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Optimization of Permanent Magnet Flux Switching Motor Using Sequential Technique

Yahkeish R. Santhiran[1], **Erwan Sulaiman**[1*]

[1] *Department of Electrical Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400, Batu Pahat, Johor, MALAYSIA*

*Corresponding Author: erwan@uthm.edu.my

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Abstract

This study focuses on the optimization of a Permanent Magnet Flux Switching Machine (PMFSM) through a sequential parameter adjustment technique aimed at maximizing torque output. PMFSMs with uneven slot-to-pole ratios typically face the drawback of reduced torque, limiting their suitability for high-performance applications. In this work, an initial baseline design was developed with fixed parameters for the stator, rotor, permanent magnets, and armature coils. The optimization process employed a sequential technique, in which these parameters were systematically modified in six distinct sequences, each involving different adjustment orders of the three core components: stator, rotor, and permanent magnets. For each sequence, the resulting machine performance was evaluated, with particular emphasis on average output torque. Comparative analysis revealed that one sequence yielded a substantial improvement in torque, effectively doubling the value compared to the initial design. The results demonstrate that sequential technique provides a practical and effective approach for enhancing the performance of PMFSMs, offering valuable insights for future design and development of high-efficiency electric machines.

1. Introduction

Currently, the use of permanent magnet flux switching machines (PMFSMs) is widespread across various industries [1]. These applications are extensively researched due to unique flux characteristics, such as axial flux and transverse flux. Furthermore, PMFSMs with segmented permanent magnets in a consequent pole configuration are being explored by industries to achieve maximum power density in their machines. PMFSMs are generally divided into two main types: permanent magnet flux switching motors and permanent magnet flux switching motors. A key advantage of using permanent magnets (PM) in electric synchronous machines is their ability to enhance efficiency and power density [2]. However, the limitation is that the flux generated by permanent magnets is fixed, presenting a significant obstacle for permanent magnet flux switching motor, where flux adjustability is needed.

This limitation can be addressed through hybrid excitation flux switching technology, which combines the benefits of field windings and permanent magnets, allowing flux variation even when using permanent magnets [3]. In this study, the optimization of a permanent magnet flux switching motor using a sequential technique is highlighted. The focus is on designing different current flow sequences to ensure the motor operates at maximum efficiency with minimal power losses. Moreover, the motor is intended to work at a stable frequency and relatively fixed voltage, with adjustable generated flux [4].

Electrical machines are devices capable of converting electrical energy to mechanical energy or vice versa, operating on principles such as electromagnetism and Faraday’s law. These include motors, generators, and transformers, which are integral to modern power systems and industrial applications [5]. Improving energy efficiency in electrical machines is essential for global conservation and green energy initiatives.

Flux Switching Machines (FSMs) have emerged as a high-torque solution featuring a solid rotor structure suitable for high-speed applications. Since their first design in the 1950s, various FSM topologies have been developed for applications ranging from automobiles to home appliances [6]. FSMs are categorized into Permanent Magnet Flux Switching Motors (PMFSM), Field Excitation Flux Switching Motors (FEFSM), and Hybrid Excitation Flux Switching Motors (HEFSM). They offer advantages such as high torque density, high-speed capability, low vibration, and reduced acoustic noise [7].HEFSM combines permanent magnets (PM) with a DC Field Excitation Coil (FEC) to provide flux control and a robust structure for high-speed operation. The polarity of the flux linkage changes with rotor movement, and flux strengthening or weakening can be achieved depending on PM and FEC alignment, allowing for a wide operating speed range [8].

PMFSM, introduced in 1999 [9], simplifies motor design by placing both permanent magnets and armature windings in the stator. This configuration delivers high torque density and eliminates rotor copper losses found in induction machines. Its operation is based on switching the magnetic field orientation through a converter to produce rotor motion. PMFSMs are particularly effective where high torque and compact design are required.
FEFSM, introduced in the 1950s, uses only a DC field excitation coil in the stator, offering a simple, robust design with variable torque capability. Modern three-phase FEFSM designs eliminate permanent magnets, improving cost efficiency and torque density while enabling bidirectional operation [10]. For high torque-to-inertia applications, studies show that certain slot-pole combinations (e.g., 6s/7p) in PMFSMs provide higher torque density but can introduce uneven magnetic forces [11]. Parameter optimization—such as split ratio, stator tooth width, and magnet thickness—significantly impacts torque output, torque ripple, and rotor inertia. Sensitivity analyses reveal that while PMFSM torque density may be slightly lower than PMSM for the same volume, reduced rotor inertia allows for faster acceleration.

With obvious indication of high-power density and efficiency, Permanent Magnet Flux Switching Machine have become a noticeable technology in the electric motor design. These appliances have very disadvantages despite their current popularity. The complexity of its magnetic circuit, flux leakage and flux cancellation can be labelled as the major issues of the PMFSM. Designs with non-integer slot-to-pole ratios, like the 6-slot/7-pole (6s/7p) arrangement, which is especially exposed to an uneven flux distribution. The 6s/7p PMFSM system has a lot of structural problems, even though it has some advantages. Main issue is the slot-to-pole ratio is not an integer; the magnetic circuit has a non-symmetric structure. This causes flux cancellation between poles and a decrease in electromagnetic torque. Harmonic distortions in the magnetic field affect the machines efficiency by increasing core losses both when they are loaded and when they are not. To find out what is causing these performance problems and come up with good ways to fix them By running the simulation of the 6s/7p PMFSM, both no load and load test provide information on the performance of the motor. Analysis on performance such as torque production, efficiency and magnetic flux distribution is assessed in JMAG software. Optimization is done sequentially towards the motor to reduce the flux cancellation, increase flux linkage and improve overall machine performance. This research focuses on developing a PMFSM design which overcomes the issues stated and making 6s/7p configuration viable. Therefore, the main objective of this paper is to design and analyse the 6s/7p configuration using JMAG Designer for open and close circuit performance. Additionally, to optimize the initial design of 6s/7p configuration, sequential technique for maximum output torque and to determine the best sequential technique by comparing the average torque.

2. Methodology

2.1 Design Methodology of the Proposed FSM

Fig. 1 shows the flowchart of this project. The project implementation is being divided into two parts, which are geometry editor and JMAG-Designer. Geometry editor is considered as the first part of the project implementation whereas JMAG designer is the second. For the first part, each component of the motor was designed separately such as rotor, stator, armature coil and permanent magnet. Meanwhile, the condition settings and simulation were done in the second part of the project implementation. For this project, the component designs were done in sequential techniques to determine the best sequence that could provide a maximum amount of average torque comparatively. Fig. 2 illustrates the parts of the PMFSM with its parameters tabulated in Table 1.

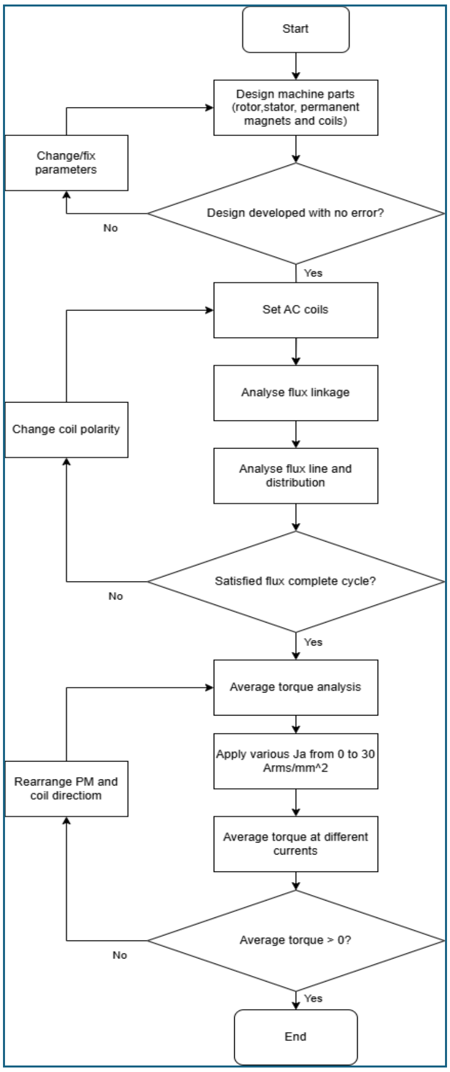
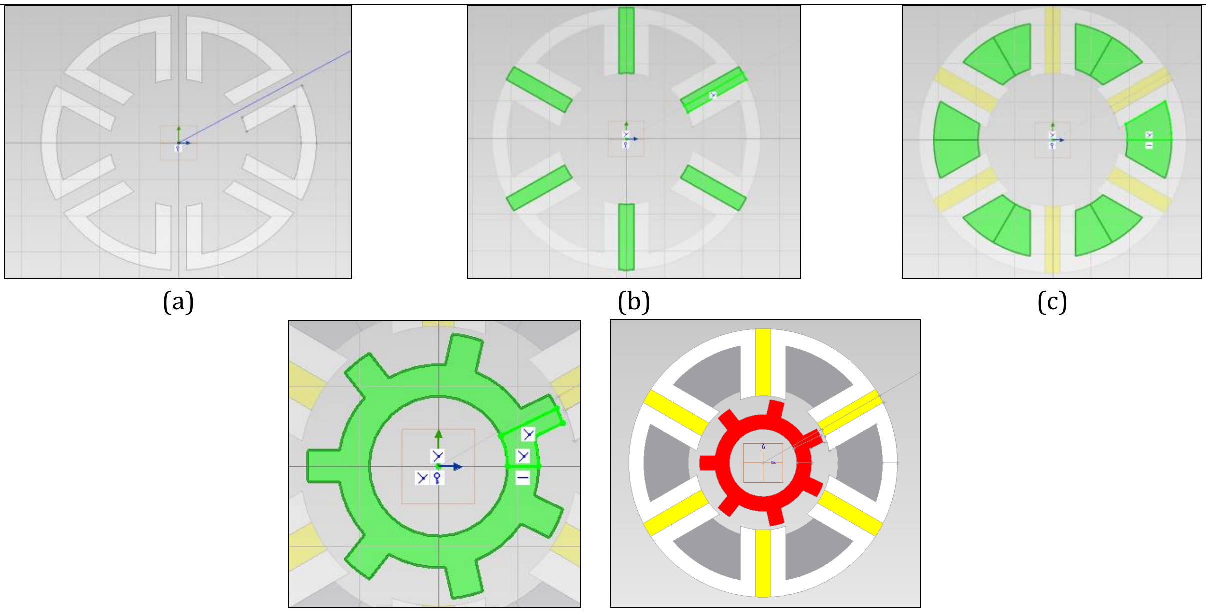


Fig. 1 *Flowchart of Simulation*


(a) (b) (c)

(d) (e)

Fig. 2 (a) *Stator, (b) PM, (c) Armature Coil, (d) Rotor Design and (e) the Final Design*

Table 1 *Parameters of the PMFSM*

Parameter	Value
Stator Outer Radius	35mm
Stator Inner Radius	17.5mm
Permanent magnet width	3.93mm
Distance of air gap	0.90mm
Area of Armature coil	83.88mm^2
Rotor outer radius	15.5mm
Armature coils outer width	10.5mm
Armature coil teeth width	16.6mm
Air gap	8.74mm
Maximum current density A/mm^2	30Arms
Stack Length	80mm
Maximum current	10 Arms

2.2 Sequential Technique Methodology

The sequential technique is an optimization approach in which design parameters are adjusted in a predefined order rather than simultaneously. This method is grounded in the principle that the effect of each design variable on performance can be more clearly isolated when parameters are modified sequentially, allowing the designer to evaluate their individual and combined impacts on the target performance metric—in this case, average torque.

In the context of the Permanent Magnet Flux Switching Machine (PMFSM), the three primary components influencing torque output are the stator, rotor, and permanent magnets. Each of these components possesses multiple geometric parameters (e.g., pole height, width, radius) that directly affect magnetic flux distribution, air-gap flux density, and electromagnetic torque generation. The sequential technique modifies these parameters one component at a time, fixing the others, to measure their impact before proceeding to the next component in the sequence. Six possible sequences were tested to account for different orders of parameter adjustment:

1. Rotor → Permanent Magnet → Armature
2. Rotor → Armature → Permanent Magnet
3. Armature → Rotor → Permanent Magnet
4. Armature → Permanent Magnet → Rotor
5. Permanent Magnet → Rotor → Armature
6. Permanent Magnet → Armature → Rotor

2.3 Material Condition and Setting

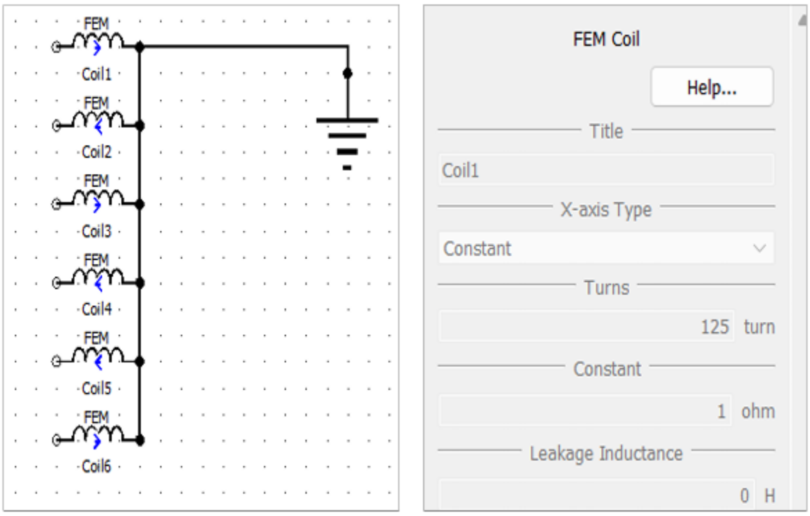
Table 2 shows the material and condition settings for the design of flux switching motor (FSM) according to different parts of it.

Table 2 *Material and Condition Settings for FSM*

Part	Material	Condition
Rotor	Nippon Steel 35H210	Motion: Rotation Torque: Nodal force
Stator	Nippon Steel 35H210	-
Armature Coil	Conductor Copper	FEM coil
Permanent Magnet	Neomax-P8H (irreversible) Magnetization Pattern: Circumferential Anisotropic pattern	-

2.4 Circuit Designing and Setting

According to the number of poles of the FSM, six separated armature coils (AC) are grouped to form a circuit as shown in Fig. 3.

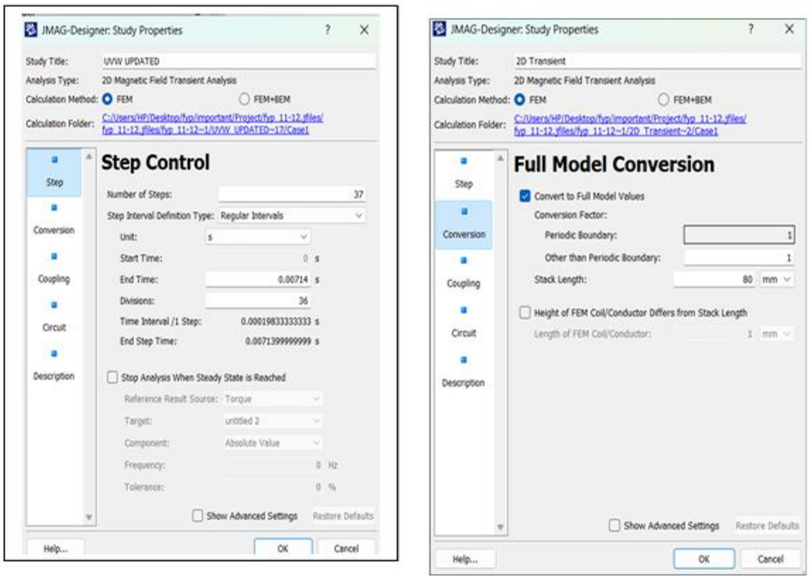


Title: Coil1
X-axis Type: Constant
Turns: 125 turn
Constant: 1 ohm
Leakage Inductance: 0 H

Fig. 3 *Armature coil circuit configuration with the initial number of turns*

2.5 Mesh and Properties Setting

All the motor components were added to the mesh setting and set to sliding mesh. Fig. 4 shows the study of properties of the flux switching motor (FSM) using two different settings: (a) Step control setting and (b) Full model conversion setting. The step control setting is done for the study properties of the motor using step-by-step approach, while the full model conversion setting allows for the study of the motor properties using a more comprehensive and detailed model.



Study Title: UVW UPDATED
Analysis Type: 2D Magnetic Field Transient Analysis
Calculation Method: ● FEM ○ FEM+BEM
Calculation Folder: C:/Users/HP/Desktop/fyp/important/Project/fyp_11-12.jfiles/fyp_11-12.jfiles/fyp_11-12~1/UVW_UPDATED~17/Case1

Step Control
Number of Steps: 37
Step Interval Definition Type: Regular Intervals
Unit: s
Start Time: 0 s
End Time: 0.00714 s
Divisions: 36
Time Interval /1 Step: 0.000198333333333 s
End Step Time: 0.00713999999999 s
☐ Stop Analysis When Steady State is Reached
Reference Result Source: Torque
Target: untitled 2
Component: Absolute Value
Frequency: 0 Hz
Tolerance: 0 %
☐ Show Advanced Settings

Study Title: 2D Transient
Analysis Type: 2D Magnetic Field Transient Analysis
Calculation Method: ● FEM ○ FEM+BEM
Calculation Folder: C:/Users/HP/Desktop/fyp/important/Project/fyp_11-12.jfiles/fyp_11-12.jfiles/fyp_11-12~1/2D_Transient~2/Case1

Full Model Conversion
☑ Convert to Full Model Values
Conversion Factor:
Periodic Boundary: 1
Other than Periodic Boundary: 1
Stack Length: 80 mm
☐ Height of FEM Coil/Conductor Differs from Stack Length
Length of FEM Coil/Conductor: 1 mm
☐ Show Advanced Settings

Fig. 4 *Study Properties*

3. Result and Discussion

3.1 Analysis of the Sequence

The initial PMFSM was optimized according to the sequential technique for all those six sequences. The chosen parameter for each part of the motor is based on the maximum average torque value that could be obtained from the design. Table 3 until Table 8 shows the chosen parameters for each part of the FSM with the average torque obtained from sequence one, two, three, four, five and six respectively.

Table 3 *Chosen parameter and average torque for sequence one*

Parameter	Value (mm)	Average Torque (Nm)
PM length and Width	11.27.5.94	2.41
AC Width	11.82	2.41
AC Length	11.56	2.41
Rotor radius	18.6	2.41
Rotor width	5.94	2.41
Rotor pole height	5.94	2.41

Table 4 *Chosen parameter and average torque for sequence two*

Parameter	Value (mm)	Average Torque (Nm)
PM length and Width	7.22,9.27	2.67
Rotor radius	18.6	2.67
Rotor width	4.94	2.67
Rotor pole height	4.94	2.73
Rotor pole height	11.82	2.73
PM length and Width	10.56	2.73

Table 5 *Chosen parameter and average torque for sequence three*

Parameter	Value (mm)	Average Torque (Nm)
AC Width	11.82	2.03
AC Length	11.56	2.19
Rotor radius	17.6	2.19
Rotor Width	6.94	2.19
Rotor pole height	4.94	2.19
PM length and Width	9.48,7.06	2.19

Table 6 *Chosen parameter and average torque for sequence four*

Parameter	Value (mm)	Average Torque (Nm)
AC Width	11.82	2.22
AC Length	12.56	2.22
PM length and Width	9.66,6.94	2.22
Rotor radius	17.6	2.22
Rotor width	4.94	2.22
Rotor pole height	4.94	2.22

Table 7 *Chosen parameter and average torque for sequence five*

Parameter	Value (mm)	Average Torque (Nm)
Rotor radius	18.6	2.43
Rotor width	5.94	2.58
Rotor pole height	4.94	2.58
PM Length and Width	11.04,6.06	2.58
AC Width	10.82	2.58
AC Length	9.56	2.58

Table 8 *Chosen parameter and average torque for sequence six*

Parameter	Value (mm)	Average Torque (Nm)
Rotor radius	18.6	2.13
Rotor width	4.94	2.29
Rotor pole height	5.94	2.33
AC Width	9.82	2.33
AC Length	10.56	2.33
PM Length and Width	11.04,6.06	2.33

3.2 Overall Discussion

Fig. 9 shows the increment of the average torque from sequence one to six according to the flow of optimization determined earlier. The sequential optimization was conducted for two cycles in all six sequences to make sure saturated value can be achieved. Abbreviations such as ACl, ACw, Rr, Rph, Rw and PMlw stand for AC length, AC width, rotor radius, rotor pole height, rotor width and PM length and width.

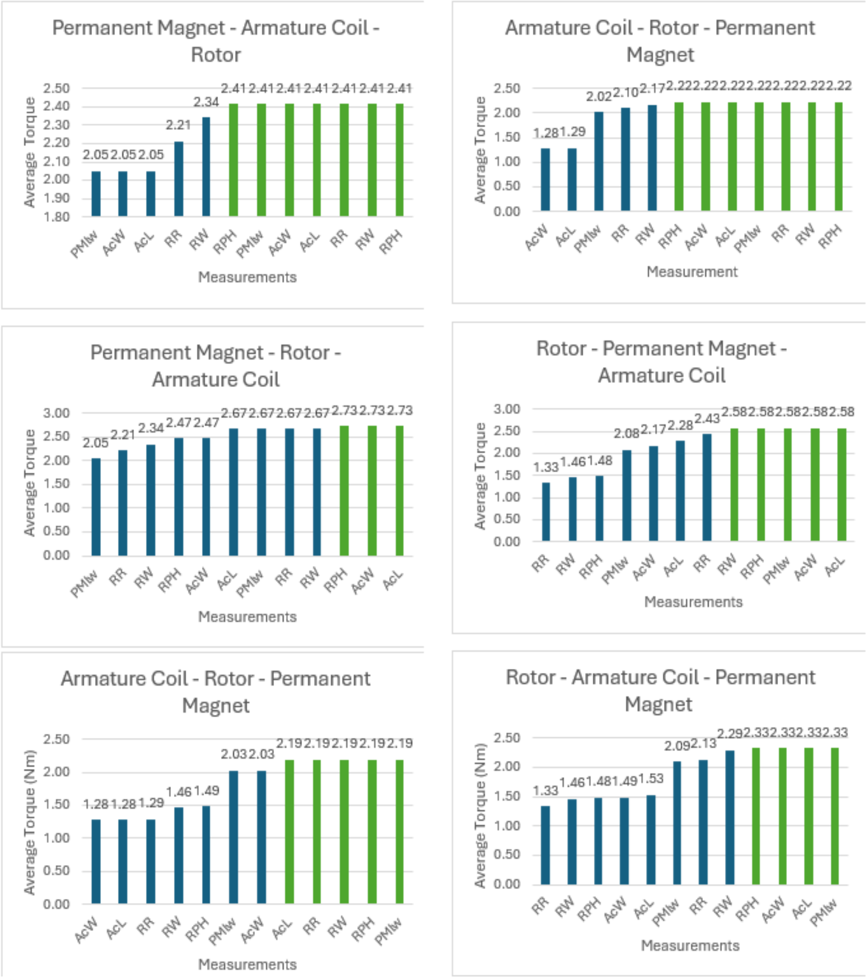


Fig. 9 *Increment of the 6 Sequences*

The sequence starts off with permanent magnet > rotor > armature coil has managed to record the highest value of average torque which peaks at 2.73 Nm which is doubled the average torque during the initial parameters of the PMFSM. From the result obtained, the relationship between the sequence conducted and the value can be clearly observed, and it has a significant effect on the torque. To provide reason on why the second sequence can produce the highest amount of torque (Permanent Magnet – Rotor – Armature Coil), initially when the optimization started off with optimizing the permanent magnet, this allows early control of the flux density B early. If magnets are weak, wrongly shaped or even short, it might cause the magnetic field to be insufficient regardless of how the rotor or armature is. Once the flux source is optimized, adjusting the parameters of rotors significantly controls the magnetic field is shaped and distributed in the air gap. Theoretically, larger radius means a larger area moment of arm for the magnetic force which increases the torque. Lastly, after having a strong field and well-shaped rotor flux path, the armature is tuned 65 to ensure maximum interaction between magnetic flux and current. This is the clear reason why this sequence managed to generate the most amount of torque compared to the other existing sequence.

4. Conclusion

In conclusion, optimization proves that the sequences certainly affect the average torture produced. The study also helps us understand whether the (6s/7p) Permanent Magnet Flux Switching Machine (PMFSM) is viable for any high torque appliances. Regardless, based on the simulation that has been compiled, we understand that the average torque certainly increases but the uneven slot to pole ratio causes flux cancellation to occur which has been a major drawback to the motor The analysis of the 6-slot/7-pole (6s/7p) Permanent Magnet Flux Switching Machine (PMFSM) has yielded important information about how well it performs both with and without load. I was able to evaluate important characteristics including torque output, magnetic flux distribution, and overall efficiency through thorough simulations and assessments. The results have emphasized the 6s/7p configuration's advantages and disadvantages, especially about its vulnerability to flux cancellation and harmonic distortions, which can have a major effect on efficiency. The foundation for future research and development targeted at improving the motor's performance will be this knowledge.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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