EVOLUTION IN ELECTRICAL AND ELECTRONIC ENGINEERING
e-ISSN: 2756-8458

EEEE

Vol. 5 No. 2 (2024) 350-358
https://publisher.uthm.edu.my/periodicals/index.php/eeee

Study of PMFSM with Direct Drive Employing Two Counter Segmental and Salient Rotor for Wind Turbine

Muhammad Ezzat Syahmie Mohammad Fauzi[1], Mahyuzie Jenal[1*]

[1] *Department of Electrical Engineering, Faculty of Electrical and Electronic Engineering, University Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*

*Corresponding Author: mahyuzie@uthm.edu.my
DOI: https://doi.org/10.30880/eeee.2024.05.02.042

Article Info

Received: 8 July 2024
Accepted: 30 September 2024
Available online: 30 October 2024

Keywords

Flux Switching Machine (FSM), Flux Switch Machines (PMFSM), Field Excitation Flux Switches (FEFSM), Hybrid Excitation Flux Switches (HEFSM).

Abstract

A wind turbine designed for harnessing electrical power from wind energy features a turbine rotor positioned for rotation in the wind and multiple blades converting wind force into rotational energy. The Flux Switching Machine (FSM), an innovative category of electric motors developed by previous researchers, has gained prominence in electrical AC motor applications. In the realm of wind turbines, employing a counter-rotating configuration with two rotor sets enhances power density twofold. The three types of FSMs include Permanent Magnetic Flux Switch Machines (PMFSM), Field Excitation Flux Switches (FEFSM), and Hybrid Excitation Flux Switches (HEFSM). PMFSM stands out for its affordability, primary outcome focus, and FEC-free winding with minimal copper losses, making it suitable for diverse performance requirements. This analysis delves into the design and investigation of a dual rotor PMFSM for a counter-rotating wind turbine. From a design perspective, the study explores various configurations of Permanent Magnet Flux Switching Machines (PMFSM), with a particular emphasis on PMFSM featuring segmented permanent magnets and a corresponding pole configuration. Additionally, PMFSM is examined with different inner and outer rotor positions, employing a dual rotor configuration with varied stator configurations to attain optimal torque, power, and speed levels for the motor. The dual rotor structure has emerged as a focal point in electrical machine research, promising improved output torque and power. conclusion, the findings from these investigations will be summarized at the conclusion of this chapter, providing a comprehensive overview of the research outcomes and their implications.

1. Introduction

A wind turbine is a device that transforms wind kinetic energy into mechanical power, which may be used for a variety of purposes, the most common of which is to generate electricity. Wind turbines are a renewable energy source that is both sustainable and ecologically good. The small-scale wind power generating has a low environmental effect and inexpensive development costs [1]. Mostly, wind turbines require a minimum wind speed of 4 m/s to generate electricity, wind energy has yet to be adequately captured in Malaysia, where the average annual wind speed is less than 2 m/s. A Permanent Magnet Flux Switching Machine (PMFSM) concept widely use in wide turbine. A PMFSM is a sophisticated form of electric motor or generator that is utilized in a variety of applications. It combines the concepts of permanent magnet machines with flux switching machines to produce high efficiency, high torque, and low cogging, making it suited for a wide range of industrial and automotive applications. The power can be increased by alternatively examined stator constructions and positions of dual rotor (inner rotor and outer rotor).

1.1 Problem Statement

When converting electricity, typical wind turbine configurations use just a portion of the available wind energy. According to Betz's theory, the greatest amount of wind energy that may be gathered is around 59 percent if the velocity difference across the rotor is two-thirds. However, the point after a single rotor is not insignificant. Installing a second rotor in the wake can extract more energy. Because the wake behind the first rotor rotates in the opposite direction as the rotor, the second rotor must rotate in the same direction as the route to capture the most energy from the wake [2].As a result, PMFSM increases overall output power to solve the PMFSM problem, with an emphasis on power distribution between the inner and outer rotors. This project offers to optimize and change the design by using a dual rotor for a counter-rotating wind turbine and recommending the optimal inner and outer rotor combination. It is vital to note that the contributions of the inner and outer rotor PMFSMs are referred to as the "internal port" and "external port," respectively [1].

2. Literature Review

2.1 Flux Switching Machine (FSM)

An electric machine known as a flux switching machine (FSM) uses the principle of flux switching to regulate the magnetic flux routes inside the device. Generators and motors can both use flux-switching devices. The flux switching machine was originally officially disclosed in 1997 (Hoang et al., 1997) as a three-phase alternator, gaining various benefits over traditional permanent magnet (PM) machines. The flux switching machine was first introduced as a single-phase alternator using permanent magnets by Rauch and Johnson in 1955. Flux switching machines (FSM) are well known with a single and simple rotor configuration yet high performance for high-speed applications. The Flux Switching Machine design provides efficiency benefits, particularly in variable speed applications, and can help to the creation of more modern and adaptable electric machines for a variety of industrial and transportation applications. Flux switching is essential to the functioning and performance of these devices. The FSM is a form of brushless motor that features armature windings and permanent magnets on the stator, as well as a dual salient configuration [1]. Fig. 1 shows the classifications of flux switching machines.

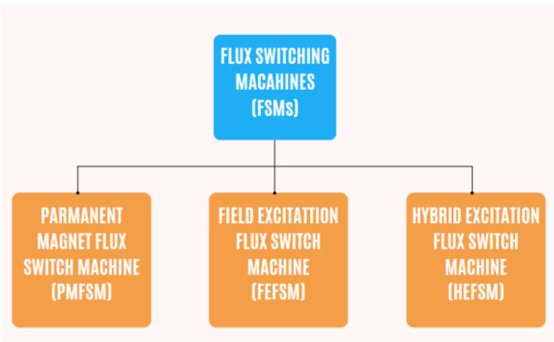


Fig. 1 *Classifications of Flux Switching Machines*

2.2 Permanent Magnet Flux Switching Machine (PMFSM)

The Permanent Magnet Flux Switching Machine (PMFSM) is a cutting-edge breakthrough in electric machine technology that combines the benefits of permanent magnet machines with the distinct capabilities of flux-switching machines. It is a relatively new structure that switches magnetic fields using permanent magnets, with the Finite Element Method used to analyze various design strategies to reduce cogging torque [3]. Because it employs a classic doubly salient construction with a passive and robust rotor, the PMFSM inherits the advantage of the PM brushless machine. PMFSM having a double salient but simple rotor design but a sophisticated stator arrangement structure that is approximately similar to the normal PM brushless motor. Furthermore, PMFSM is well-suited to severe working environments such as wind energy, aerospace, and automotive. However, PMFSM has various flaws, including the fact that it is only concerned with imbalanced pull radial force due to the odd rotor pole number and its speed, which is limited by the time constant. Fig. 2 shows an illustration the example of three-phase 12S-10P PMFSM.

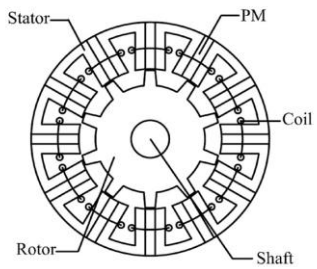


Fig. 2 *Examples of 12S-10P PMFSM*

2.3 Switching Voltage Regulator

Switching As the name implies, a counter-rotating wind turbine PMFSM is a wind turbine with two rotors spinning in opposite directions, each fitted with a permanent magnet flux switching machine (PMFSM) for power generation. Counter-rotating wind turbines, either alternate-row or dual-rotor, are more efficient than single-rotor wind turbines in terms of power generation, producing 1.4% more power and 22.6% more power than the control case. Dual rotor wind turbines, also known as direct dual rotor direct drive co-rotating wind turbines, are a new technology in the second class of intrinsic drive wind turbines that circle in the same direction (co-rotating). PMFSM is used in this configuration with a dual-rotor design, with the front turbine attached to one set of rotors and the distinctive side wind turbine coupled to the other. The rotating of twin rotors in the front and back sides of wind turbines increases power density when compared to a single rotor. The sufficient power generated by front and rare side wind turbines is cumulative.

3. Methodology

For an overview of dual-rotor permanent magnet flux switching machine (PMFSM) design, focusing on rotor pole combinations. The primary tool for modelling and configuring permanent magnet setups in this context is JMAG-Designer or JMAG. JMAG, renowned for its ability to support users from initial conceptualization to comprehensive analysis, is utilized for evaluating the performance of electromechanical systems and designs, with an emphasis on user-friendly functionality. The JMAG program is structured into two key segments: Geometry and Designer. JMAG Designer 16.0 is employed for disassembling 2D FEA models, while JMAG-Geometry's editor is utilized for the individual design of each motor component—rotor, stator, armature coil, and permanent magnet. JMAG-Designer precisely defines the material state and arrangement, along with conducting motor simulations for each component.

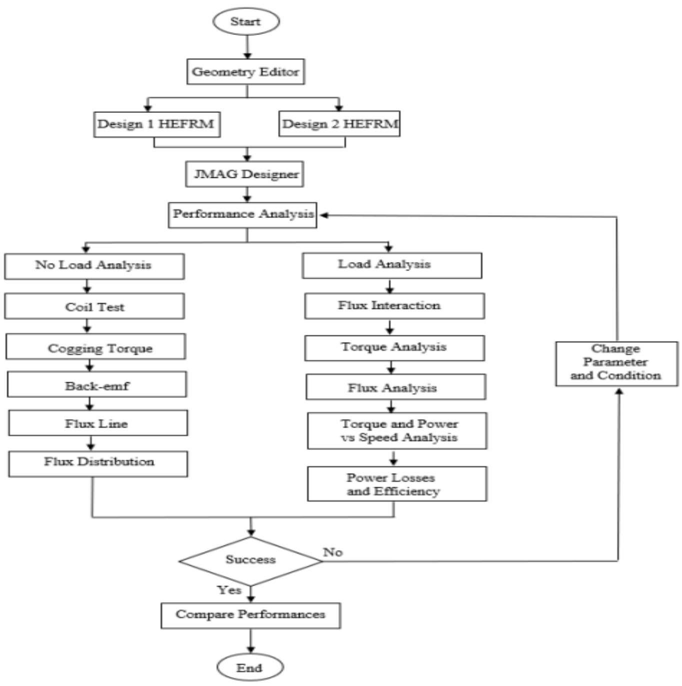


Fig. 3 *Flowchart of Operation of study*

3.1 Design Restriction Specifications

Fig. 3 shows the flowchart of operation of study. Whilst, Table 1 shows dual rotor PMFSM design restriction and specifications.

Table 1 *Dual rotor PMFSM Design Restriction and Specifications*

Parameter (Unit)	Value
Outer rotor outer radius (mm)	132
Outer rotor outer radius (mm)	112
Outer rotor yoke radius (mm)	122
Stator outer radius (mm)	111.5
Stator inner radius (mm)	81.5
Inner rotor outer radius (mm)	81
Inner rotor inner radius (mm)	61
Inner rotor yoke radius (mm)	71
Inner/outer rotor yoke width (mm)	10
Inner/outer rotor pole height (mm)	10
Inner/outer rotor pole width (mm)	10
PM width (mm)	9
PM height (mm)	30
Stator flux bridge width (mm)	5

3.2 JMAG Geometry Editor

During the utilization of JMAG-Designer to formulate configuration and simulation scenarios, the geometry editor serves as the platform for sketching various motor elements such as the rotor, stator, armature coil, and permanent magnet. The primary flow chart of the JMAG-Geometry editor is illustrated in the figure. Upon accessing the geometry editor to design motor components, a toolbar promptly appears. This toolbar encompasses icons for actions like saving, sketch editing, creating circles and lines, sketch trimming, region formation, regional mirror copies, and regional radial patterns. Fig. 4 shows the flowchart of the JMAG geometry editor.

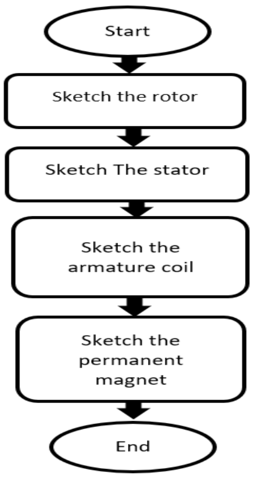


Fig. 4 *Flowchart of the JMAG geometry editor*

3.3 JMAG Designer Setting

The model is arranged in a very critical procedure based on the kind of material used, the condition setting, the FEM coil circuit, the magnetic study, the mesh, the run analysis, and the plot graphs in the JMAG designer. Furthermore, since the simulation results provided are trustworthy and reversible, the JMAG designer saves money and time. Fig. 5 shows General flow chart of the JMAG-Designer Setting.

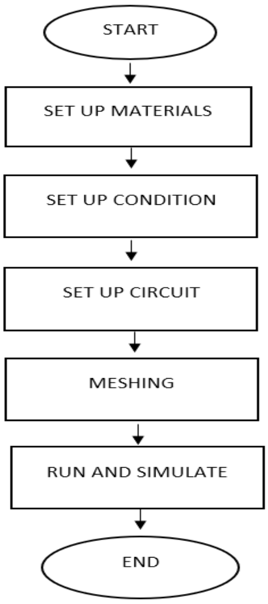


Fig. 5 *General flow chart of the JMAG-Designer Setting*

3.4 Circuit setting

The rotor rotation set and the state of the armature coil are the following steps, with the rotor rotation speed set to 1500 revolutions per minute. In addition, the node's force is applied to the rotation axis in an upward direction. This is used to determine and compute the torque operating on the magnetic substance.

3.5 Investigation of Operating for Dual Rotor PMFSM

The analysis of the coil test was conducted on both the inner and outer rotors under no-load conditions to ascertain the operational principles of the Dual Rotor Permanent Magnet Flux Switching Machine (PMFSM). Fig. 6 shows the flow chart of coil test.

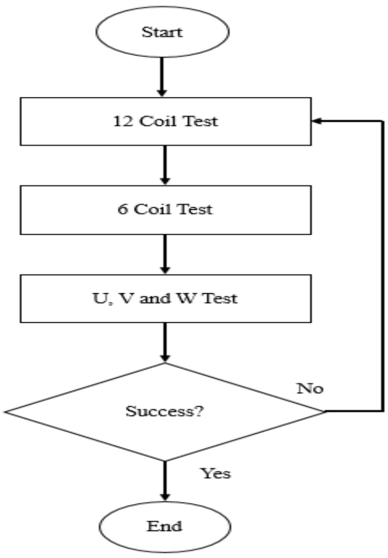


Fig. 6 *Flow chart of coil test*

4. Result and Discussion

This chapter delves into the overall design and investigation of Permanent Magnet Flux Switching Machines (PMFSM). Specifically, the outcomes of the proposed design for the combination of rotor poles in the Dual Rotor PMFSM are presented under no-load conditions. All pertinent parameters, including materials, conditions, and mesh configurations, are precisely defined within the simulation software. The initial step involves a thorough analysis of coil arrangement to scrutinize the operational principles of the three-phase armature coil. Consequently, this section provides a comprehensive discussion and analysis of the design configuration

4.1 Design Configuration

Fig. 7 shows The design of (a) dual rotor PMFSM with double salient pole rotor for counter-rotating wind turbine, (b) dual rotor PMFSM with rotor outer salient pole rotor and inner segmented pole for counter-rotating wind turbine, (c) dual rotor PMFSM with outer segmented rotor and inner salient pole rotor for counter-rotating wind turbine, and (d) Dual Rotor PMFSM with double segmented pole rotor for counter-rotating wind turbine.

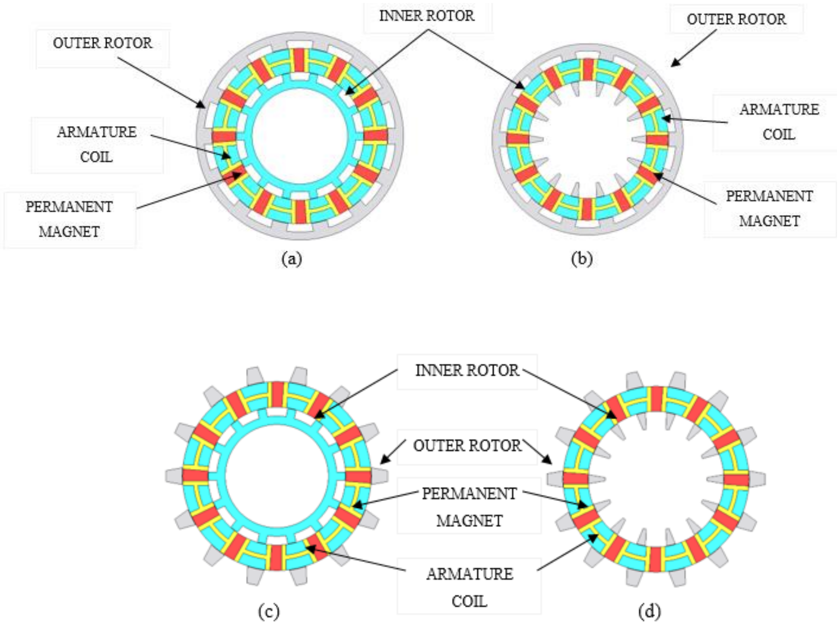


Fig. 7 *The design of (a) Dual Rotor PMFSM With Double Salient Pole Rotor for counter-rotating wind turbine (b) Dual Rotor PMFSM With Rotor Outer Salient Pole Rotor and Inner Segmented Pole for counter-rotating wind turbine (c) Dual Rotor PMFSM With Outer Segmented Rotor and Inner Salient Pole Rotor for counter-rotating wind turbine (d) Dual Rotor PMFSM With Double Segmented Pole Rotor for counter-rotating wind turbine*

4.2 Flux Leakage Test

The correct connection and coil linkage are essential for conducting U, V, and W coil tests. In the initial test, three different arrangements of coils for all design of motor resulted in the grouping of armature coils 3, 6, 7, and 10 as armature coil 1, denoted as U, V consists of armature coils 1, 4, 9, and 12, functioning as armature coil 2. Conversely, armature coils 2, 5, 8, and 11 are combined to form armature coil 3, labeled as W. The flux for the three-phase flux-linkage, designated as U, V, and W,

Fig. 8 shows the flux linkage of dual rotor PMFSM U,V and W of (a) dual rotor PMFSM with double salient pole rotor for counter-rotating wind turbine, (b) Dual Rotor PMFSM with rotor outer salient pole rotor and inner segmented pole for counter-rotating wind turbine, (c) dual rotor PMFSM with outer segmented rotor and inner salient pole rotor for counter-rotating wind turbine, and (d) dual rotor PMFSM with double segmented pole rotor for counter-rotating wind turbine.

4.3 Cogging Torque

The presence of an air gap in the machine can lead to cogging torque. This cogging torque occurrence amplifies the flux connection, resulting in reduced torque for the motor. Motor vibrations are most pronounced when the cogging torque is at its maximum, while the minimum cogging torque signifies an optimal machine state. Fig 9 shows cogging torque comparison result for (a) dual rotor PMFSM with double salient pole rotor for counter-rotating wind turbine, (b) dual rotor PMFSM with rotor outer salient pole rotor and inner segmented pole for counter-rotating wind turbine, (c) dual rotor PMFSM with outer segmented rotor and inner salient pole rotor for counter-rotating wind turbine, and (d) dual rotor PMFSM with double segmented pole rotor for counter-rotating wind turbine.

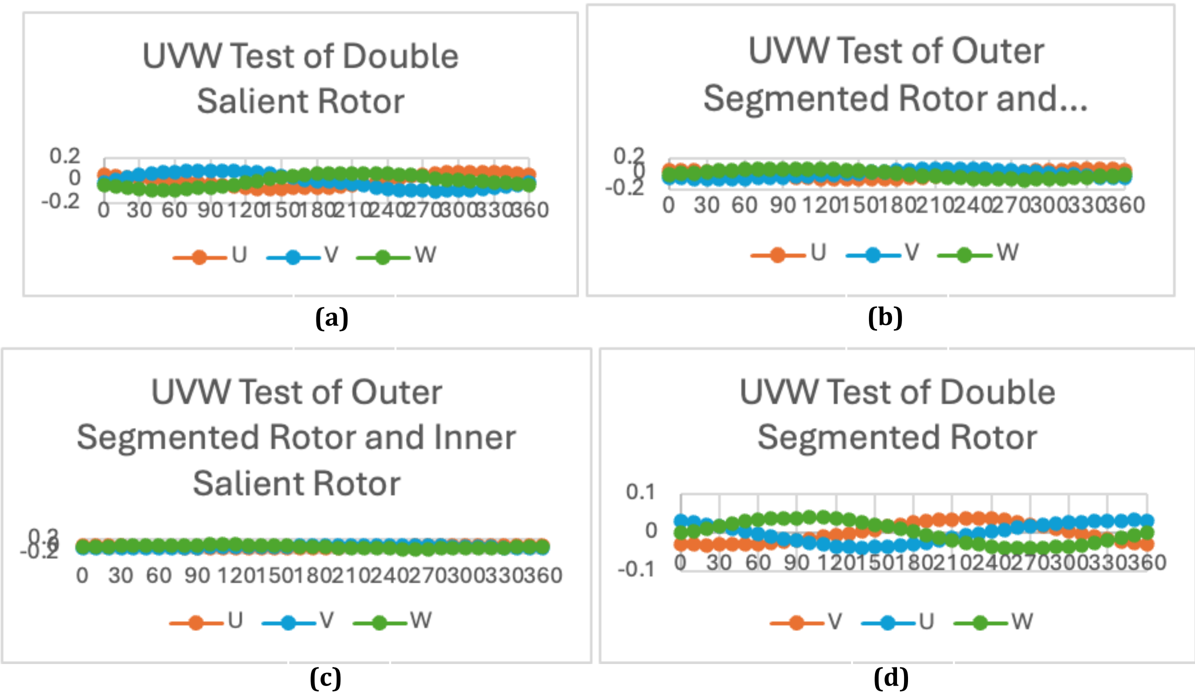


Fig 8 *Flux linkage of Dual Rotor PMFSM U,V and W of (a) Dual Rotor PMFSM With Double Salient Pole Rotor for counter-rotating wind turbine (b) Dual Rotor PMFSM With Rotor Outer Salient Pole Rotor and Inner Segmented Pole for counter-rotating wind turbine (c) Dual Rotor PMFSM With Outer Segmented Rotor and Inner Salient Pole Rotor for counter-rotating wind turbine (d) Dual Rotor PMFSM With Double Segmented Pole Rotor for counter-rotating wind turbine*

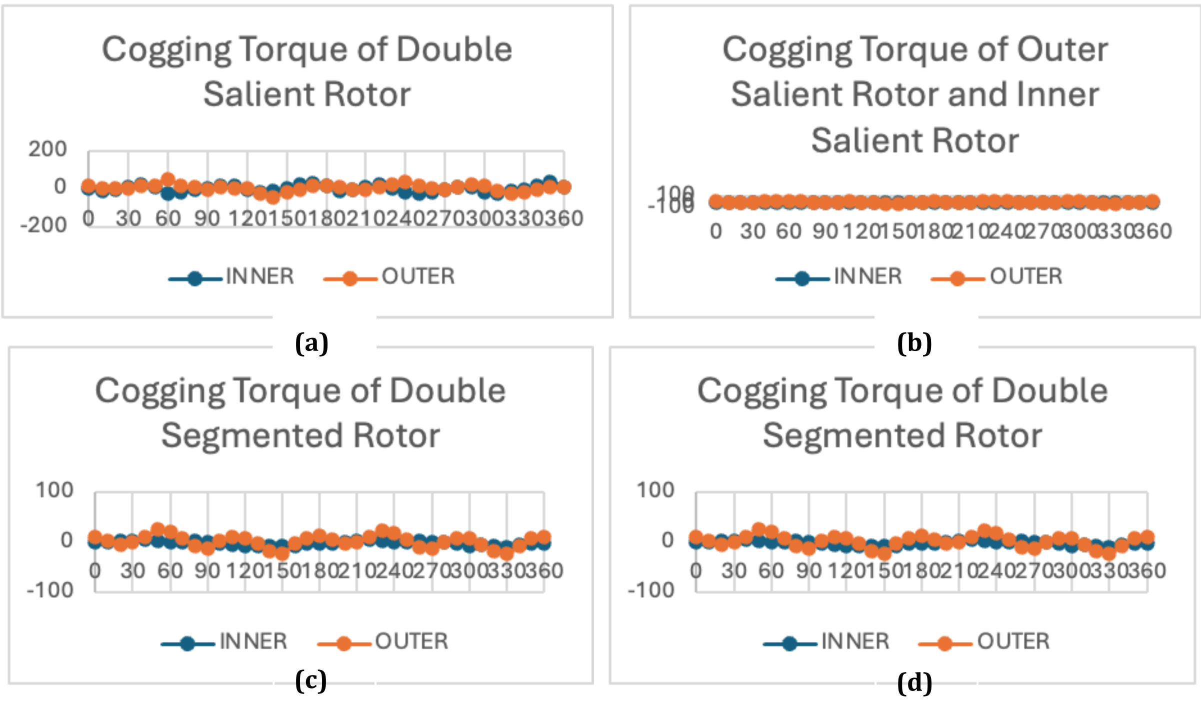


Fig 9 *Cogging Torque Comparison Result for (a) Dual Rotor PMFSM With Double Salient Pole Rotor for counter-rotating wind turbine (b) Dual Rotor PMFSM With Rotor Outer Salient Pole Rotor and Inner Segmented Pole for counter-rotating wind turbine (c) Dual Rotor PMFSM With Outer Segmented Rotor and Inner Salient Pole Rotor for counter-rotating wind turbine (d) Dual Rotor PMFSM With Double Segmented Pole Rotor for counter-rotating wind turbine*

4.4 Load Test

As shown in Table 2 and Table 3, the load analysis is carried out by supplying the current density of the armature coil, Ja. Torque and flux relationships are studied at different Ja regions to determine the pattern of torque variation when different current levels are supplied into the motor's FEM coil. During the load test, the armature current density varies from 0 to 30 (A/mm2).

Table 2 *12S-14P Double Rotor PMFSM Input current of armature coil (Outer)*

Armature coil current density, JA (A/mm2)	Input current of armature coil, IA (A)	Input current of armature coil, Arms (A)
0	0	0
5	20.86471	29.50715
10	41.72942	15.7626
15	62.59413	88.52146
20	83.45883	118.0286
25	104.3235	147.5358
30	125.1883	177.0429

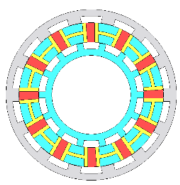
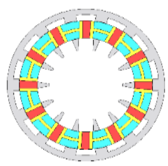
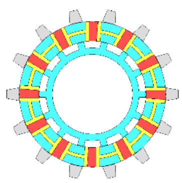
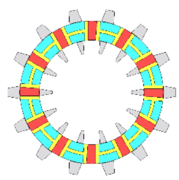
Table 3 *12S-14P Double Rotor PMFSM Input current of armature coil (Inner)*

Armature coil current density, JA (A/mm2)	Input current of armature coil, IA (A)	Input current of armature coil, Arms (A)
0	0	0
5	20.86471	29.50715
10	41.72942	15.7626
15	62.59413	88.52146
20	83.45883	118.0286
25	104.3235	147.5358
30	125.1883	177.0429

4.5 Overall Comparison of the Proposed Design

Table 4 shows the overall comparisons of the proposed designs for every criterion. Based on their performance, conclusions may be drawn from Table 4. There are significant differences between Proposed Design 1, Design 2 Design 3 and Design 4 across various performance parameters.

Table 4 *Comparison of Proposed Design 1, Design 2 Design 3 and Design 4 across various performance parameters*

Criteria	Design 1	Design 2	Design 3	Design 4
				
Rotor	Outer	Inner	Outer	Inner
Efficiency, n %	96.93	95.60	93.74	99.44
Torque, Nm	84.18	16.01	16.5	16.86
Speed, rpm	1881.76	2996.46	2204.64	6407.72
Power, kw	3763.52	47974.78	36425.91	108071.66
Iron Loss, pi	265.74	1303.81	1502.61	422.30
Copper Loss, cc	112.71	902.23	931.08	190.09
Maximum U Flux, wb	0.2158	0.14	0.17	0.14
Average Torque, m	5.46	7.60	7.067	3.25
Average Speed, rpm	1911.24	1900	1300	2858.72
Average Power, kw	63749.56	13800	8600	13594.49

5. Conclusion

This project explores the design and study of a dual rotor Permanent Magnet Flux Switching Machine (PMFSM). The design procedure has been comprehensively detailed. A no-load analysis was conducted to examine magnetic flux linkages, cogging torque, induced voltage, and flux line distribution in the dual rotor PMFSM. To ensure the machine operates within a three-phase system, a coil arrangement test was performed to determine the respective phases of each armature coil. The design process for the proposed machine has been thoroughly specified for further development. The models were subjected to a coil arrangement test to validate each stage of the armature coil and the functionality of the equipment. Under no-load conditions, the cogging torque, back electromotive force (emf), flux line, and flux distribution of the proposed PMFSM design were analyzed.

Acknowledgement

The authors would also like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia for its support.

Conflict of Interest

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

Author Contribution

The author attests to having sole responsibility for the following: planning and designing the study, data collection, analysis and interpretation of the outcomes, and paper writing.

References

[1] Ullah, W., Khan, F. and Hussain, S., 2022. Dual mechanical port power distribution in dual rotor permanent magnet flux switching generator for counter-rotating wind turbine applicationsAnalysis of Counter-Rotating Wind Turbines. (n.d.). ResearchGate. https://www.researchgate.net/publication/229050697 _Analysis _of_Counter-Rotating_Wind_Turbines

[2] E. Sulaiman, and M.Jenal , "Comparative Study on A New Permanent Magnet Flux Switching Machine Configuation Over Segmental and Salient Rotor Structure," ARPN J. Eng. Appl. Sci., vol. 10, no. 19, pp. 8846–8852, 2015.

[3] Husin, Z., Sulaiman, E., Khan, F., Mazlan, M., & Othman, S. (2015). Design study and performance analysis of 12S-14P field excitation flux switching motor for hybrid electric vehicle. , 1660, 070115.