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A PARAMETERISED MAGNETIC GEARED DOUBLE-STATOR PERMANENT MAGNET GENERATOR FOR TORQUE IMPROVEMENT

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Abstract

This paper studies a magnetic geared dual-stator machine with a dual-iron ring structure, which is proposed for low-speed power generators. To improve the torque performance, a parameterised design approach using 2-D finite element method (2D-FEM) is used to calculate the transmission torque and analyse the relationship between the geometrical parameters and maximum torque. The geometrical design parameters include the thickness of the pole pieces, thickness, and width of the magnets. The operating principle of the magnetically geared generator is based on three permanent magnet rotors that rotate independently. The magnetic geared generator's operating principle is discussed and presented. In addition, the transmission torque characteristics of the parameterised generator are analysed and reported. The results demonstrate that the parameterised design analysis can increase the torque density of the magnetically geared PM machine.

Keywords: Dual-iron, Dual-stator, Element method, Finite, Magnetic gear (MG), Parameterised, Torque.

1. Introduction

Recently, research on Permanent Magnet (PM) machines with a double-stator topology have increased because of their greater performance characteristics, compared to conventional single-stator permanent magnet machines as reported in some studies [1, 2]. Wang et al. [3] reported that various types of dual-stator PM machines produce higher output torque with high-torque densities. Magnetic gearing and magnetic geared integrated machines have generated renewed interest in the last decade because magnetic gears are potential new emerging technologies to replace mechanical gears and address problems of oil, lubrication, friction, non-contact transmission and inherent overload protection.

Magnetically geared machines are a new category of electrical machines, which can be designed as magnetic geared motors [4] or magnetic geared generators [5, 6]. In addition, the magnetic gears integrated with dual-stator PM machines have produced various proposed designs of dual-stator Magnetically Geared PM Machines (MGDSPMMs). Although there have been little publications on this class of magnetically geared PM machines, which may be likely because of its complex structure and difficulty in the mechanical assembly.

The structure of this type of machine is derived by integrating a dual-stator PM machine with a coaxial magnetic gear. Jian et al. proposed a magnetic geared electronic-continuously variable PM machine and found that the use of Halbach arrays could reduce cogging torque and improve transmission torque [7]. Liu et al. [8] proposed a magnetic geared dual-stator single-rotor machine with single-ring and dual-ring structures. A 2D finite element method was used to evaluate the two presented machine designs and the results showed that the dual-iron ring structure produced a torque density greater than the single iron-ring structure. Although the two proposed structures were characterised by high cogging torques.

Liu et al. [8] presented a dual-stator dual-rotor magnetic geared PM machine for an electrical continuously variable transmission system and found that the transmission torque can be improved by skewing the stators. Wang et al. [9] presented two new designs of magnetically geared mnemonic machines. The two proposed machine designs were analysed and compared using 2D finite element method. The performance analysis results showed that the dual-layer machine achieved greater torque density than the single-layer machine. Although the two proposed machine designs were characterised with high torque ripples and cogging torques as a result of reluctance torque. However, improvement of the transmission torque for magnetically geared dual-stator PM machines, which is one of the most important factors for high-torque density performance has not been investigated.

In addition, the cogging torque is another area that needs to be addressed as it can result in high torque ripple, noise and vibrations to the machine. This study aims to improve the torque capability of a magnetically geared generator and achieve an optimal design with high torque density. In this paper, a parameterised magnetically geared dual-stator PM machine to improve transmission torque performance and reduce cogging is presented. Moreover, the performance characteristics of the parameterised machine are compared with the proposed original structure shown in Fig. 1.

2. Design of Magnetic-Geared Generator

2.1. Machine structure

A magnetic-geared generator, which is derived from a three rotor magnetic gear integrated with a dual-stator PM machine in a magnetically coupled configuration is shown in Fig. 1. Eight poles of PMs are mounted on the inner and outer rotors while 26 poles of PMs are mounted on the middle prime rotor. Two iron rings composed of 17 ferromagnetic poles pieces are inserted between the field magnets and prime magnets. A three-phase concentrated winding scheme is used for the 12-slot outer and inner stators. The specifications of the magnetically geared generator are listed in Table 1.

Table 1. Specifications of the magnetically geared generator.

Parameter	Value
Number of pole-pair field magnets	4
Number of pole-pair prime magnets	13
Number of pole pieces	17
Number of stator slots (inner and outer)	12
Outer diameter (mm)	150
Axial length (mm)	30
Airgap length (mm)	1
Gear ratio	3.25

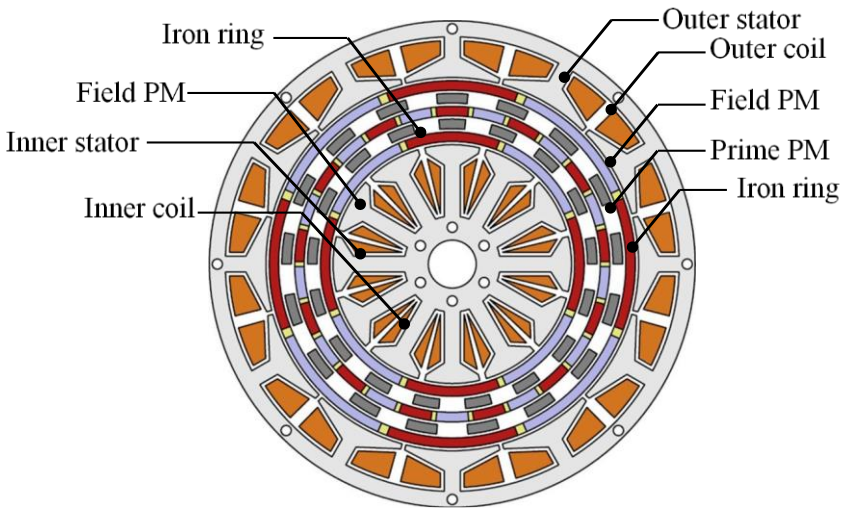


Fig. 1. Magnetically geared dual-stator PM generator.

2.2. Principle of operation

The proposed dual-stator magnetically geared generator is comprised of three permanent magnet rotors; an outer high-speed rotor, a middle low-speed rotor and an inner high-speed rotor. The MG and generator both have mutual magnetic circuits in a magnetically coupled configuration [10, 11]. The input shaft is coupled to the middle prime rotor and when it is rotated, the stationary pole pieces modulates the asynchronous space harmonics in the air gap magnetic fields

produced from the PMs. The mechanical assembly of the MG generator is achieved by integrating a three-rotor magnetic gear with the dual-stator PM machine. A magnetically coupled configuration with few numbers of PMs is realized by placing the PMs between three bone rotors.

Atallah and Howe [12] explained that the inner and outer pole-pair numbers of permanent magnets govern the operating principle of a magnetic gear and space harmonic flux density distribution produced can be expressed by:

$$p_{m,k} = |mp+kn_s|$$

$$m = 1,3,5, \ldots, \quad (1)$$

$$k = 0, \pm1, \pm2, \pm3, \ldots, \pm\infty$$

where p is the pole-pair number of PMs and n_s the number of steel pole pieces. The angular speed of the magnetic flux density space harmonics is expressed by:

$$\omega_{\mathrm{m,k}} = \frac{mp}{mp+kn_{\mathrm{s}})}\omega_{\mathrm{r}} \quad (2)$$

where ω_r is the angular rotational speed of the PM rotor. From Eq. (2), it can be seen that the introduction of steel pole pieces results to space harmonics with velocities different from the velocity of the PM rotor. Therefore, for torque to be transmitted at various angular speeds, the pole-pair number of magnets must be equal to the pole-pair number of space harmonic for which, $k \neq 0$. In addition, for $m = 1$, $k = 1$, which is the greatest asynchronous space harmonic, the pole-pair number of magnets must be equal to (n_s-p). A constant torque is produced as p_1, p_2 and n_s are governed by:

$$n_s = p_1 + p_2 \quad (3)$$

If the ferromagnetic pole pieces are kept stationary the magnetic gear ratio can be determined by:

$$G_{\mathrm{ratio}} = \frac{p}{p-n_s} \quad (4)$$

3. Simulation Analysis of Torque Characteristics

The middle prime rotor is rotated in according to the gear ratio speed of the magnetic gear. The outer and inner rotors are rotated at an increased ratio of 3.25 relative to the speed of the prime rotor.

A parametric analysis approach is used to investigate the transmission torque for improvement. Transient magnetic field analysis is conducted by using 2D FEM that includes the nodal force method [13, 14].

Parametric studies

Parametric analysis is an analytical method for finding a parametric solution for optimizing an electrical machine design [15, 16]. A variable is assigned to various geometrical structures of the electric machine and the simulation steps are conducted within the upper and lower boundary limits. For the parameterised design, geometric parameters such as the thickness of the PMs and pole pieces are parametrically solved to obtain the optimal values of the MG machine design for improving transmission torque. In this study, the parametric analysis is conducted

on the magnetic gear part only in order to obtain an optimum level of physical dimensions for the proposed magnetic geared generator. The analysis is given as:

- Effect of variable pole piece thickness on generator torque and power.
- Effect of variable pole piece thickness on generator torque.

Before starting the parametric analysis the initial 2D geometry model is created with the FEM software by defining all the parameters that will be assigned variables. The effect of the variable pole piece and permanent magnet thickness on transmission torque is investigated in this study by assigning initial model parameters with boundary constraints.

Figure 2 illustrates a quarter section of the magnetically geared generator with geometry parameters that are parameterised. Those parameters are field magnet thickness, prime magnet thickness, and pole piece thickness.

In this study, a parameterization approach method was selected for improving the transmission torque while the geometric design variables selected are shown in Fig. 2 with the parameter constraints as in Table 2. The parameterization approach method used is illustrated in Fig. 3.

Table 2. Selected parameters from the model that are parameterised.

Parameter (mm)	Boundary constraints (min, max)
t_{pp1}	Wang et al. [3] and Mustafa et al. [10]
t_{pp2}	Wang et al. [3] and Mustafa et al. [10]
t_{inner}	Wang et al. [3] and Liu et al. [8]
t_{outer}	Wang et al. [3] and Liu et al. [8]
t_{prime}	Wang et al. [3] and Liu et al. [8]

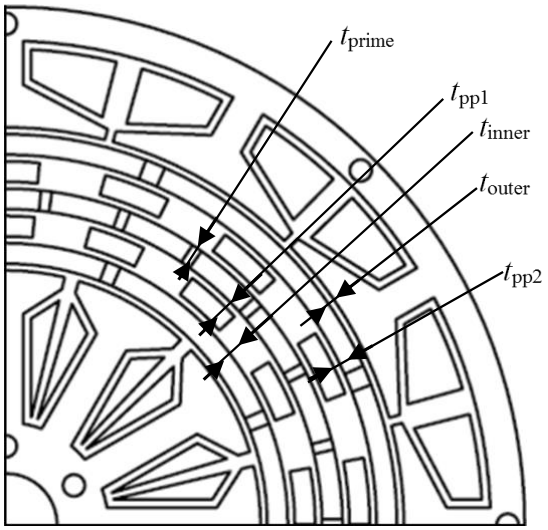


Fig. 2. Cross-section of magnetically geared generator with parameters selected for parameterization.

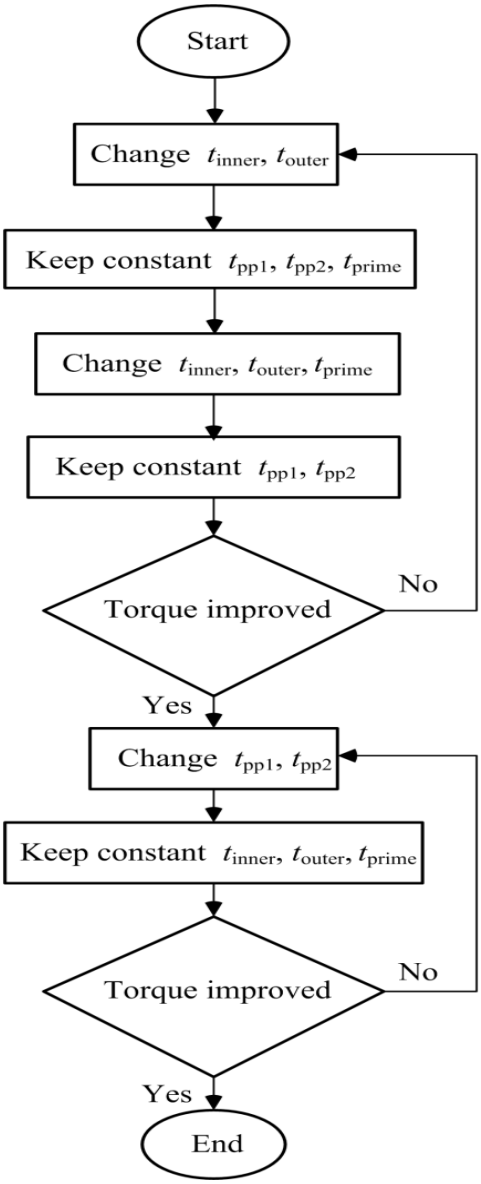


Fig. 3. A flowchart of parameterization approach used for magnetically geared generator.

4. Results and Discussion

The torque improvement of the magnetically geared generator was selected with the aim of increasing the transmission torque on the prime, inner and outer rotors respectively. Although optimization would have been a suitable design choice due to the complexity of the machine and a large number of design variables required, a detailed optimization is beyond the scope of this study. With these design variables selected, two possible combinations were investigated firstly, by maintaining the iron ring thickness constant and varying the permanent magnets

and secondly, by maintaining permanent magnets thickness constant and varying the iron ring dimensions. All parametric designs were evaluated by 2D FEM and the results are illustrated in Figs. 4 and 5.

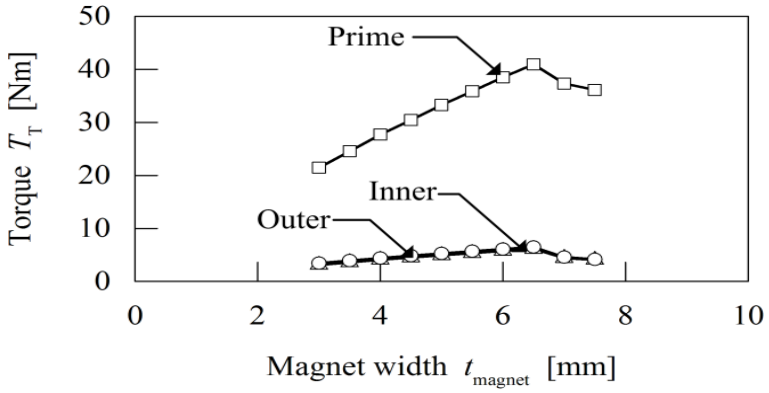
4.1. Effect of magnet thickness

When the permanent magnets are increased in thickness as shown in Fig. 4(a) it is observed that the transmission torque on the prime PM rotors increases linearly at maximum ≈ 43 Nm before decreasing further due to saturation. In addition, the cogging torque shown in Fig. 4(b) from the outer stator is much greater compared to the inner stator because as the outer magnet increases in width, the magneto-motive force generated from the outer field PMs increases, therefore, resulting to greater magnetic flux density in the outer stators. It can be argued that a suitable choice for the permanent thickness would be between 6-6.5 mm, where the prime torque is at maximum value, however, if the permanent magnet thickness is too large, it would result to saturation of the MG machine.

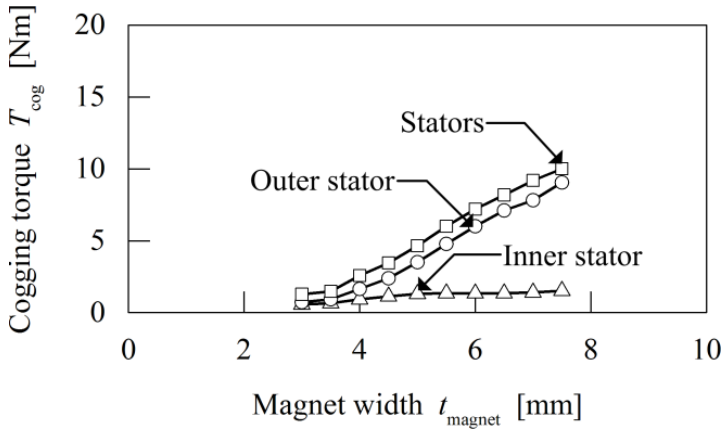
4.2. Effect of pole piece thickness

In Fig. 4(c), when the iron ring thickness is increased with constant PM dimension, the prime torque increases further at maximum ≈ 63 Nm until the torque is constant. In addition, the cogging torque as shown in Fig. 4(d) is greater particularly from the outer stator due to the increased length of the outer field PMs This observation demonstrates that the iron ring has a greater influence on transmission torque and all three permanent magnets should have equal thickness because the three permanent magnets are in a magnetically coupled configuration. If the iron rings are lesser in thickness than the permanent magnets, saturation will occur, therefore, resulting to decrease in transmission torque.

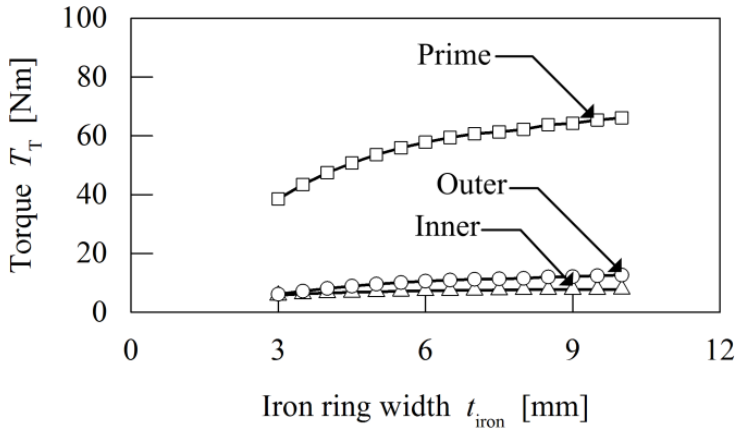
As shown seen in Fig. 5(a) the torque waveforms of the outer rotor, inner rotor, and prime rotor are characterised with lesser ripple as a result of low cogging torque while the improved transmission torque waveform shown in Fig. 5(b) is characterised with high torque ripple because the cogging torque is increased. A summary of the transmission torque characteristics is listed in Table 3.



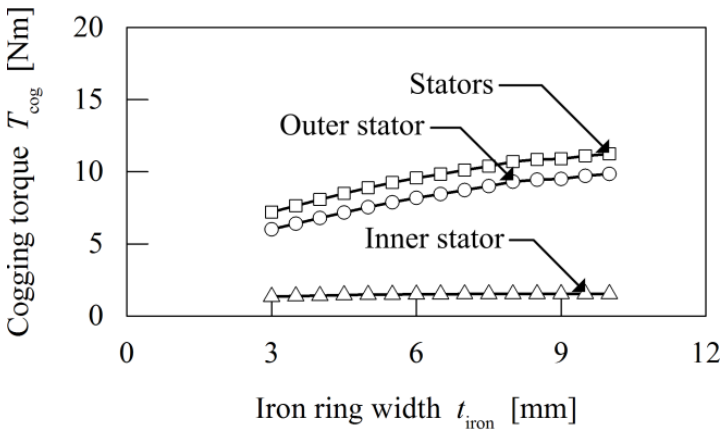
(a) Effect of permanent magnet thickness on transmission torque.



(b) Effect of permanent magnet thickness on cogging torque.



(c) Effect of iron ring thickness on transmission.

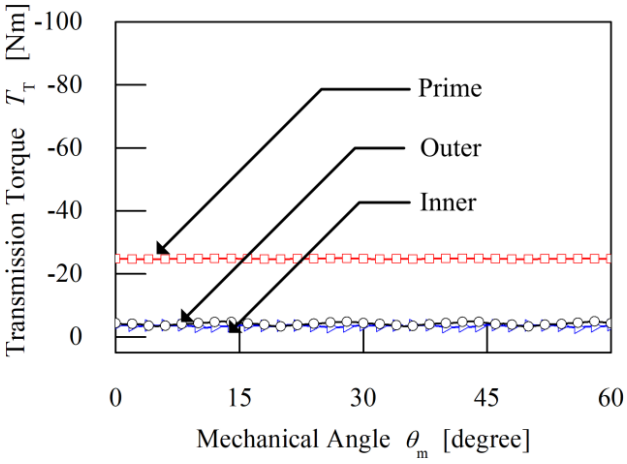


(d) Cogging torque as a function of iron ring thickness.

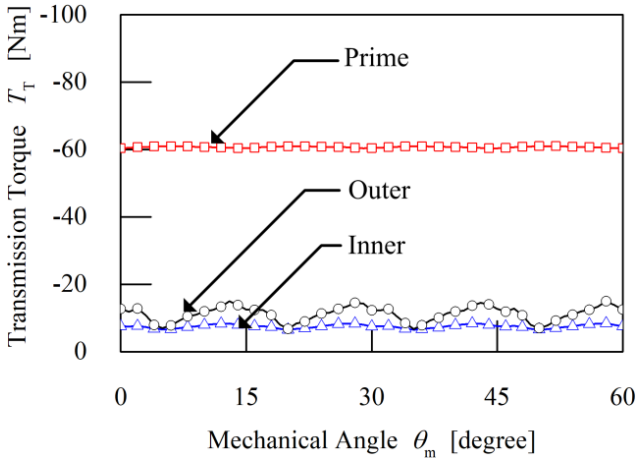
Fig. 4. Improved torque by parameterization with a fixed iron ring of 3 mm and variable permanent magnet thickness.

Table 3. Summary of magnetic geared generator's transmission torque.

Parameter	Original model	Parameterized model
Prime rotor torque	23 Nm	63 Nm
Outer rotor torque	4 Nm	10 Nm
Inner rotor torque	3 Nm	9 Nm



(a) Transmission torque waveform from original model.



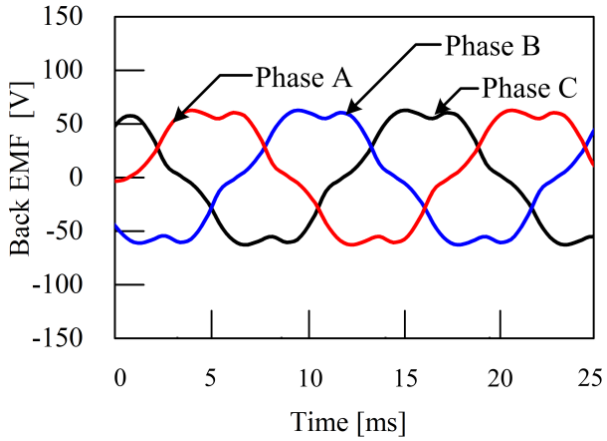
(b) Improved transmission torque from parameterised model.

Fig. 5. Transmission torque waveforms of magnetically geared generator.

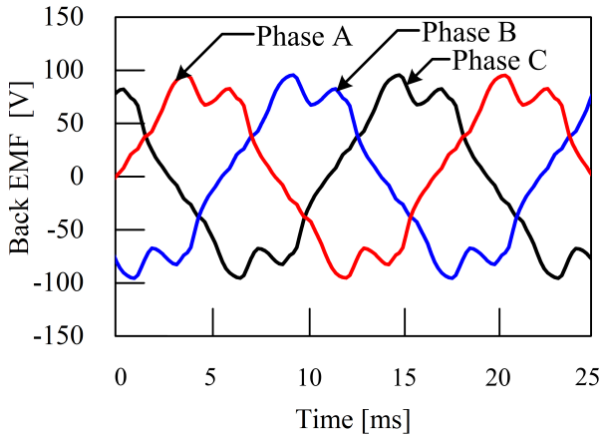
4.3. Effect on back EMF voltage

The back EMF as a result of varying the magnet thickness is shown in Fig. 6. The back EMF increases as the magnet thickness are increased. The voltage waveform from the original model in Fig. 6(a) is much better than the parameterised model in

Fig. 6(b), however, the voltage waveform from the improved model is greater in amplitude because the electromotive force produced from the field magnets is higher due to increased width and thickness. The induced peak-to-peak voltages from the original and parameterised model are 55 V and 100 V respectively for a double layer three-phase concentrated winding. The back EMF peak-to-peak voltages generated from the original and parameterised models are 55 V and 100 V respectively. It can be seen that the no-load voltage waveforms display non-sinusoidal properties as a result of harmonics, which is common in three-phase concentrated windings. Though, these harmonics could be mitigated by appropriate choice in the coil winding design.



(a) Back EMF of original MG generator model.



(b) Back EMF of parameterised MG generator model.

Fig. 6. Back EMF waveforms of both models at prime speed of 200 rpm.

The results from the parameterised model are shown in Fig. 7 and it can be observed that the best solution is obtained when the magnet thickness is = 6 mm while the pole pieces are = 5 mm. If the magnet thickness is increased the pole piece also needs to be increased in thickness to avoid magnetic flux saturation. In

addition, the prime and field magnets need to be equal in dimension to obtain a balanced design similarly for the pole pieces. A summary of the results from the parametric analysis of the magnetically geared generator is shown in Table 4.

Table 4. Parameterized results of the magnetic geared generator.

Parameter	Initial value (mm)	Best value (mm)
Prime magnet thickness	3	6
Outer field magnet thickness	3	6
Inner field magnet thickness	3	6
Outer pole piece thickness	3	5
Inner pole piece thickness	3	5

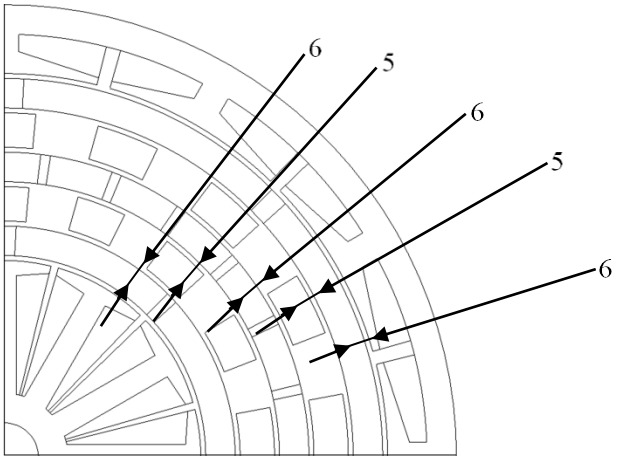


Fig. 7. Structure of parameterised magnetic geared double-stator PM generator for torque improvement (mm).

5. Conclusions

A parameterised magnetically geared dual-stator PM generator has been presented in this study for the purpose of improving the transmission torque capacity of the generator. A 2D FEM has been conducted by selecting the magnet and pole piece thickness as design variables. The purpose of varying the magnet and pole piece was to yield further improvement in the transmission torque and also identify their effect on the cogging torque.

The analysis results showed that to obtain optimum results the prime and field magnets should have the same thickness similarly for both inner and outer pole pieces. There was at least a 50% increase in torque for the prime rotor, outer field rotor, and inner field rotor respectively. The parameterised model proved to be a better solution for torque improvement including increased no-load output voltage. Though the back EMF waveform is not sinusoidal and is characterised by harmonics. In addition, the improved model has greater cogging torque, which needs to be minimized for proper operation of the magnetically geared generator.

Nomenclatures

G_{ratio}	Magnetic gear ratio
n_s	Pole piece number
p_1	Pole-pair number of outer permanent magnets
p_2	Pole-pair number of inner permanent magnets
t_{inner}	Thickness inner field permanent magnet
t_{outer}	Thickness outer field permanent magnet
t_{pp1}	Thickness outer pole piece
t_{pp2}	Thickness inner pole piece
t_{prime}	Thickness prime magnet

Greek Symbols

ω	Angular rotational speed of rotor.

Abbreviations

FEM	Finite Element Method
MG	Magnetic Gear
PM	Permanent Magnet

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