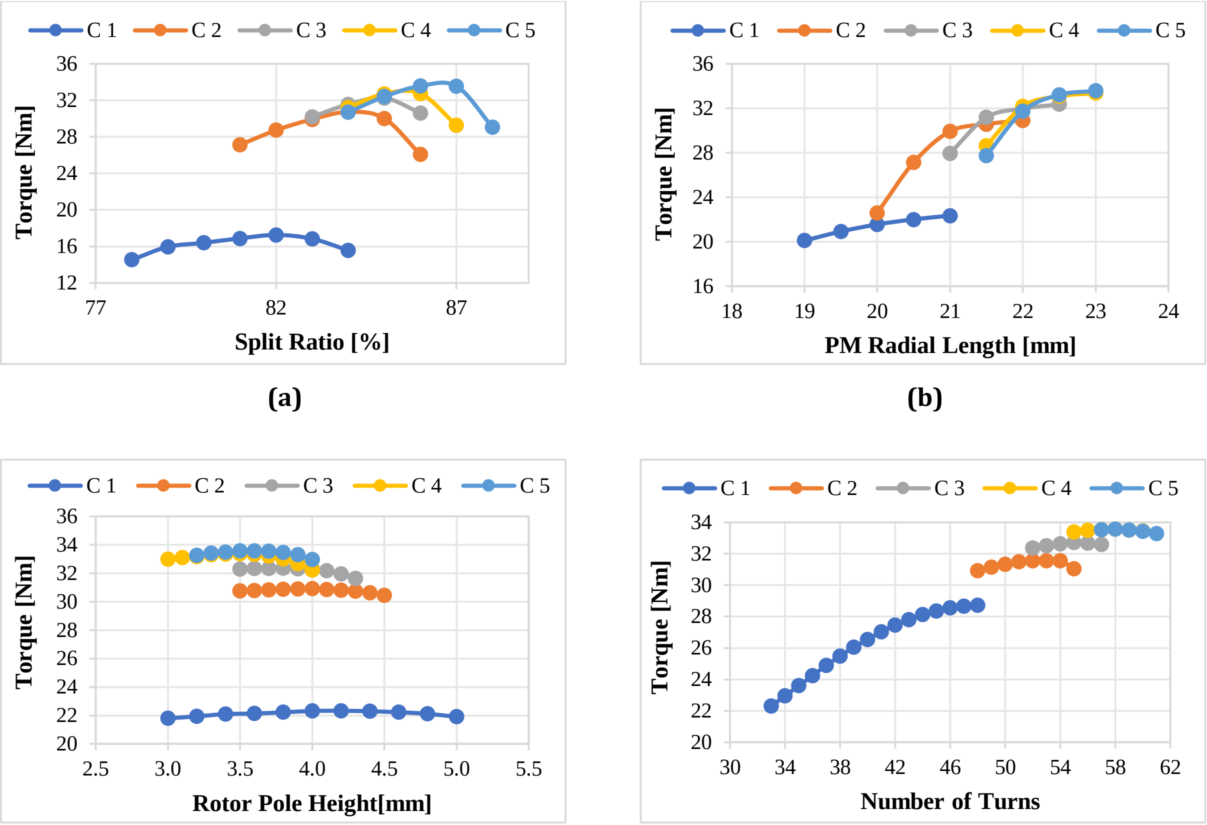


Fig. 9 *Power vs. Speed*

3.3 Optimization Using Deterministic

To enhance torque performance in the outer rotor PMFSM, several key parameters were optimized and the results are shown in Fig. 10. The stator-to-rotor radius ratio increased from 0.8 to 0.86, expanding the slot area and improving torque output. Permanent magnet (PM) dimensions were refined by reducing the width from 3.49 mm to 1.9 mm, cutting weight from 1.26 kg to 0.79 kg and increasing the radial length from 19 mm to 23 mm for better efficiency. Rotor pole width and depth were adjusted from 3.49 mm and 5 mm to 4.4 mm and 3.6 mm, respectively, improving torque and reducing losses. Lastly, increasing the number of coils turns to 58 with optimized slot dimensions (A1 = 13.94 mm, A2 = 21.20 mm) further boosted torque, all achieved through iterative deterministic optimization. Table 2 tabulates the modeling parameters of initial and optimize model used in this work.



(a) **(b)** **(c)** **(d)**

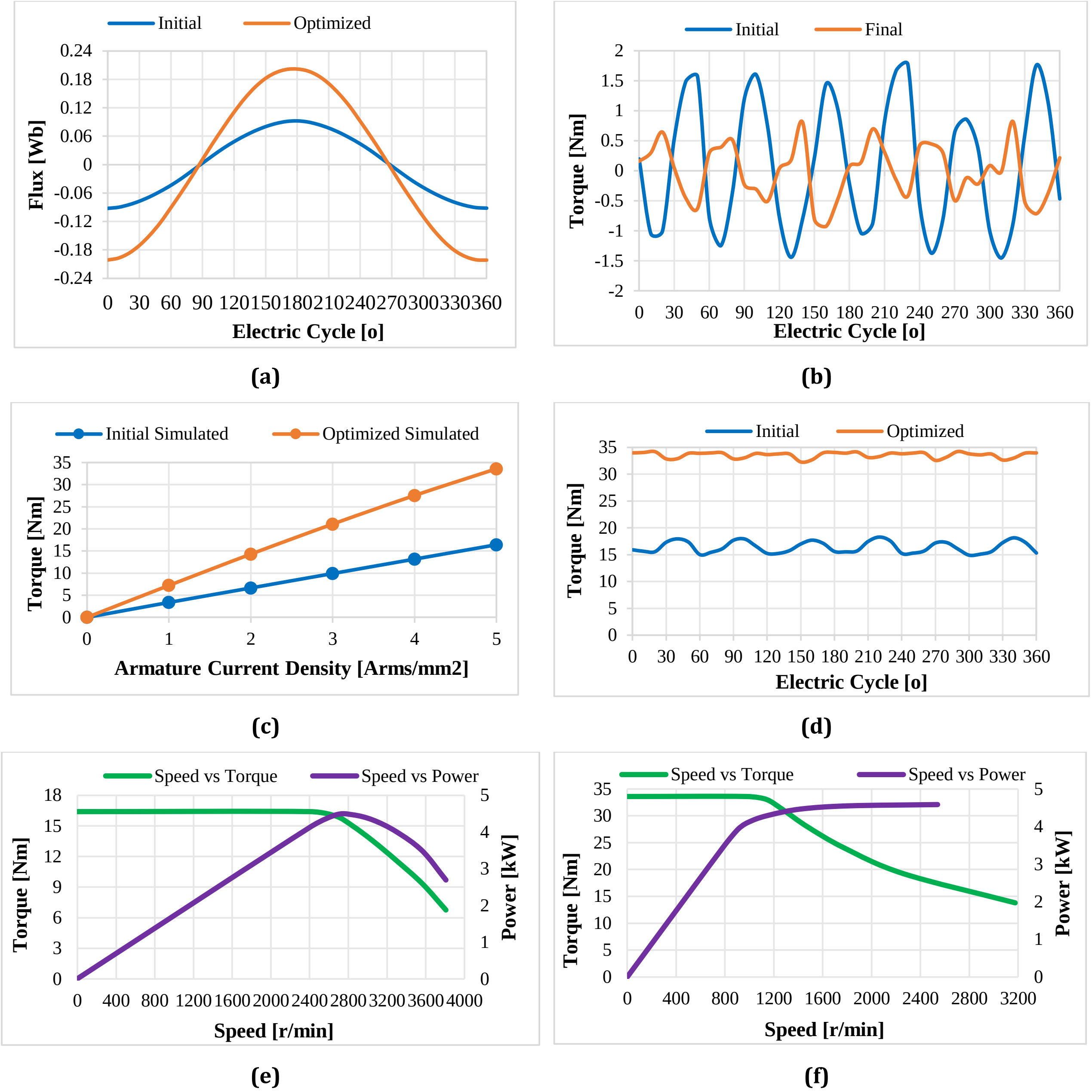
Fig. 10 *(a) Split ratio analysis, (b) Torque vs PM radial length deviation, (c) Torque vs Rotor pole variation and (d) Output torque in relation to the number of rotations*

Table 2 *Modeling parameters of initial and optimize model*

Parameters	Initial	Optimized
Rotor inner radius [mm]	40.5	43.5
Rotor pole width [mm]	3.49	4.4
Rotor pole height [mm]	5	3.5
PM width [mm]	3.49	1.9
PM radial length [mm]	20	23
Armature slot width [mm]	10.41	13.94
Armature slot length	17.26	21.20
Number of turns	33	58
Armature slot area [mm^2]	50.73	89.16
PM weight [kg]	1.26	0.79
Average torque [Nm]	16.58	33.57
Air gap [mm]	0.5	0.5

3.4 Performance Analysis

The performance analysis of optimized 12-slot/22-pole PMFSM illustrated in Fig. 11 shows significant performance improvements. At 1000 r/min with zero armature current, u-phase flux linkage increased to 0.2 Wb, double the original, due to reduced rotor pole height that improved flux concentration and reduced leakage. Cogging torque decreased from 3.2 Nm to 1.76 Nm by lowering PM weight, enhancing stability and reducing vibration. Torque performance improved from 16.58 Nm to 33.95 Nm at 5 Arms/mm^2 by increasing the leakage factor and flux linkage. Although the base speed dropped from 2434.45 rpm to 984.61 rpm, the output power remained strong at 3.88 kW, surpassing the 2.73 kW target. The summarization of performance correlation of initial and optimized model is tabulated in Table 3.



(a) (b)

(c) (d)

(e) (f)

Fig. 11 *(a)U-phase flux linkage of initial and optimized topology, (b) Cogging torque analysis, (c) Torque comparison, (d) Output torque comparison, (e) Initial Torque-power vs speed and (f) Optimize torque-power vs speed.*

Table 3 *Performance correlation of initial and optimized model*

Parameters	Initial	Optimized
Magnetic Flux [Wb]	0.09	0.2
Cogging Torque [Nm]	3.21	1.76
Average Torque [Nm]	16.58	33.95
Speed [r/min]	2126.93	984.61
Power [kW]	4.18	3.88
Torque Density [Nm/kg]	2.11	4.3
Power Density [kW/kg]	0.53	0.43
PM weight [kg]	1.26	0.79

Although the optimization process successfully improved average torque and reduced cogging torque, a slight drop in power density was observed. This reduction is likely due to design changes such as increased rotor pole width and additional coil turns, which may have slightly increased the machine's overall volume. While power density is an important metric, in downhole applications where torque and thermal reliability are more critical, this trade-off is acceptable. Future work could explore balancing torque gains with compactness to maintain or even enhance power density.

The improvements in torque output and reduction in cogging torque directly enhance the performance and reliability of downhole tools, especially in high-pressure, high-temperature (HPHT) environments. Lower cogging torque reduces vibration and noise, which leads to more stable operation and longer lifespan of components. The use of outer rotor design also supports easier cooling and better structural integrity, improving overall tool durability. Additionally, optimized material usage—such as reduced permanent magnet weight—helps lower production costs and simplifies manufacturing, making this design more practical and cost-effective for real-world deployment in the oil and gas industry.

4. Conclusion

This study effectively designed and improved a 12-slot/22-pole outer rotor permanent magnet field synchronous motor for downhole applications. The initial design demonstrated encouraging outcomes but with deterministic optimization, the machine attained markedly enhanced torque production, diminished cogging torque, reduced permanent magnet weight, and improved overall efficiency. The finalized optimized model satisfies the requisite criteria of higher torque, compact measurements and thermal durability, rendering it an acceptable choice for downhole conditions. The improvements prove the effectiveness of deterministic optimization in enhancing the performance, reliability, and manufacturability of the PMFSM.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***designing and planning the study, data collection, analysis and interpretation of the outcomes, and paper writing****: Muhammad Fadhlan Hazim Khairul Fadzilah;* ***manuscript verification:*** *Erwan Sulaiman.* All authors reviewed the results and approved the final version of manuscript.

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