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ANALYSIS OF COGGING TORQUE REDUCTION FROM DESIGN COMPUTATIONAL PERMANENT MAGNET SYNCHRONOUS MOTOR WITH TAGUCHI METHOD

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Abstract

Permanent Magnet Synchronous Motor (PMSM) applications include electric vehicles, industrial pumps, wind turbines, aerospace technology, and many others. In this study, cogging torque is the central aspect of the discussion, which is the motor model, the thickness of the permanent magnet rotor, and the air gap in the electric motor influence. The Taguchi method uses parameter levels on the motor, which are divided into 16 types of orthogonal arrays, where the process is carried out twice in iterations. The first stage of simulation testing was to produce the primary model where number 4 (A1B4 series) was obtained as the most optimal motor model with a cogging torque of 1.56 Nm and an air gap flux density of 768 mTesla (mili tesla). Then the second test was to modify several parts of the motor with the following 16 orthogonal array types, which produced number 8 (A2B4 series) with a cogging torque of 1.08 Nm and an air gap flux density of 733 mTesla. One of the parameters apart from the cogging torque must be maintained is the air gap flux density. This variable affects the permeability of the motor so that later it will affect the amount of material used and the production costs of electric motors. The final result is a model that produces the lowest cogging torque while maintaining other parameters on the motor.

Keywords: *Cogging Torque, Taguchi Method, Air Gap, PMSM*.

1. INTRODUCTION

Technological developments in the electricity sector are increasingly being carried out in line with the implementation of the new renewable energy program. Electric motors are essential device that supports operations and consumes a lot of energy in industrial business processes. [1]. Permanent magnet synchronous motors (PMSM) support several functions in the industrial world. In addition to the economic aspect, attention to the efficiency and durability of the equipment is also considered [2]. PMSM applications include electric vehicles, industrial pumps, wind turbines, aerospace technology and many others. Because of its high efficiency level, the development of PMSM is increasingly widespread in supporting all aspects of life.

Research related to the development of electric motors can be found in various articles or journals. The design of supporting devices for electric motor vehicles is made in support of motor performance to get maximum performance. Alif's research makes a device that responds to battery temperature and carries out an automatic cooling process [3]. The

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application of other ways to support motor performance is also found in the phase models of electric motors. Chen, changed the phase for the aerospace starter-generator to help astronauts produce electrical energy [4]. The motor's interior was modeled in Zhi-Xiong's research, and optimization of cogging torque was carried out to reduce rotating ripple, which causes noise [5]. Optimizing the cogging torque is done to reduce the impact of noise on the surrounding environment. Ya Huang made modifications to the interior of the PSMS motor slot to reduce the cogging torque [6]. Various ways can be done in the process of optimizing the performance of electric motors by adjusting to user needs.

Cogging torque is an inherent characteristic of electric motors. That is related to the level of rotation based on the motor's geometry. Cogging torque (T_{cog}) can cause torque ripple resulting in reduced motor efficiency, causing noise and vibration. Cogging torque affects the ability to start using the motor even when there is no load [7]–[10]. The cogging torque occurs independently of the amount of current in the stator coil [8]. In the experimental process cogging torque test, the current in the coil must be disconnected and unloaded. However, the review using the cogging torque test simulation design can be done by analyzing the "T_{cog}" variable in the simulation output results [11]. The effect of cogging torque on the Permanent Magnet Synchronous Motor (PMSM), which is used in many industrial tools, makes this issue a topic for various studies related to cogging torque. Research on motors was carried out to effectively maximize torque density due to reluctance and magnetic torque through the protruding rotor structure [12]. The weakness of the previous motor design is the possibility of distortion of the motor torque, such as ripple and cogging torque [11]. Thus, applying the PMSM model to gearbox systems such as servos is difficult because motor performance is significantly affected by noise and vibration caused by torque distortion [12]. Reducing distortion in torque can be done by adjusting the tilt of the permanent magnets usually applied to the rotor by analyzing the tilt angle. However, this method reduces average torque and torque distortion [13]. Various research efforts have been made to mitigate these drawbacks to decrease torsional ripple to an acceptable level.

In this paper, the cogging torque feature generated by a single PMSM is analyzed in depth using several variations. The primary variations can be based on slot skewing, pole-arc optimization, slot shifting, and additional slots or gears for magnetic pole shifting. Then the PMSM design concept was introduced to show the difference from other models. The design consists of several adjacent magnets according to a combination of the number of poles and slots. The model used is synchronous with a DC input or a Brushless DC (BLDC) motor [8], [12], [14]. A practical approach for cogging torque reduction is based on the tooth width of the stator slots and then proposed [10]. The method used to study motors with the number of integral and fractional slots per motor part is the Taguchi method. The Taguchi method helps to eliminate cogging torque with any order harmonics without producing new order harmonic cogging torques [12].

2. METHOD

The research process is divided into three phases. Pre-process is the step to determine the basis of writing. Then the Process stage is managing the review of data originating from references with certain modifications, according to the author's goals at the beginning of the research process. After that, there is a post-process to provide conclusions and suggestions for research [15]. The limitations of the problems in this study are based on optimizing the cogging torque, reducing the cogging torque at the low peak, and maintaining the results of other perspectives in excellent/reasonable condition to keep the quantities in balance.

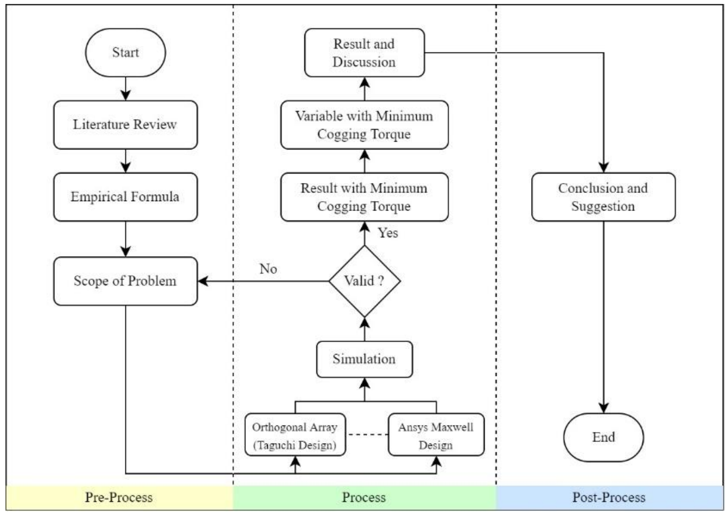


Figure 1: Research Flowchart

2.1 Tagucchi Method

Taguchi optimization is a method for finding robust design a problem in designing/producing an optimal design [12]. *Taguchi optimization* uses simple calculations to reduce the number of trials from the total available combinations [12]–[14], [16]. After getting the combination, several designs were compared to get the main combination with the conditions considered the best. The combination parameters used in the analysis are changes in the stator variation's shape and the basin's shape on the magnet. Changing the pole slot model on the stator and the number of magnets on the rotor can be used to change the cogging torque [17]–[23]. Each model is divided into four levels for pole slots using pole types 1, 2, 3, and 4 with the variable represented (A). Then for the number of magnets plus the coil type using the type 4 magnet model with the first and second rotors as many as four magnets, and the fourth and five rotors ten magnets represented by the symbol (B). These variations are used to form a choice of motor models, and then a speed analysis is carried out to obtain the optimal cogging torque.

Table 1. 1st - Factor Design

FACTOR	SYMBOL	LEVEL			
		1	2	3	4
Pole Type	(A)	P1	P2	P3	P5
Magnet + Coil	(B)	M4C3	M4C4	M10C3	M10C4

After getting the results with the desired cogging torque, the simulation is repeated. The second simulation is run on the parameters that affect the empirical formula of the calculation of the cogging torque. The following is the formula of cogging torque [12]:

$$\boldsymbol{T_{cog}} = -\frac{1}{2}.\emptyset^2.\frac{dR}{d\theta} \qquad (1)$$

where,

$\emptyset_2$ = flux in the air gap

R = air gap reluctance

θ = angular rotor position

The air gap flux can use calculations:

$$\boldsymbol{\emptyset^2 = B.A} \tag{2}$$

where,
B = air gap flux density amplitude
A = the area of air cut by the flux flow

Air gap flux density amplitude:

$$\boldsymbol{B = \frac{b_r . l_m}{(r_r + l_g)_{ln} \cdot \left(\frac{r_r + l_g}{r_r - l_m}\right)}} \tag{3}$$

where,
b_r = magnetic remanence (see on magnet datasheet)
l_m = magnetic length
r_r = rotor radius
l_g = air gap width

Then for R (air gap reluctance) at dR obtained by:

$$\boldsymbol{\Re = \frac{l_g}{\mu_0 . A_g}} \tag{4}$$

where,
R = air gap reluctance
l_g = air gap width
A_g = the area of the air gap cut by the flux

Equation of the empirical formula from the basic calculation helps look for a perspective to determine the factors that affect cogging torque. The Taguchi method helps in the realization by testing gradually according to the specified level to help find the motor structure [12],[14],[16]. In the process, an orthogonal array is used with 16 simulation trials.

Table 2. Orthogonal Array 16 Tipe

NO	A	B	NO	A	B
1.	1	1	9.	3	1
2.	1	2	10.	3	2
3.	1	3	11.	3	3
4.	1	4	12.	3	4
5.	2	1	13.	4	1
6.	2	2	14.	4	2
7.	2	3	15.	4	3
8.	2	4	16.	4	4

(A) Magnet pole type on rotor,
(B) Combined magnet number and coil type.

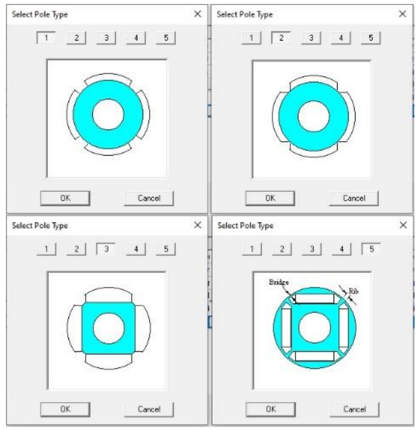


Figure 2: Type of Pole

Each pole magnet model has its designation, especially what is of particular concern at the moment is its use for the phenomenon of optimizing the cogging torque. The different types of poles affect the magnetic field that is formed on the rotor. So, changing the type of pole on the rotor can affect the work of the electric motor [15]. The experimental results from each cogging torque simulation are then compiled into a discussion with a low ripple output. Then a final comparison is made to obtain the most optimum model from reducing cogging torque and supporting aspects such as efficiency and air gap flux density.

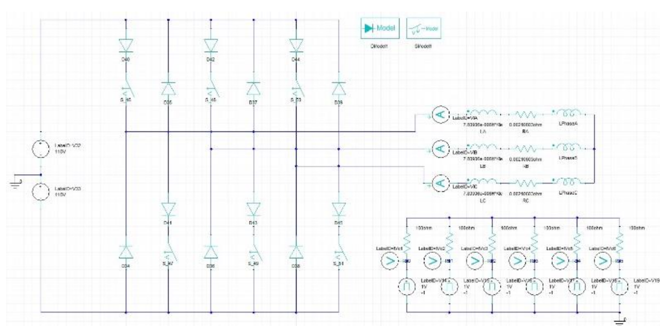


Figure 3: Circuits Model PMSM

The source voltage that passes through the coil on the stator must be connected to the replacement circuit. The circuit connected to the source acts as the coil's input, divided into phases A, B, and C. In the excitation setting, the source is changed to “External,” which means the designed coil is connected in a separate display circuit, as shown in Figure 3. The process can be changed to the opposite direction by using a switch controlling the flow towards the diode [24]–[28].

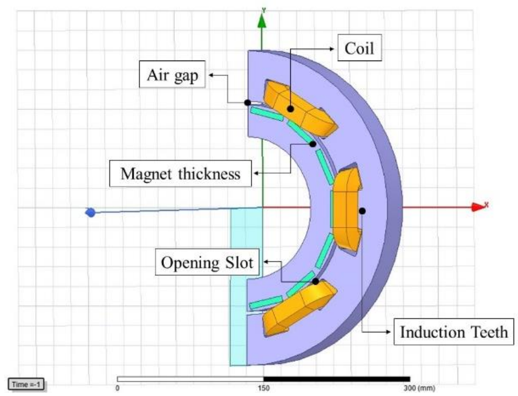


Figure 4: 3D Model BLDC Motor

After the variations and motor parameters are entered, the simulation starts with each model. Then observations were made on the results based on the 16 variation models prepared previously. Figure 4 shows an example of a manageable and simulated design. Overall, the motor design parameters can be seen in Table 3.

Table 3. Motor Design Parameter

DESCRIPTION	VALUE	UNIT
Stator outer diameter	320	mm
Stator inner diameter	217	mm
Stator length	75	mm
Rotor outer diameter	210	mm
Rotor inner diameter	145	mm
Air gap	7	mm
Magnet thickness	6	mm
Power loss (friction)	24	W
Stacking factor	0.95	
Reference speed	13300	rpm

After the simulation, a shape with good cogging torque is obtained. Then the second stage of the process is carried out in the repetition of the Taguchi method using the parameters of the air gap and the thickness of the magnet. The goal is to determine whether the increase in the shape that has been obtained can be increased cogging torque [29]. This selection is influenced in part by three methods related to permanent magnet cogging torques, namely [12]:

- Formation of magnetic poles. The rate of change of the air gap flux density at the edge of the magnet affects the cogging torque. This method can generally reduce the cogging torque by designing a reduced magnet width or magnet length. This method reduces the desired torque because less magnetic flux is available to the stator windings.
- This method involves playing with the magnet orientation to make the derivative of the radial magnetic field concerning the angular position (dR/dθ) zero on every face of the magnet. Although it may not reach zero in practice, it significantly decreases the cogging torque. Skewing can be applied to magnets and slots, but each approach has drawbacks. Tilting the magnet increases its charge while inclining the slots increases the copper loss due to the longer length of the wires.

- Reducing the magnetic flux density lowers the air gap flux and thus reduces the cogging torque, as can be seen from equation (1). By changing the magnetic value directly, the magnetic flux density can be decreased, leading to a corresponding reduction in the air gap flux.

  The new model is found by selecting the change in composition in the first and third ways. The air gap was selected in the modification section due to its empirical formula for the magnitude factor's role in calculating the cogging torque. The rotor pole is represented by the thickness of the magnet, which impacts the flux density rate at the magnet edge in the air gap [9].

Table 4. 2nd - Factor Design

FACTOR	SYMBOL	LEVEL			
		1	2	3	4
Magnet Thickness (mm)	(A)	5.5	6	6.5	7
Air Gap (mm)	(B)	1	1.25	1.5	1.75

As before, the design factors are combined into 16 variants using orthogonal arrays. After the appropriate model is obtained, a comparison process is carried out with both models from the double Taguchi method process so that an explicit comparison is obtained and a large percentage of increase occurs.

Models can be drawn in FEM software or uploaded CAD files in the simulation. Material and mechanical properties are determined by setting the LUA script. Domains are combined, and the user defines boundary conditions. This software uses triangular elements to connect domains and linear functions to approximate solutions [12],[14]. There are approximately 35,000 nodes for all BLDC motor models. The simulation diagram is presented in Figure 4. The meshing process and calculation of the cogging torque are carried out together with the rotor position being raised to a specific condition. The process is repeated according to the design factor, and the results are recorded at each incremental test [30].

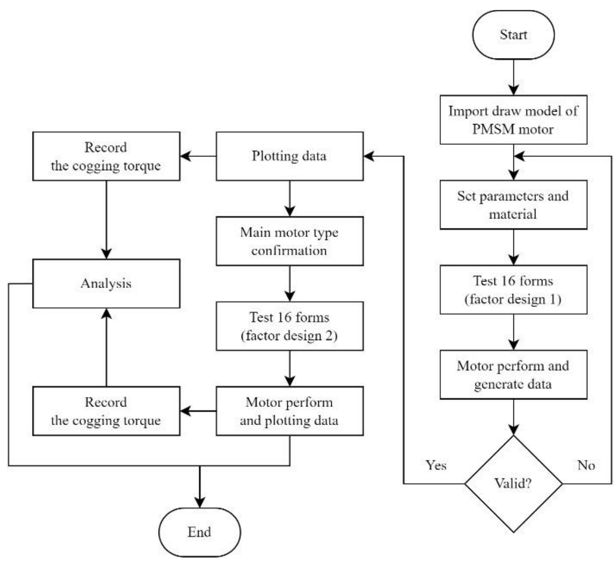


Figure 5: Simulation Process Chart

The Taguchi test was carried out in two repetitions. Then, we can analyze the differences from the best model for each simulation experiment [31]. The data obtained has a continuous process and serves as a role model for testing the Taguchi method with new steps.

3. RESULTS AND DISCUSSION

In the first process, the simulation results of reducing the cogging torque are carried out by changing the type of pole magnet, the number of magnets, and the slot coil in the electric motor. As expected, experiments according to the first Taguchi method scheme resulted in a reduction in cogging torque with the four best schemes, namely P1M10C3, P1M10C4, P5M10C3, and P5M10C4. Then the model with the best results, P1M10C4, is taken as a motor scheme for the next stage.

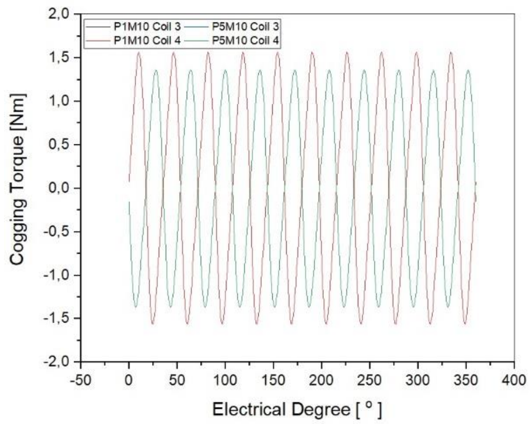


Figure 6: Best Model Simulation Result for Cogging Torque

The experiment was obtained by testing 16 orthogonal arrays with the parameters in Table 3. The construction of the motor with the slightest cogging torque is the magnetic pole model number 5, with ten magnets circling the rotor and the coil slots using slot types numbers 3 & 4. Figure 6 shows simulation results for each peak. The smallest cogging torque value is 1.36 Nm for P5M10 Coil 4 and Coil 3. The second smallest value is 1.56 Nm for P1M10 Coil 3 and 4.

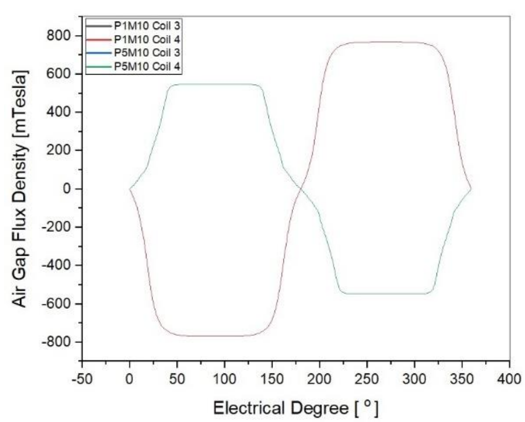
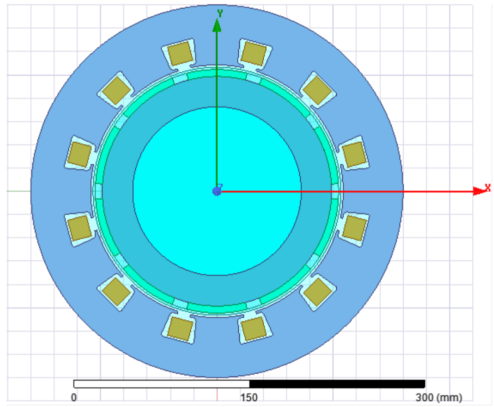
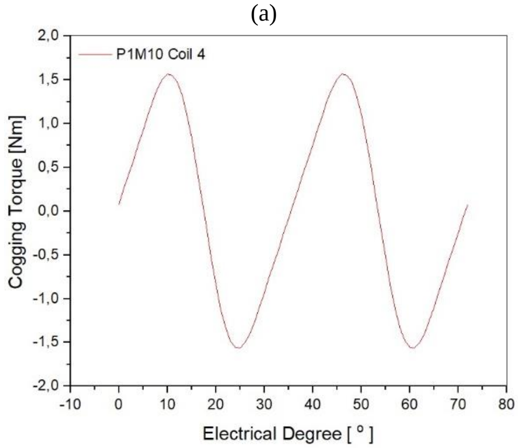


Figure 7: Result for Flux Density

The perspective that makes Air gap Flux Density a determinant is that if the flux value is higher than the permeability of the rotor-to-stator magnetic circuit will decrease so that the production value of the motor can be more economical. Air Gap Flux density of 768 miliTesla (the highest) accompanied by good cogging torque is found in the P1M10 Coil 4 motor with an efficiency of 97% or can be seen in the orthogonal array in model number 4 with the A1B4 model series. Later the motor with the P1M10C4 model was chosen as a further simulation into the second stage of the process.



(a)



(b)

Figure 8: (a) Result of Optimum Models Motor P1M10C4, (b) P1M10C4 in 70º Period

The results show that the P1M10C4 wave requires 35º of rotation in one period. The 70º diagram is used to see the point of view of the differences between the initial model and the final result, with a cogging torque value of 1.56 Nm and a peak Air Gap Flux Density of 768 milliTesla. The second process is an experimental implementation of the simulation using the design factors of Table 4. Then from the design factors, a model with 16 orthogonal arrays is created, and the simulation is carried out according to the classification.

Table 5. Orthogonal Array 16 Type for Second Simulation Process

NO	A	B		A	B
1.	5.5	1	9.	6.5	1
2.	5.5	1.25	10.	6.5	1.25
3.	5.5	1.5	11.	6.5	1.5
4.	5.5	1.75	12.	6.5	1.75
5.	6	1	13.	7	1
6.	6	1.25	14.	7	1.25
7.	6	1.5	15.	7	1.5
8.	6	1.75	16.	7	1.75

(A) Magnet thickness type on the rotor,
(B) Air gap between stator and rotor.

Changing the geometry in both simulations with the thickness of the magnet with the Air Gap makes the cogging torque change into several conditions. Some models experienced a cogging torque of more than 100 Nm, and these results are unsuitable for further research. Superior results were also obtained in the second simulation. The optimal cogging torque of the modified model is shown in Table 5 No.8 with the A2B4 series. The second design factor modification with the A2B4 series results in a cogging torque of 1.08 Nm, producing minimum torque if compared to other models with Taguchi method.

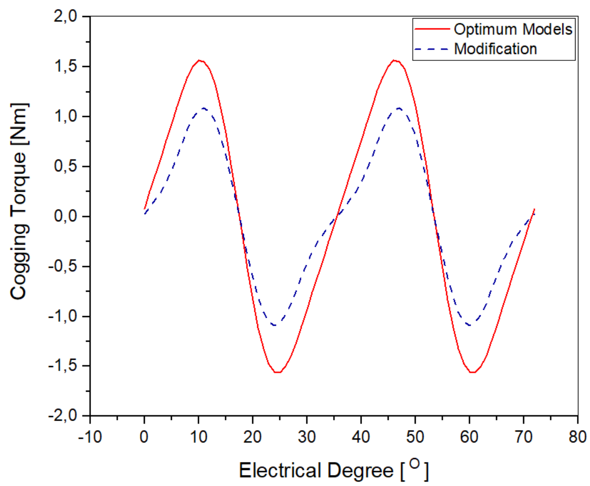


Figure 9: Comparison of the Cogging Torque between First and Second Simulation

The motor modification results in a lower cogging torque by adjusting the magnet and Airgap thickness. The percentage increase that occurs is 30.7% from the initial cogging torque. The cogging torque is reduced by decreasing the (dR/dθ) and g variables. As seen in the Figure 9, the modification reduces the first simulation torque from 1.56 Nm to 1.08 Nm in the second design optimization model. By equation (1) used to calculate the cogging torque, the width of the air gap can affect the value of the cogging torque. Adjusting the gap between the rotor and stator to 1.75 mm on type 1 magnetic pole model helps reduce the motor cogging torque by 0.48 Nm.

Table 6. Comparison of Cogging Torque Reduction

Journal Author	Motor Type	Modification	Reduction (N.m)
This study	PMSM	Geometry size	0.48
Srisiriwanna dan Konghirun [13]	BLDC	Dummy slot	0.04
Liu, et al. [23]	PMM	Slot-opening shifted	2.2
Zhu, et al. [17]	FRPM	Space gap	0.9

In another study shown in Table 6, the changes in cogging torque done by changing the geometry of the electric motor were carried out by Srisiriwanna and Konghirun, where reduction using a dummy slot changed the cogging torque value from 0.06 Nm to 0.02 Nm [13]. Then there is Liu et al., where Slot-opening analyzes the shifted cogging torque, reducing the cogging torque from 4 Nm to 1.8 Nm [23]. In this paper, the cogging torque reduction has changed from 1.56 Nm to 1.08 Nm. Research shows that the higher the value of the cogging torque, the more significant the reduction that can be made.

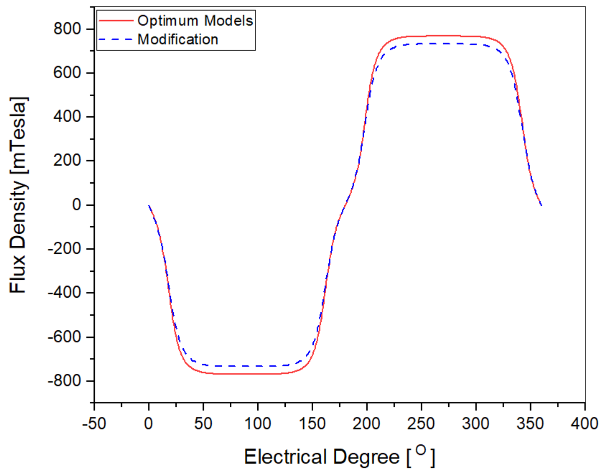


Figure 10: Comparison of the Air Gap Flux Density between First and Second Simulation

Changing the air gap width causes a decrease in the air gap flux density. The cause of the decrease in air gap flux is because the adjustments made are by widening the gap in the air gap. The highest peak value of the field flux decreased from 768 mT to 733 mT, a decrease of 35 mT. However, in percentage terms, the decrease only occurred by 4.5% from the value of the first simulation flux. Thus, at the air gap, flux density decrease can be tolerated and does not significantly impact motor performance.

Motors with modifications to the second simulation process have even better advantages. The efficiency level of the motor reaches 97%. From the best results of the two simulation processes in reducing the cogging torque, the air gap significantly influences the motor. The suitable range for the model P1M10C4 air gap is 1.5 – 2 mm.

4. CONCLUSIONS

Simulation in cogging torque reduction by Ansys Maxwell studied in writing papers. The principle of the Taguchi method is an effective way of modifying the level parameters of the design so that the modified model has a valid simulation data structure. The increase in cogging torque from the simulation results of the modified model (table 5 - series A2B4) was obtained by 30.7% compared to the initial model of the first simulation P1M10C4 (table 2 - series A1B4). However, the air gap flux density on the motor has decreased by 4.5%. The motor efficiency has not changed, reaching 97%. The air gap is the main aspect of reducing cogging torque. The cogging torque can increase significantly if the gap model is too comprehensive. However, if the air gap is too narrow, the cogging torque can also increase more than the minimum value. Its effect on the air gap flux density can increase the motor permeability, affecting the motor production costs.

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