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Abstract. The cogging torque on a brushless DC (BLDC) motor, in this case on the Internal Permanent Magnet V-Shape motor, causes torque ripple and speed fluctuations. This can interfere with motor operating performance because the motor will not rotate smoothly due to noise and vibration, especially at low rpm. Therefore, the cogging torque must be reduced or eliminated so that the operating performance of the BLDC motor IPM V-Shape that has been designed and built can be better. Several studies have shown various ways to reduce or eliminate cogging torque. This paper will analyze and apply one of the methods to eliminate cogging torque, which is the Skew Method in the stator of the BLDC motor IPM V-Shape through Finite Element Analysis (FEA) simulation using ANSYS Maxwell. The motor's torque, speed, and efficiency will be analyzed to determine the effectiveness of the Skew Method on the stator of BLDC Motor IPM V-Shape. The result shows that the Skew Method in the BLDC Motor IPM V-Shape can reduce by almost 100% of cogging torque and produce a motor design that has good performance.

INTRODUCTION

Permanent magnet brushless direct current (PM BLDC) motors are currently seeing wider implementation across the industry, particularly in the automotive sector[1,2] Because of the numerous benefits that PM BLDC motors offer including high torque density, small size, great efficiency, and good control throughout a broad wide speed range, their use in a variety of applications and designs is becoming increasingly common[3]. When comparing to induction machines and mechanical commutated dc motors, the use of permanent magnets in these motors contributes to their increased efficiency and decreased size[4].

However, cogging torque is unavoidably inescapable in PM BLDC motors due to an inherent magnetic contact between the stator and the rotor. This interaction makes cogging torque rather evident in moderate load and low speed conditions[5,6]. The strong cogging torque can generate massive output torque ripple as well as a rougher working motor, both of which would lead to noise. This seems to be particularly appear at low speeds, when the inertia is unable to properly smoothing the output torque due to the motor's rough running[7]. Generally, the methods that can be used to reduce the amount of cogging torque in order to increase torque performance can be divided into two primary groups. The first one is a strategy that involves altering the design of the motor so that the pulsing torque component is reduced to the smallest possible amount[7,8,9]. The second method is based on control techniques that can be used to adjust the waveform of the stator's excitation in order to generate smoother torque[10,11,12]. This paper focuses on reducing cogging torque varying air gap distance values and adding skew in the stator slot. Those methods are carried out using commercial finite element analysis (FEA) software.

Through regulation No. 55 of 2019, The Indonesian Government concerns the battery-based Electric vehicle program to accelerate the domestic electric car industry's development. Various types of Battery-based Electric vehicles have developed in Indonesia such as two-wheeled and bus electric vehicles, yet the four-wheeled electric vehicle has many chances to be developed. This research was conducted to develop a small four-wheeled electric vehicle that will be used as a feeder in residential areas. A small-capacity feeder of electric vehicles (less than 10 people) that can reach residential areas at 10-30km/h is a reasonable option to consider. The powertrain characteristics of this type are working at a low speed with a small battery capacity and having high power density. The requirements for the powertrain or an electric motor needed can be seen in **TABLE 1** below,

TABLE 1. Electric Motor Design Requirement

Design Parameter	Value	Unit
Targeted Power	10.60	kW
Targeted RPM motor	3000	Rpm
Targeted Torque	33.74	Nm
Battery voltage	72	VDC

In this research, a BLDC motor IPM V-shape has been chosen as electric motor propulsion since a BLDC motor IPM V-shape has high power density, high efficiency, and high reliability, which matches EV application[13]. To achieve those requirements, a BLDC motor IPM V-shape was designed with specifications as shown **TABLE 2** below

TABLE 2. *BLDC motor IPM V-Shape Specification*

Design Parameter	Value	Unit
Motor type	BLDC IPM V-shape	
Voltage	72	VDC
Rated Power	10.6	kW
Rated Speed	3000	Rpm
Rated Torque	33.74	Nm
Number of stator poles	8	
Number of Stator Slots	12	
Length	160	mm
Outer Diameter of Stator	140	mm
Inner Diameter of Stator	83.5	mm
Stacking factor	0.95	
Number of Rotor Slots	12	
Outer Diameter of Rotor	82.5	mm
Air Gap	0.5	mm
Inner Diameter of Rotor	25	mm
Magnet Type	NdFe52 180°	
Magnet thickness	2	mm
Magnet width	14	mm
Number of segment magnet	4	
Skew	0	deg

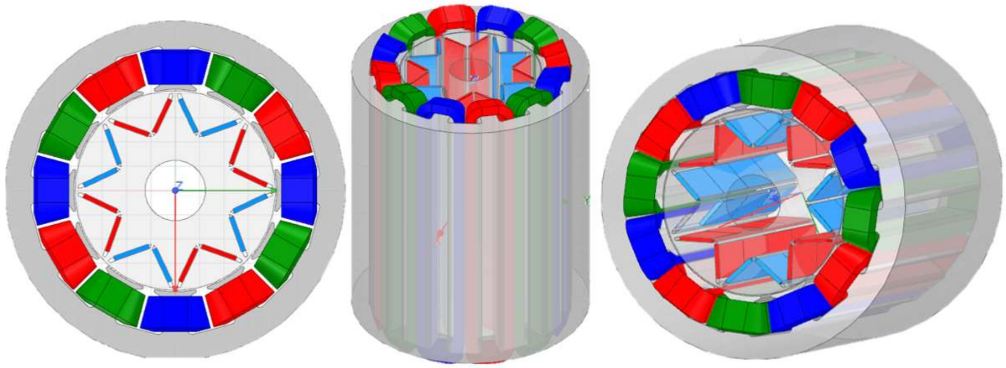

FIGURE 1. The *3D Design of BLDC motor IPM V-Shape on Ansys Maxwell*

(a) 3D Design *(b) Actual Prototype*

FIGURE 2. *Prototype of BLDC motor IPM V-Shape*

(a) Stator *(b) Rotor*

FIGURE 3. *Actual Motor*

As specified above, a BLDC motor IPM V-type comes with a segmented magnet. Since a BLDC motor is designed with high speed and a large frequency carried from the permanent magnet, the eddy current loss of the permanent magnet is high. Therefore, an axial section method of segmenting a permanent magnet is widely applied to reduce the eddy current loss[14]. In addition, the reason for choosing four segmented permanent magnets is for manufacturing convenience and local permanent magnet supply. This BLDC motor IPM V-type with 4 segmented magnets has done magnetic force line analysis as shown in **FIGURE 4**. The result of four segmented magnets is already the same as the result of one permanent magnet segment.

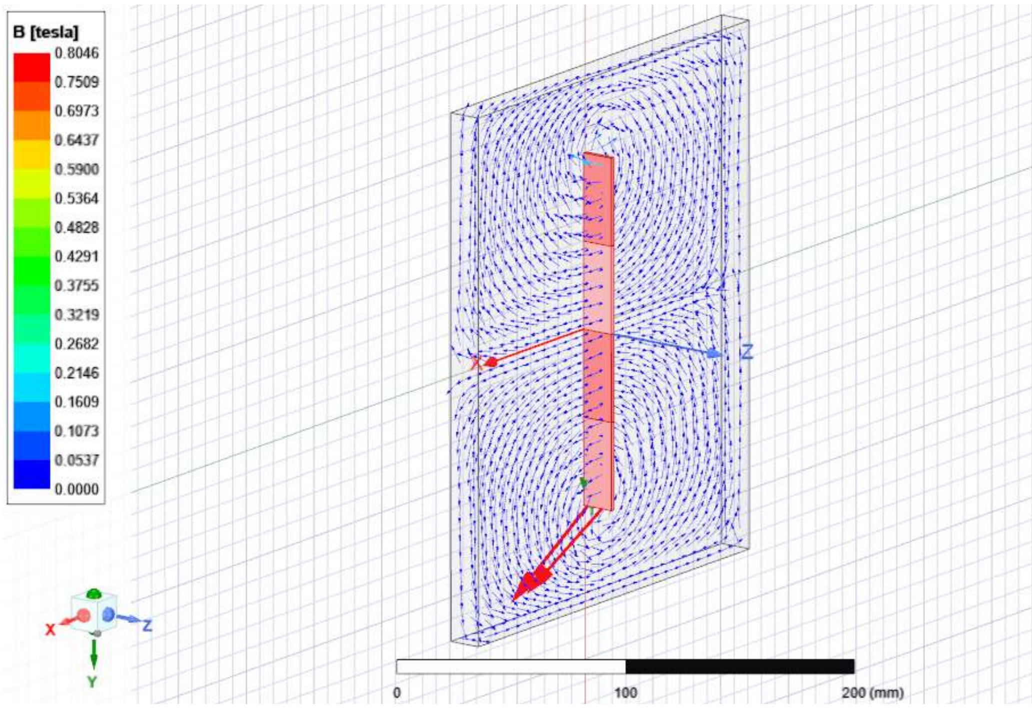

FIGURE 4. *Magnetic Force Line of 4 Segmented Magnet BLDC Motor IPM V-type*

By simulating on Ansys Maxwell, the result of a motor which design has mentioned **TABLE 3** in below.

TABLE 3. *Result of Simulation*

Parameter	Value	Unit
Airgap	0.5	mm
Speed	3000	Rpm
Power Output	10.6	kW
Cogging Torque	12.973	Nm
Torque Ripple	12.088	%
Shaft Torque	33.74	Nm
Max Torque	35.140	Nm
Eff	93.899	%

Based on the simulation result, the motor design has met the predetermined target requirements. However, there is the presence of the cogging torque. The BLDC motor generally generates 3 types of torque; mutual torque, reluctance torque, and cogging torque. The cogging torque occurs because of interaction between permanent magnets and the stator slotted iron structure. The presence of cogging torque is one of the weaknesses of the BLDC motor since it causes the torque ripple, causing shaft vibration and noise that prevents the motor from running smoothly, especially at low speeds and light loads[15].

METHODOLOGY

A. Cogging Torque Analysis

Cogging torque is also known as magnetic locking, the state when the motor refuses to start up and remains stationary. This situation can be caused by the same number of stator and rotor slots. So that when the stator and rotor slots are facing each other, the magnetic path is in a minimum condition, which causes the rotor position to tend to remain[16]. Common studies related to cogging torque on electric machines as the following assumptions were used:[17]

- the magnetic energy is stored only in the airgap and PMs volume;
- the PMs and air permeability are equal to the vacuum permeability;
- the permeability of the iron is assumed to be infinite; and
- the airgap flux density is constant along the radial direction.

The cogging torque of the machine can be described by the energy method. Torque is obtained as a derivative of the magnetic co-energy (W) function of the displacement movable part (ϑ_r), which can be explained by the following equation:

$$T_{cog}(\vartheta_r) = -\frac{\partial W}{\partial \vartheta_r} \tag{1}$$

Based on the assumptions, the magnetic energy (W) can be explained by the following equation:

$$W = \frac{1}{2\mu_0} \int_{V_g} B^2 dV \tag{2}$$

The magnetic energy depends on the volume of the airgap (V_g), μ_0 is the vacuum permeability, and B is the flux density of the airgap at no-load[18]. Based on the above equation, the magnetic energy that affects the cogging torque is a periodic variable along the air gap. By using the periodicity feature, it can be expressed by the following equation:[19]

$$T_{skew}(\theta) = \sum_{i=1}^{\infty} K_{sk} T_i \sin\left(iC_p\theta_m + \theta_i\right) \tag{3}$$

Where K_{sk} is the skew factor. If the motors are non-skewed motor laminations, the value of K_{sk} is 1. T_i is absolute values of the harmonics, C_p is the least common multiple between the number of poles and number of stator slots, θ_m is the mechanical angle between the stator and rotor axis while the motor is rotating, and θ_i is phase angel K_{sk}. The skew factor can be expressed by the following equation:

$$K_{sk} = \frac{\sin(i\, C_p \pi \alpha_{sk}/N_s)}{i\, C_p \pi \alpha_{sk}/N_s} \quad i = 1,2,3, \dots \tag{4}$$

Where α_{sk} is the skew angle and N_s is the number of slots. The skew angle is shown by the following equation:

$$\alpha_{sk} = \frac{360^0}{N_s N_{period}} \tag{5}$$

N_{period} is the period of the cogging torque in one slot pitch. To get the optimum skew angle to reduce cogging torque is related to N_{period}, the equation is as follows:

$$N_{period} = \frac{N_p}{HCF(N_{s,} N_p)} \tag{6}$$

Where HCF is the highest common factor of stator slot number and number of poles.

Based on the causes of the cogging torque and the theoretical equations, several aspects can be analyzed. The explanation that magnetic energy is related to the air gap can be analyzed by the effect of the air gap on the Cogging Torque. The construction of the stator is changed to avoid the minimum magnetic energy condition by using the skew method. In this method, the optimum skew angle is to reduce the cogging torque of the machines.

B. Design Goal for Cogging Torque

The optimization and validation of a simulation of reducing cogging torque will be executed by the design of the IPM V-shape BLDC Motor with the following specifications as **TABLE 4**:

TABLE 4. *Target specifications of the IPM V-Shape BLDC Motor*

Design Parameter	Value	Unit
Rated Torque (T_n)	33.74	Nm
Number of phases (m)	3	-
Rated Power (P_m)	10.60	kW
Rated Voltage (V)	72	Vdc
Rated Speed	3000	rpm

The design specifications will be simulated to get the most optimum cogging torque value. The changes are made by changing the air gap between the stator and rotor. In addition, making changes to the construction by applying the skew method to the stator, and changing the skew angle on the stator to get the optimum cogging torque value.

C. Finite Element Analysis

In this study, the magnets attached to the rotor are segments with four layers on each pole along with the rotor core. Changes to the air gap are carried out by eroding the rotor core and fixed stator inner diameter. Because it is easier to reduce the outer diameter of the rotor on an electric motor prototype. For adding skew to the continuous type stator slot, it is hoped that the slot fill factor on the motor will not decrease significantly.

IPM V-Shape BLDC Motor designs are simulated using Ansys Maxwell. Modelling for simulation is used by combining features in Ansys Maxwell, such as RMXPRT, 2D Maxwell, and 3D Maxwell. The following is an example of the skew creation method using RMXPRT mentioned in **FIGURE 5.**

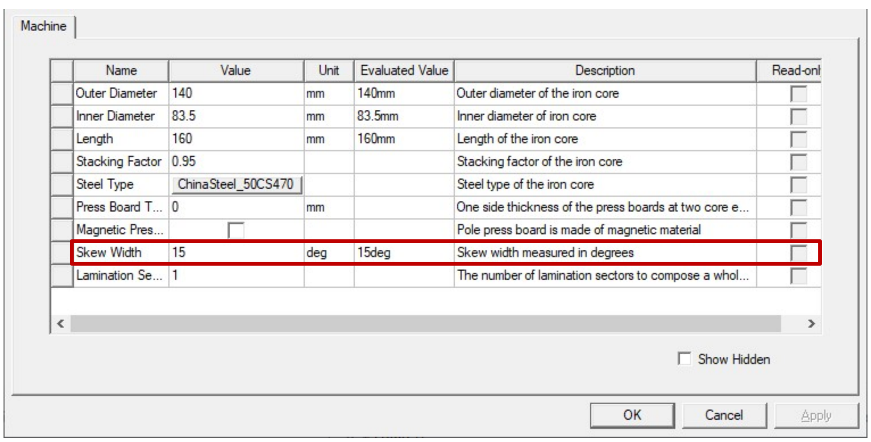

FIGURE 5. Set Up the Skew Width in RMXPRT

RESULTS AND DISCUSSION

The presence of cogging torque needs to be reduced. Referring to the methodology that has been developed to reduce the cogging torque in electric motors, the first step is to enlarge the air gap by reducing the outer rotor diameter. The amount of air gap applied is still within the range that meets the good performance of the electric motor's working target. If the result of the cogging torque obtained is still not as expected, it is necessary to consider continuously adding skew to the stator slot. The results of these changes are validated by simulation using the FEA method or using Ansys Maxwell.

The simulation of the electric motor model by changing the air gap from 0.5 mm to 0.75 mm has been carried out. **FIGURE 6** shows the construction of the design after changing the air gap.

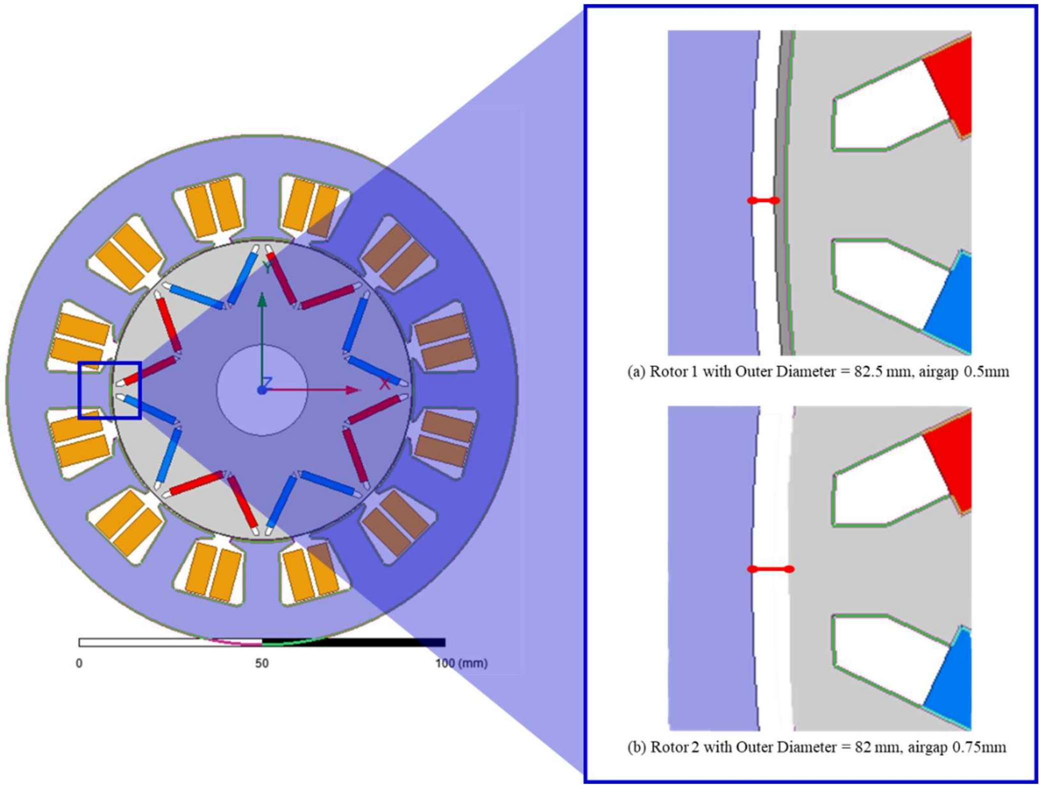

FIGURE 6. *Design IPM V-Shape BLDC Motor with Air Gap Modifications*

The simulation results show that the motor performance still meets the requirements after airgap change. The peak-to-peak of cogging torque value is 12.973 Nm at airgap 0.5 mm and the peak-to-peak of cogging torque value is 10.254 Nm at airgap 0.75 mm as shown in Table 5. Cogging Torque is the result of the magnetic attraction between the stator and rotor. Based on the mathematical equation of the cogging torque, if the displacement value of the movable part (rotor) is increased, the value of the cogging torque will be decreased.

It can be said that there's a reduction of cogging torque, but it is still high. So, calculations and simulations are carried out by adding skew to the stator slot. The calculation of the skew angle is determined by the number of poles and stator slots as shown in Equations 5 and 6. The optimal skew angle for 8 poles and 12 stator slots is 15 degrees. **FIGURE 7** shows the construction of the design after using the skew method.

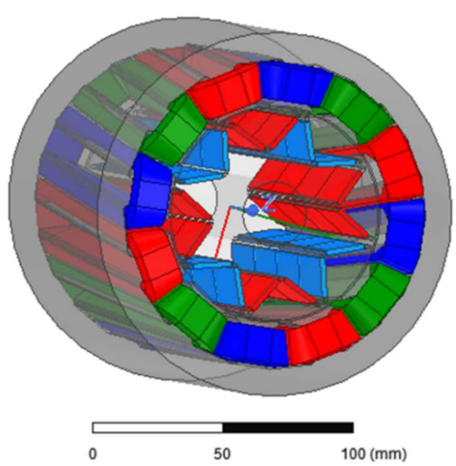

FIGURE 7. *Design IPM V-Shape BLDC Motor using Skew Method*

The summary of simulation results is shown in **TABLE 5** and the comparation of cogging torque is shown in **FIGURE 8**.

TABLE 5. *Result of Simulation by Increasing the Airgap and Adding Skew to the Stator*

Parameter	Value	Value	Value	Unit
Airgap	0.5	0.75	0.75	mm
Skew Width	0	0	15	deg
Speed	3000	3000	3000	Rpm
Power Output	10.6	10.6	10.6	kW
Cogging Torque	12.973	10.254	0	Nm
Torque Ripple	12.088	12.274	0,0156	%
Shaft Torque	33.74	33.74	33.74	Nm
Max Torque	35.140	34.505	35.781	Nm
Eff	93.899	93.722	93.148	%

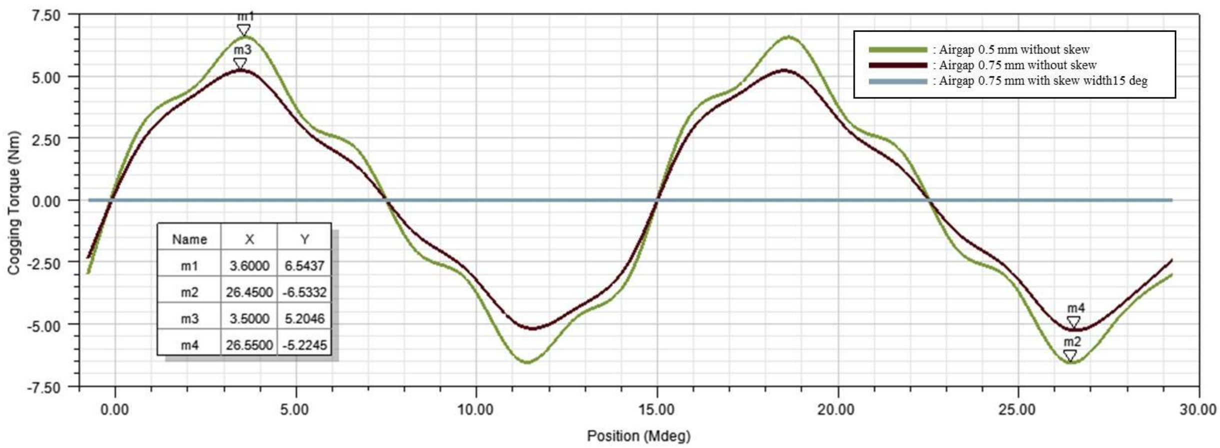

FIGURE 8. *Graphic of Cogging Torque with Airgap 0.5 mm, 0.75 mm, and Skew Width 15 degree*

Based on the FEA simulation results shown in **TABLE 5** and **FIGURE 8**, the skew method will reduce the flux variation and the cogging torque will be reduced. With the motor design 15 degrees skew angle in stator slots and the airgap 0.75 mm, there is a decrease in cogging torque. By comparing the cogging torque on the airgap 0.75 mm, the prior cogging torque value is 10.254 Nm, then decrease to approximately 0 Nm. While the stator design that does not use the skew method does not occur flux variations in the slot width and slot length simultaneously.

The addition of skew in the stator slot has the effect of decreasing the torque ripple from 12.274% to 0.0156%. However, the addition of skew in the stator slot has an effect on efficiency, which causes a slight decrease from 93.722% to 93.148%. Since increases in the length of the stator winding cause an increase in copper losses.

CONCLUSION

In the study and simulations, several methods were carried out to reduce the cogging torque on the IPM V-Shape BLDC Motor. Based on the mathematical equation of the cogging torque, the first method is to change the value of the air gap value. This method is closely related to magnetic energy between stator and rotor. Based on the results of the simulation carried out with the addition of an air gap from 0.5 mm to 0.75 mm, there was a decrease in cogging torque but not significant, with a decrease of about 21% from the initial cogging torque value. The second method used is the skew method, with a mathematical equation that the value of the cogging torque skew method is related to the skew angle, the optimal skew angle value is 15 degrees. This method can reduce the cogging torque by almost 100%. In both methods, there is a slight reduction in the efficiency of the motor performance.

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