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Output Torque Improvement of Segmental Rotor Permanent Magnet Flux Switching Motor Based on Finite Element Analysis

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Abstract: The flux switching machine (FSM) is a brushless machine that has attracted a large number of researchers in developing more potential traction motors. In general, this machine is divided into three types but this study focuses on permanent magnet flux switching machines (PMFSM). Segmental Rotor (SegR) PMFSMs have the advantage of higher torque and power density. The purpose of this project is to optimize the output torque performance by varying several motor structure parameters and comparing the output torque of the initial and final design. The initial SegR. PMFSM has been developed from the previous project and still not in optimum performance which is considered as low output torque. This project consists of two sections: JMAG- Geometry Editor is used to design the part of the motor which are the Rotor, Stator, Permanent Magnet, and Armature coil. JMAG-Designer is used to perform the 2-D Finite Element Analysis (FEA). JMAG Designer Software Version 16.0 is used to get the motor performance and compare the performance of the initial and optimized designs. Finally, the motor's output performance in terms of cogging torque, back-EMF, flux line, flux distribution, and output torque has been presented and evaluated. The initial and final design of the 12S-10P SegR. PMFSM has been proposed, and the results obtained. Throughout this project, the final design motor produced a higher output torque than the initial design, increasing by 46% from 3.3328 Nm to 6.1859 Nm. It's proven that varying structure parameters can enhance output torque and improve motor performance.

Keywords: PMFSM, Optimization, Segmental Rotor, Output Torque

1. Introduction

An electric motor is a device that converts electrical energy to mechanical energy. It has two parts which is a stator and a rotor, which may be utilised to create force. Flux Switching Machines (FSMs) are a new type of electric machine that can cause a great deal of torque and power density. In the mid-1950s, the FSM concept was developed and established. Several unique arrangements and combinations

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have been developed for various applications and functions in the last decade, including electric cars, household appliances, industries, and aerospace uses [1].

The field excitation winding, armature winding or permanent magnets known as active parts are positioned on the stator while the rotor is only laminated steel. FEC provides variable flux control capabilities in terms of field strengthening or field weakening conditions. There are three types of FSM which are Permanent Magnet (PMFSM), Field Excitation (FEFSM) and Hybrid excitation (HEFSM) [1]. HEFSM combines with FEC and permanent magnet. Meanwhile, both the PMFSM and FEFSM have permanent magnets and FEC as their main flux sources [2].

For single-phase FSM, recent research has adopted a segmental rotor (SegR.) structure, which provides lots of benefits over other topologies. [3]-[5]. The main function segment design is to provide a defined magnetic path for field flux to the adjacent stator armature coil during rotor rotation, hence achieving bipolar flux linkage in the stator [6]. Figure 1 shows the conventional design of FEFSM with SegR. The initial motor of PMFSM with a segmental rotor that has been developed by previous students is still not in optimum performance. The purpose of this project is to obtain the optimal output torque by applying design structure refinement and comparing the output torque between the initial and refinement design.

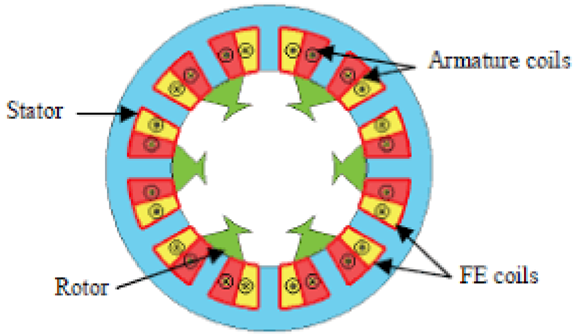

Figure 1: Conventional design of FEFSM with segmental rotor

2. Deterministic optimization method

This project's major goal was to increase the output torque by changing a structural parameter. A deterministic optimization approach was recently proposed in a prior study to enhance the torque and power of single-phase 12S-6P FEFSMs employing segmented rotors and non-overlapping windings. The back-emf disruption issue, an imbalanced flux of armature current solely, and unsmooth FE flux linkage are further issues that are anticipated to be resolved by the deterministic optimization approach. The process of the deterministic optimization approach is shown in Figure 2. Each optimization cycle is separated into three parts, namely the rotor, armature slot, and FEC slot, as seen in the picture when comparing the torque optimised at the conclusion of each cycle with the torque performance of the preceding cycle, it may be determined if the optimization process was successful or not [7]. As shown in Figure 3, the optimization procedure typically involves the following seven parameters: R1, R2, R3, A1, A2, F1, and F2. It should also be noted that the following parameters need to be kept as initial parameters during the optimization process: the stator's outer radius (So), the armature and field excitation's number of turns (NA and NE), the air gap (Ag), and the current input of the armature and field excitation (IA and IE) [7].

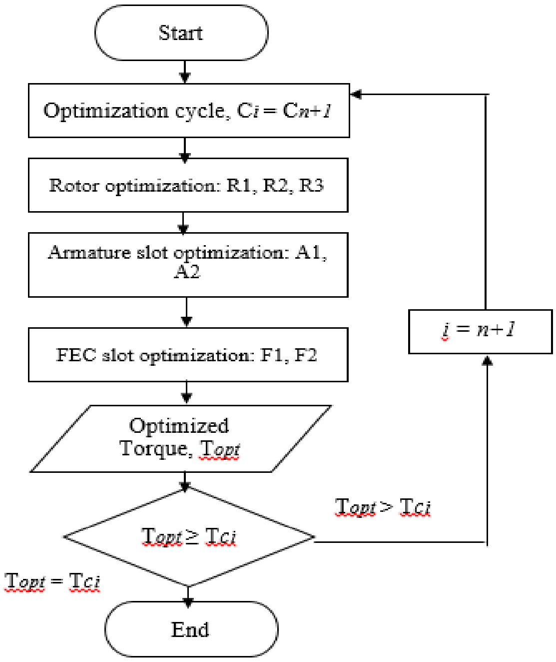

Figure 2: Optimization process

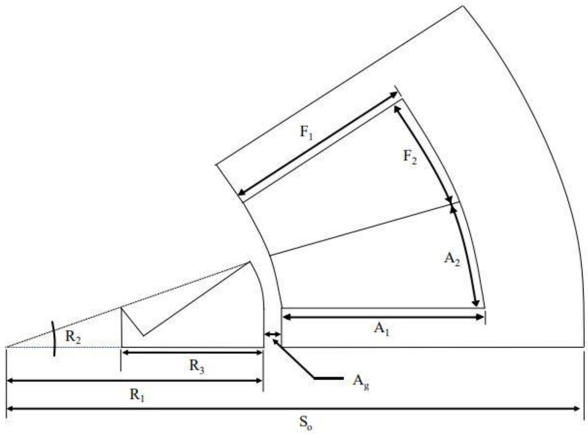

Figure 3: Parameter sensitivities in the optimization process

3. Methodology

This section discusses the design process and the criteria that are set by the JMAG Geometry Editor and JMAG-Designer software. This section also determines the armature coil and the number of turns. The motor's circuit construction and general workflow for several test analyses have been demonstrated and explicated with appropriate motor materials in this project. In general, design and analysis can be separated into two stages: the first is the drawing of motor parts using the JMAG-Geometry Editor, and the second is the analysis. Motor materials and condition settings are being used by JMAG-Designer.

3.1 Design specifications of the initial design

The initial design restriction is illustrated in Table 1 and Figure 4 demonstrates the structure of 12S-10P segmental rotor PMFSM. The maximum armature current density, JA is set of 30 Arms/mm2, respectively. The electrical Nippon steel 35H210 material is used for the stator and rotor body. While, stator outer diameter, rotor outer diameter, and air gap are restricted to 96 mm, 59 mm, and 0.5 mm, respectively.

Table1. Parameter and Specification of Segmental Rotor PMFSM

Parameter	Unit	Quantity
Diameter of stator	mm	96
No. of slot	-	12
No. of pole	-	10
Stator length	mm	15
Rotor length	mm	24.5
Air gap length	mm	0.5
Shaft	mm	5
Armature coil turns	-	3
Armature coil length	mm	15
Permanent magnet length	mm	15
Stack length	mm	50
Permanent magnet weight	kg	0.5
Rotor speed	rpm	1000

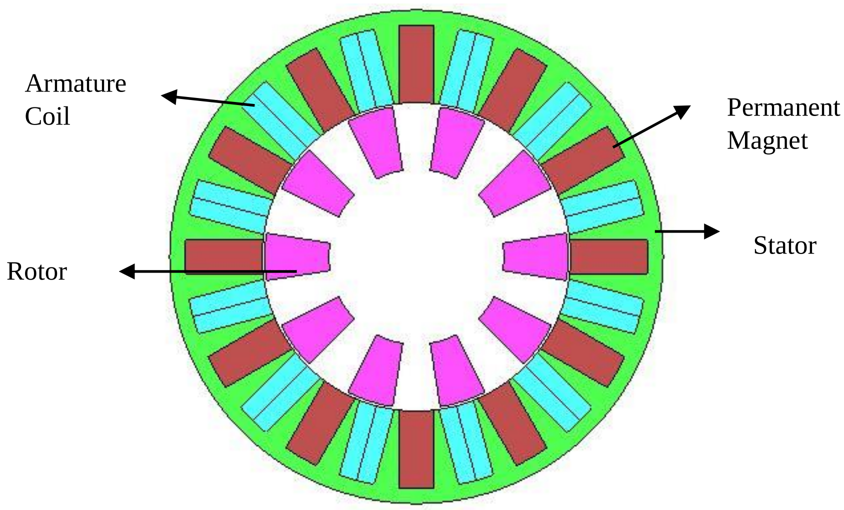

Figure 4: Initial design of 12S-10P segmental rotor PMFSM

3.2 12 Coil Test

Figure 5 shows the coil testing results for each pattern coil, from coil 1 to coil 12 for the initial design. This procedure is carried out in order to discover the pattern of flux relations produced by each armature coil and to test the flux linkage's characteristics. The flux linkage is categorised according to a similar manner. As a consequence, coil 1 is the same as coils 4, 7, and 10, coil 2 is the same as coils 5, 8, and 11, and coil 3 is the same as coils 6, 9, and 12.

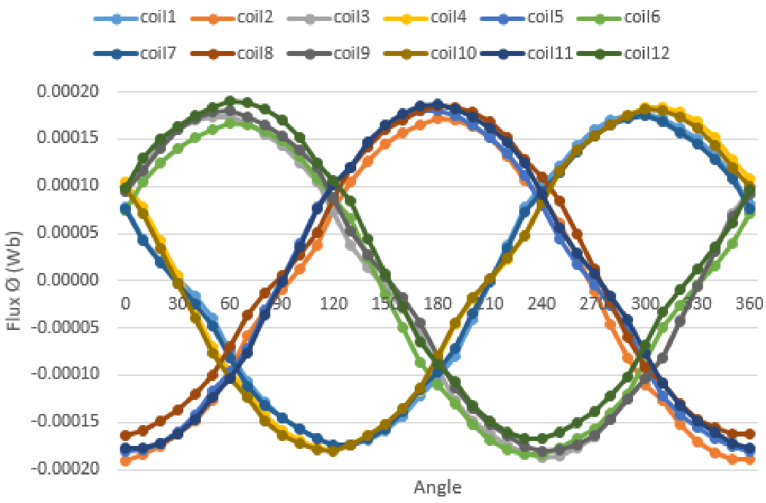

Figure 5: Result of 12 coil arrangement test

3.3 U, V, W Test

Based on the results of the 12 coils test, the same flux was selected for the coil. When the same waveform flux is combined, three patterns are formed. The waveforms of U, V, and W may be seen as a consequence. The connection and coil link for U, V, and W coil test circuit must be in the right connection for U, V, and W tests. The first combination resulting from the three coils arrangement test is V, which represents group coils 1, 4, 7, and 10. A second combination is a group of coils 2, 5, 8, and 11 represented as U. Finally, for the other group coils, 3, 6, 9, and 12 are represented as W. Figure 6 shows the flux of a three-phase flux linkage defined as U, V, and W.

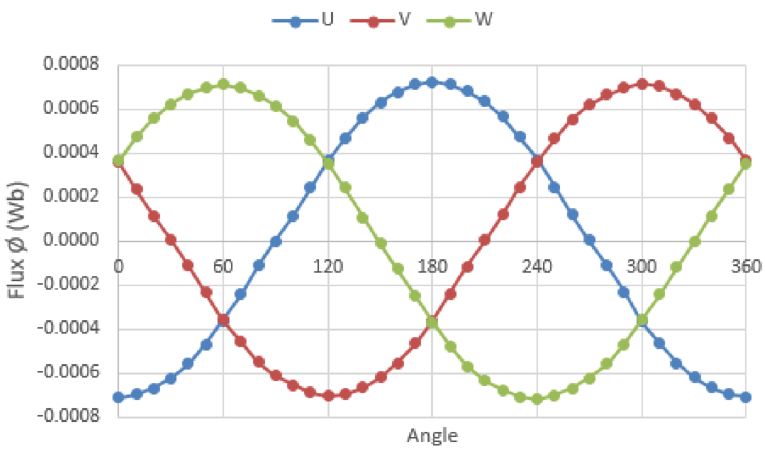

Figure 6: Flux linkage of SegR. 12S-10P PMFSM

3.4 Cogging torque

The cogging torque graph for the 12S-10P SegR is represented in Figure 7. At no load condition, the cogging torque produces six cycles with peak-to-peak of SegR. PMFSM is around 2.0227 Nm within 360° of the electrical cycle.

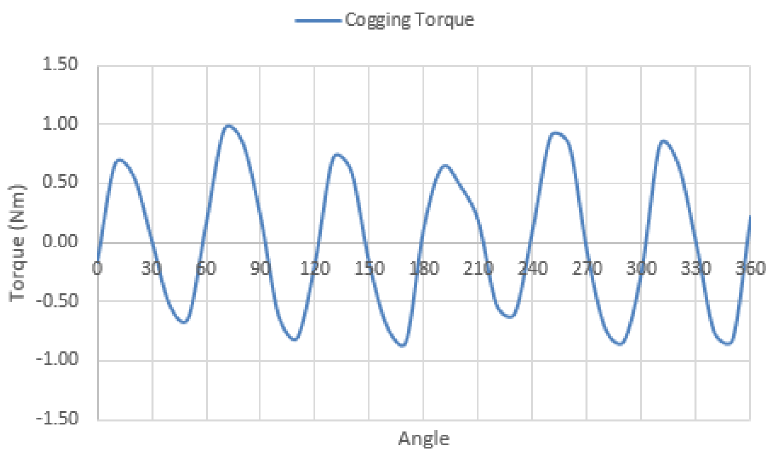

Figure 7: Cogging torque for initial 12S-10P SegR. PMFSM

3.5 Induced Voltage

Induced voltage, also known as back-electromotive force (EMF), is the voltage generated in electric motors when the stator windings move relative to the rotor magnetic field. The back EMF of the PMFSM has been investigated at no-load and analysed at 1000 rpm for this initial design motor. In application, a low-distortion induced voltage waveform can give a great performance. Back EMF voltages for initial SegR. PMFSM is 0.791V, as shown in Figure 8.

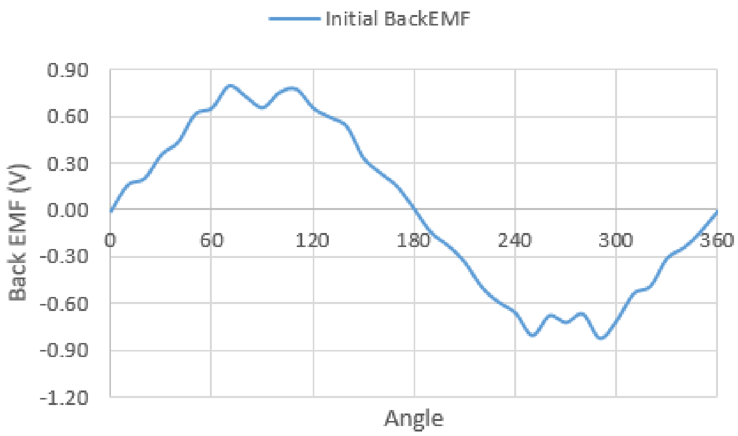

Figure 8: Back EMF for initial 12S-10P SegR. PMFSM

3.6 Flux Line Analysis

The permanent magnetic flux line for the 12S-10P SegR. PMFSM can be seen in Figure 9 under no-load conditions. The magnetomotive force (MMF) between the permanent magnet and the armature coil produces the flux path. This indicates that the flux line appears to have the same properties and flow pattern as the stator-rotor transfer. As a consequence, the flux cycle is completed when PM flux passes from the stator to the rotor and back to the stator. From the observation, it can be analyzed that the flux path generated from the PM and most of the flux flows at the stator around the armature coil. The high flux flows into the rotor cause the high air gap density. This condition will occur flux leakage and flux cancellation.

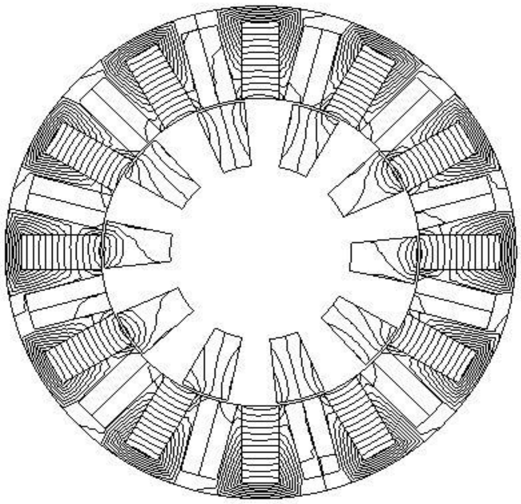

Figure 9: Flux line for initial 12S-10P SegR. PMFSM

3.7 Flux Distribution Analysis

Figure 10 shows the flux distribution for SegR. PMFSM. The proposed motor's flux distribution is separated into multiple colours for the purpose of analysing the flux distribution and determining the magnetic flux density. According to Figure 9, the greatest and minimum flux density values at this position are 2.1408T and 0.0006T, respectively, with red colours representing the highest saturation.

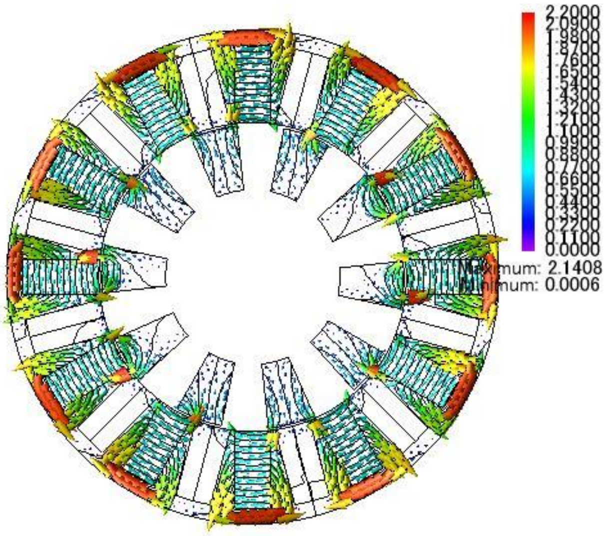

Figure 10: Flux Distribution for initial 12S-10P SegR. PMFSM

3.8 Load Test Analysis

The analysis was carried out to identify whether the graph's direction is increasing or decreasing. The torque value used is the average of the maximum values from Ja 0 to 30 A/mm2. The relationship between torque and armature current density, Ja, is seen in Figure 10. During the load test, Ja values ranging from 0 to 30 were produced while injecting the input current, Ia, into the armature coil. The torque for the original 12S-10P SegR. PMFSM was directly proportional to its current density, Ja, as shown in Figure 11, and the maximum output torque is 3.3328 Nm.

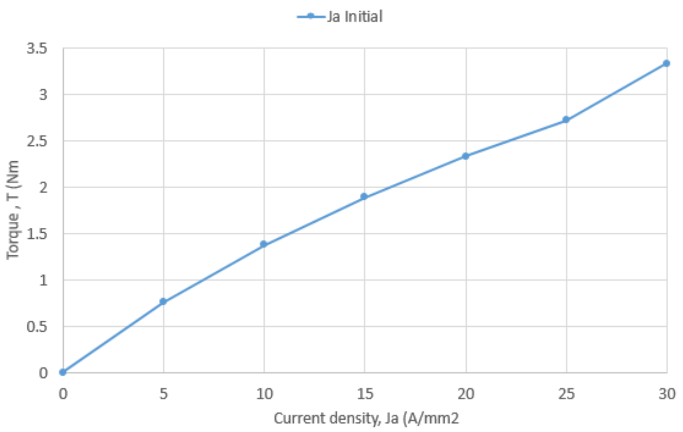

Figure 11: Torque vs armature current density, Ja for initial 12S-10P SegR, PMFSM

4. Results and Analysis for 12S -10P PMFSM in Design Optimization

Deterministic optimization with variable mechanical structure is used to carry out the optimization procedure in order to enhance the torque performance for the original design of Segmental Rotor PMFSM. The back-emf disruption issue, an imbalanced flux of armature current solely, and unsmooth FE flux linkage are further issues that are anticipated to be resolved by the deterministic optimization approach. Figure 12 shows the parameter sensitivity in the optimization process. The four steps of each optimization cycle are the rotor, stator, armature coil, and permanent magnet. By comparing the torque optimised at the conclusion of each cycle with the torque performance of the initial design, it is possible to establish whether the optimization process was successful or not. As shown in Figure 12, the optimization procedure typically involves eight parameters: R1, R2, R3, A1, A2, P1, P2, and S1. Additionally, it should be remembered that throughout the optimization process, the outer radius of the stator (So), the number of spins on the armature (NA), the air gap (Ag), and the current input of the armature must all be kept as starting parameters (IA). The contrast between the original and final design parameters is seen in Table 2.

Each parameter is cycled through eight times while retaining the starting parameter in order to achieve the best outcome. In order to improve the output torque, the stator rotor high (R1&S1) is initially performed. The process of parameter optimization was repeated for the rotor angle span, permanent magnet high and width, and armature coil high and width. In the conclusion, the combined and initial output performance will be compared with the optimal output torque that was obtained from each parameter adjustment. The process for the deterministic optimization strategy is shown in Figure 13.

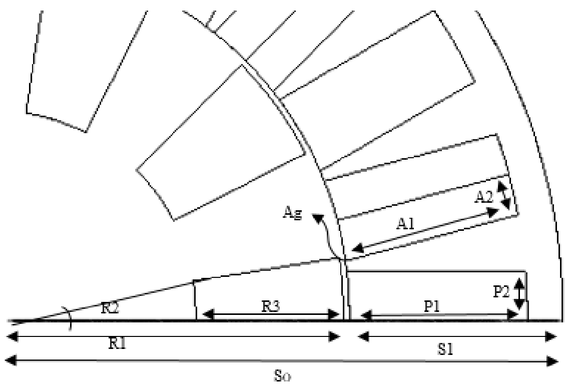

Figure 12: Parameter sensitivities in the optimization process

Table 2: Design specification of the Initial and Optimized Design

	Parameter	Initial	Opt.	Unit
R1	Rotor Outer Radius	29.5	30.5	mm
R2	Segmental Rotor Span	9	8	degree
R3	Segmental Rotor High	12.5	13.5	mm
A1	Armature Slot High	15	14	mm
A2	Armature Slot Width	3.5	3.75	mm
P1	Permanent Magnet High	15	16	mm
P2	Permanent Magnet Width	3.458	3.241875	mm
So	Outer Stator Radius	48	48	mm
S1	Stator Inner Radius	18	17	mm
Ag	Air Gap	0.5	0.5	mm

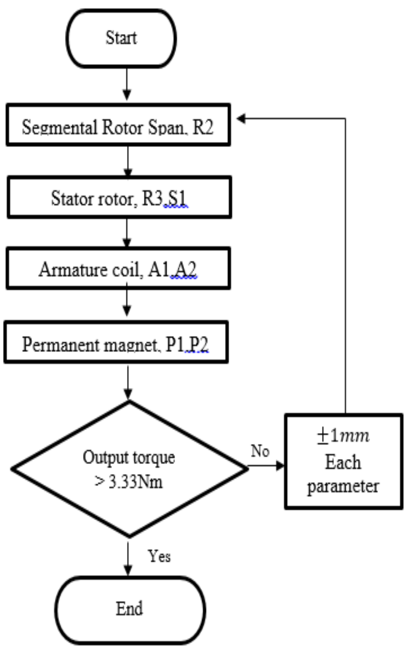

Figure 13.: Workflow diagram of the deterministic optimization

4.1 Result of Flux Linkage

The phase of the U flux must be zero at the rotor location, the flux line proved the condition of zero rotor position in which the magnetic flux is zero when the rotor positions at 90° and 270°. When U flux is not at zero, estimate the degree of change and adjust the rotor clockwise or anticlockwise. The rotor's initial position is adjusted between 0° and -3° to achieve the rotor's zero position for the U flux. Figure 14 clearly shows that the maximum flux of the initial design is 0.00072Wb while for final optimization design is 0.00105Wb. However, the magnetic flux increases, more sinusoidal and more balanced when refinements are made to the motor.

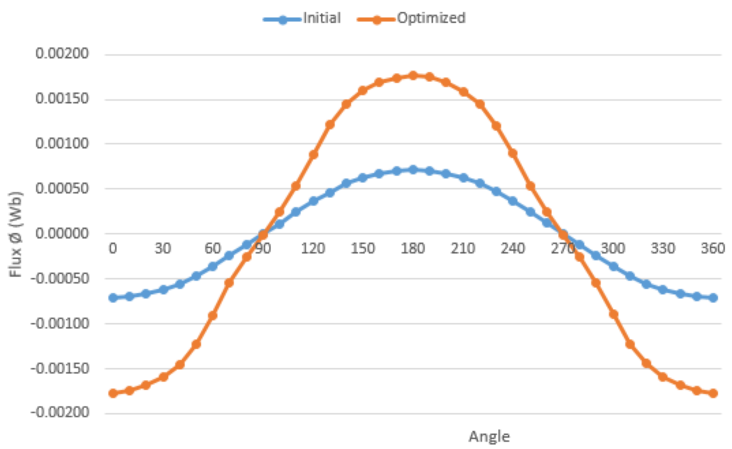

Figure 14: Flux linkage of SegR. 12S-10P PMFSM

4.2 Result of Cogging Torque

The cogging torque graph for the 12S-10P SegR is represented in Figure 15. At no load condition, the cogging torque produces six cycles with peak-to-peak of SegR. PMFSM is around 2.0227 Nm within 360° of an electrical cycle while the final design produces six cycles with peak-to-peak is around 2.9131 Nm within 360° of an electrical cycle. However, this cogging torque can be reduced by using cogging torque reduction techniques that do not affect the output torque performance.

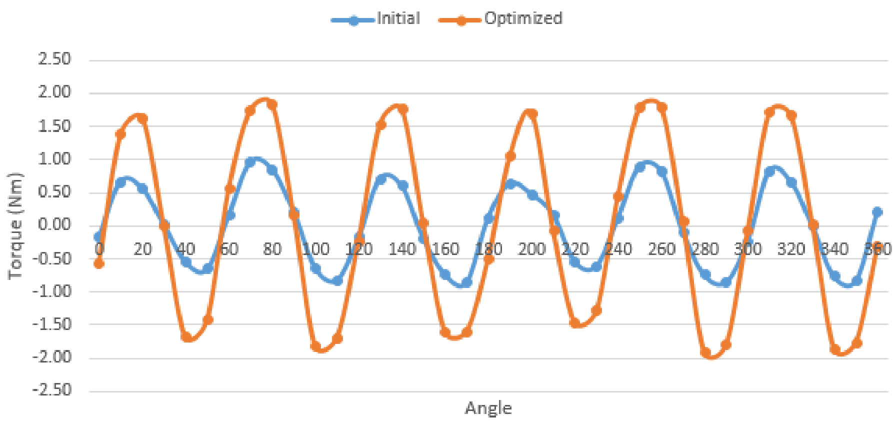

Figure 15: Cogging torque of initial and final design

4.3 Result of Induced Voltage

Induced voltage, also known as back-electromotive force (EMF), is the voltage generated in electric motors when the stator windings move relative to the rotor magnetic field. The back EMF of the PMFSM has been investigated at no-load and analysed at 1000 rpm for this initial design motor. In application, a low-distortion induced voltage waveform can give great performances. Back EMF voltages for initial SegR. PMFSM is 0.791V as shown in Figure 16. Though, the final design shows more sinusoidal than the initial and produced a lot of improvement. Back-EMF voltages for the final design are 0.577V which is worthy to prevent problems such as rotor heating and pulsating torque that might shorten the motor life [8]-[9].

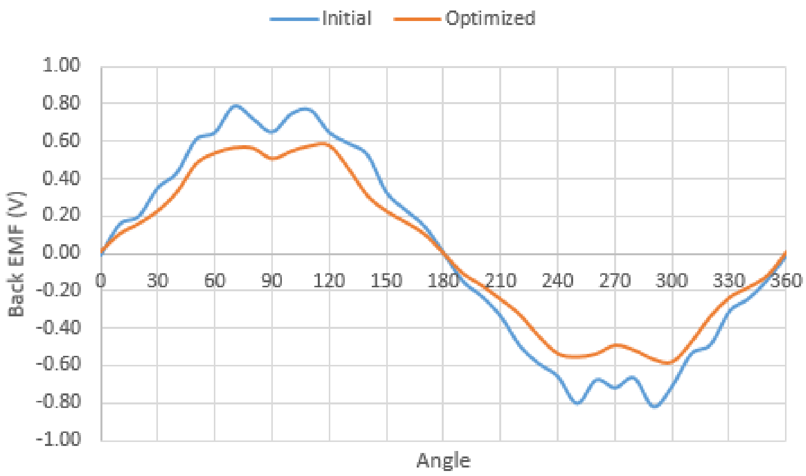

Figure 16: Flux linkage of SegR. 12S-10P PMFSM

4.4 Load Test Analysis

Based on Figure 17, the torque for the initial and final design is 12S-10P SegR. PMFSM was directly proportional to its current density, Ja, and the results show that the final design achieved higher output torque than the initial design at the maximum value of current density, Ja (30A/mm2) with 6.1859Nm while 3.3328Nm for the initial design. The final design improved by 46.1 % over the initial design, indicating that the final design delivered higher output torque than the initial design, indicating that the goal was met.

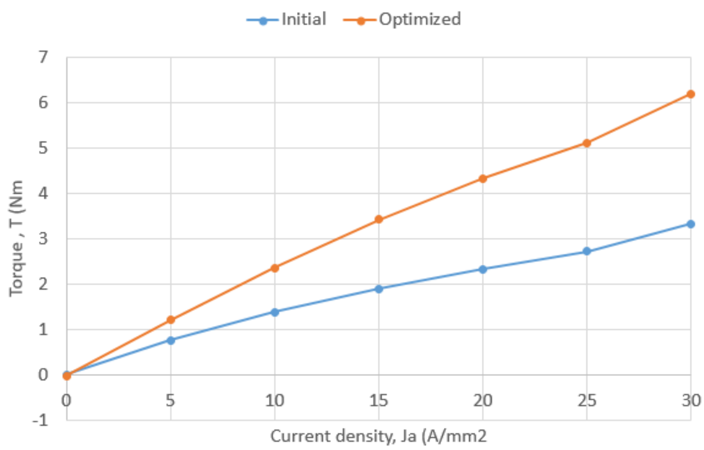

Figure 17: Torque vs armature current density, Ja for initial and final 12S-10P SegR, PMFSM

5 Conclusion

In conclusion, the main goals of this project were met satisfactorily in terms of enhancing output torque performance via deterministic optimization by varying mechanical structure parameters. Initially, the motor's output torque is considered still low. By modifying the mechanical structural parameters of the motor and utilising a deterministic optimization approach, it was proven that the final design may help to enhance output torque greatly by minimising the peak and more sinusoidal waveform for Back-EMF compared to the initial design. Furthermore, the optimised segmental rotor of PMFSM is completely examined in terms of coil test analysis, cogging torque, back-Emf, flux line, and flux distribution. The optimised design's output performance for no load analysis and load analysis has also been compared to the initial design. Throughout this project, the final design motor produced a higher output torque than the initial design which increased by 46% from 3.3328Nm to 6.1859Nm. The final design's high output torque is good to the motor since it increases its ability to do work.

Acknowledgement

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