International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 15, No. 1, March 2024, pp. 91~97
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v15.i1.pp91-97

Hybrid-excited magnetic gear topology for improved gear efficiency at increasing rotor speed

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Article Info

Article history:

Received Dec 13, 2022
Revised Feb 20, 2023
Accepted Mar 6, 2023

Keywords:

Eddy current loss
Efficiency
Electrical machine design
Hybrid excited machine
Magnetic gear

ABSTRACT

Concentric magnetic gear (CMG) and rotating pole piece magnetic gear (RPMG) are two topologies that produce high torque density in magnetic gear (MG) for electrical machine. However, due to the eddy current loss, both suffer high losses when operated in high speed condition. Thus, to overcome this matter, a second flux source is proposed to the RPMG stator. This approach will then transform it into hybrid excited magnetic gear (HMG) topology to achieve higher gear efficiency. Three tooth slot designs were considered, and the outcome of these designs are summarized and ranked. The proposed structures are assessed using JMAG designer 2D finite element software in high speed condition. It is found that partially closed slot structure achieved the highest gear efficiency of 95.34% and average outer rotor torque of 115.64 N.m.

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1. INTRODUCTION

The topic of magnetic gear (MG) is one of the most actively researched nowadays mainly because contactless torque and rotation transmission can be achieved [1]. Physical contacts are required in mechanical gears to transfer torque, which usually leads to oscillation-induced noise, tooth wear, and the possibility of tooth failure [2]. MGs present no wear, no friction, and no fatigue, in addition to requiring no lubricant, and can be customized for other mechanical properties, such as stiffness or damping. Additionally, MG are also able to protect the structure and mechanism against overload. Besides that, MG are suitable for through-wall transmission requiring no joints or sealing [3]. As a result, the higher reliability and stability could give way for MG to replace mechanical gears in the near future. MG have been used more and more in robotic applications that require high operating speeds and step-less speed control, such as electric vehicles and robot joints [4]–[6]. MG are also studied and developed in aerospace and renewable energy applications that require precise power transfer [2], [3], [7]. In the late of 19th century, the discovery of rare-earth neodymium-iron-boron (NdFeB) permanent magnets (PM) appears to have piqued the curiosity of machine designers. A spur magnetic gear structure employing the NdFeB PM was simulated and verified with 2D analytical calculations. The torque density achieved after extrapolation reached 30 kN.m/m^3 at the smallest air gap of 0.5 mm [8], [9]. The research for high-performance magnetic gears continued and in 2001, a high-performance coaxial MG design was published [10]. Coaxial can be translated as the rotor input and output sharing the same center point. Torque and rotation were transferred from one rotor to another using the flux modulation technique. Figure 1 shows the structure of a coaxial magnetic gear, which is also known as concentric magnetic gear (CMG), using the flux modulation principle. It consists of three coaxial components, i.e., stationary ferromagnetic pole pieces (FMP), an inner pole pair (IPP), and an outer pole pair (OPP). Both IPP and OPP rotors are made of surface-mounted PM and a yoke [10]. The magnetic field of the inner rotor is modulated through the stationary FMP. The prototype of the CMG was fabricated and reported in later publications. According to Atallah *et al.* [11], [12], the transmitted torque density can reach up to 100 kN.m/m^3 and 97% gear efficiency at 1500 rpm.

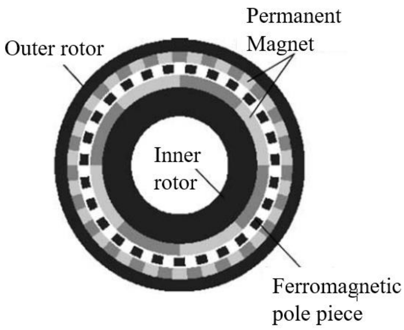

Figure 1. Structure of surface-mount CMG [10]

Since the demand for high efficiency and compact gears has increased, hence also the need to accommodate devices that incorporate miniscule and energy efficiency in their design. The presence of high-energy-density PM in CMG contributes to a large increase in eddy current loss in magnetic gears, particularly during high-speed operations, and lowering gear efficiency [13]–[16]. A reduction in gear efficiency weakens torque capability, hence rendering for lower torque density. An alternative operating topology is by making the FMP to deliver the torque and rotation, while the OPP is let stationary. This would yield a higher torque transmission. This topology is referred to as the rotating-pole-piece magnetic gear (RPMG) [17], [18]. Since the outer components of the RPMG is stationary, a second flux source can be designed on it to reduce the use of PM material in RPMG. There were several designs published concerning dual-flux source MG [5], [19], [20]. In this paper, an auxiliary DC winding is added to the RPMG to improve the gear efficiency, and is evaluated on RPMG using 2D finite element method in high-speed operation. Three tooth slot designs were considered, and the outcome of these designs are summarized and ranked. This paper is organized as: i) Section 2 describe the method used to design the second flux source of the HMG and simulation configuration; ii) Section 3 shows the result of the simulation which includes the heat map of the magnetic field density, torque and gear efficiency; and iii) Section 4 summarize the work and highlights the important finding.

2. METHOD

A secondary flux source is designed and added to the outer yoke of RPMG. A DC current is channeled to the winding according to the allowable current density. This design is then simulated at increasing rotor speed. The torque and efficiency behaviors are recorded and compared.

2.1. General setting

The torque and efficiency models are constructed with increasing rotor speed. The rotor speed conditions are shown in Table 1. Table 2 lists the items utilized in this simulation. The torque measurements at the inner and outer rotors are in transient mode. As a result, the integral average is employed to compute efficiency. The gear ratio is 7.66, with pole pair combinations of 6, 46, and 40 for the inner pole pair, ferromagnetic pole piece, and outside pole pair.

Table 1. Rotor speed conditions to construct torque and efficiency models

	Rotor speed condition (rpm)							
	Case 1		Case 2		Case 3		Case 4	
Gear ratio	Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
7.66	1532	200	3064	400	6128	800	12256	1600

Table 2. Material used in simulation

Component	Material	Remarks
Inner yoke	NSSMC 35H210	Saturation point: 1.8T
Outer yoke		
Pole piece		
Magnet	Hitachi NEOMAX 35AH	1.2 T residual

2.2. DC flux source's influence on gear efficiency

To reduce the effect of eddy current during high-speed operations in the CMG or RPMG, an auxiliary DC flux source is proposed to be used to reinforce the magnetic field at the air gap. This type of MG can be described as a hybrid-excited magnetic gear. The most suitable location to place the DC flux source is at the stationary component. However, since the stationary component in the CMG is the FMP, the flux modulation principle would not work. The FMP provided the flux path in two directions, and thus a single flux direction produced by the DC coil would interfere with the modulation process. If an AC coil is used, a power electronics driver (PED) will be required to match the direction of the flux while it rotates. Furthermore, the PED design would have to consider the gap between the FMP to accurately time the flux direction. A more practical solution is to employ a DC coil on the outer yoke of the RPMG. There are a few options to place the coil to supplement the flux to the existing outer PM. The stator tooth shapes are structured so that the flux induced from the DC coil flowed in series to the flux produced by the outer PM. Three basic shapes are considered based on the slot opening [20]–[22]. Open-slot shape, partially-closed-slot shape and fully-closed-slot shape with different tooth sizes are examined. Figures 2(a)-2(c) show the rectilinear view of the stator tooth shapes under consideration. To ensure a fair comparison, a similar volume is designed on the stator tooth for each shape. Other structure specifications and dimensions are the same as in Table 1 and Table 2. Table 3 shows the dimension of the stator tooth shape.

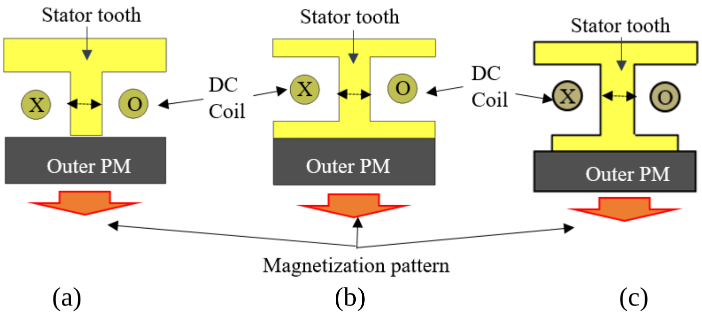

Figure 2. Rectilinear view of stator tooth shapes under consideration: (a) open slot, (b) fully closed slot, and (c) partially closed slot

Table 3. Dimension of stator tooth shape

Parameter	Unit	Open slot	Fully closed	Semi-closed
R1	mm	100	100	100
R2	mm	95	97.5	95.42
R3	mm	80	80	80
R4	mm	-	82.95	81
R5	mm	-	-	2
Θ1	degree	4.5	4.5	4.5
Θ2	degree	2	2	2
Θ3	degree	2	2	2

Based on several publications, the filling factor, or the ratio of the area occupied in a slot, can be set within 0.5 to 0.85 range [23]–[25]. To allow enough room for assembly, the filling factor is set at 0.5. The maximum current density set in this project is 20 A/mm^2. The coil on the other hand is connected in a closed circuit to a DC source. As current wrapped around the tooth, it created a flux within the tooth in the similar direction to the PMs' flux direction. A larger radius was set for the OPP to allow enough room for this addition.

2.3. Simulation flow

The first step of the simulation is to construct the magnetic gear structure according to dimension described in Table 3. This can be done through the JMAG geometry editor. The next step is to import the geometry to the JMAG designer environment. In this step, the materials for each of the MG components are set. Coil is added within the slot and is connected to an external current source. The rotation condition is based on Table 1. The mesh size for this study is 0.5 mm. 2D transient analysis is performed for each rotation condition and current density. A contour magnetic field density plot is used to observe the flux leakage. The torque data for both IPP and FMP can be obtained directly after the simulation completed. The gear efficiency can be calculated based on the average torque and the rotational condition.

3. RESULTS AND DISCUSSION

This research is being carried out in order to determine the optimal stator tooth form that will provide a good flux coupling between the PM and the yoke, hence enhancing the magnetic flux density at the air gap. The selected designs have the same dimension as that of the original shape of the RPMG. The changes are at the OPP, where the stator and slot are created on the yoke. The OPP's radius is extended to 95 mm to allow the incorporation of the stator tooth and slot. The open-slot shape, fully-closed-slot shape and partially-closed-slot shape were evaluated in this analysis. The flux linkage can be analyzed by observing the magnetic flux density of the structure. Figures 3(a)-3(c) show the magnetic flux density for each of the stator tooth shape. The contour plot level was the same in all graphs and is shown in Figure 3(d). According to the result, the open-slot shape allowed the flux to flow around the tooth. The flux path in the fully-closed-slot shape was longer and had denser flux lines. In the fully-closed-slot shape, the yoke around the outer PM short-circuited the flux that was meant to flow around the tooth. On the other hand, the partially-closed-slot shape showed a better linkage between the flux from the outer PM and the stator. Since the PM flux cannot flow to the adjacent PM, it was forced to choose the tooth as its flux path. Most teeth showed signs of magnetic saturation. It is well known that soft iron has very little reluctance. However, saturation becomes more apparent as it approaches a specific limit, depending upon the material's characteristics. The B-H curve for NSSMC 35H210 shows that saturation occurs around the 1.8T level.

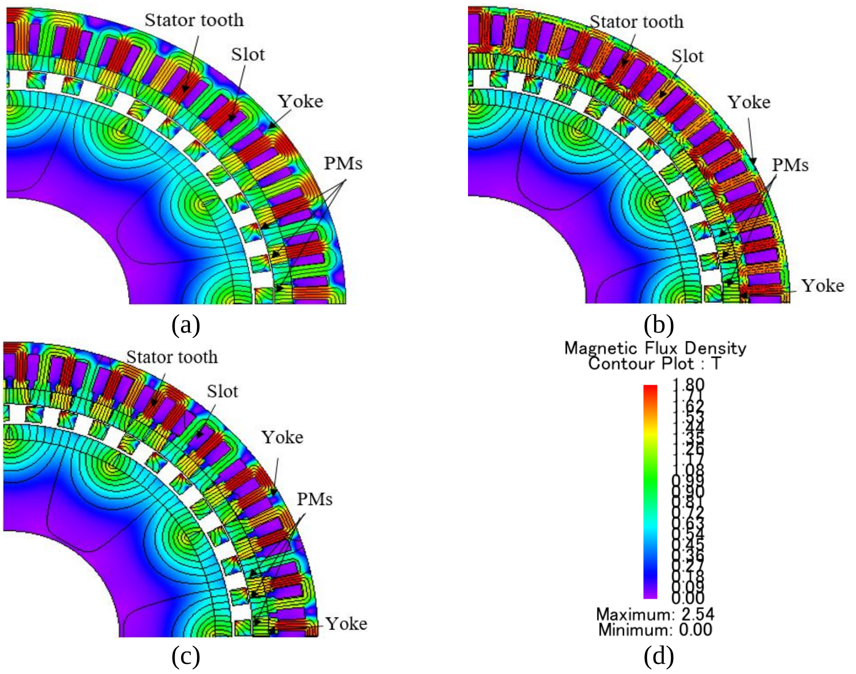

Figure 3. Magnetic flux density for: (a) open-slot shape, (b) fully-closed-slot shape, (c) partially-closed-slot shape, and (d) contour levels for (a), (b) and (c) plots

Further measurements at the outer air gap revealed that the magnetic flux density was also the same for all the shapes when the current density (J_e) was either at 0 A/mm^2 or 20 A/mm^2. Figure 4 displays magnetic flux density at the outer air gap from the open-slot shape. Magnetic flux density is the most important factor influencing the amount of electromagnetic torque that the RPMG could produce. If no changes were observed in the magnetic field density magnitude when J_e increased, the same effect should be expected on the torque generation. Figures 5(a) and 5(b) indicate that the inner rotor torque and outer rotor torque in the RPMG employing the closed-slot shape at three J_e values. Figure 6 shows η_G values calculated for the closed-slot shape at increasing speed. The changes seen in η_G at different J_e levels were low, especially at the inner rotor. Table 4 summarized the results obtained from the stator tooth shape's evaluation. In general, there were noticeable slight increases in magnetic flux density, torque and efficiency. Yet, the increase in η_G still can be improved [20]. The improvement in η_G is trivial if a lower J_e was applied.

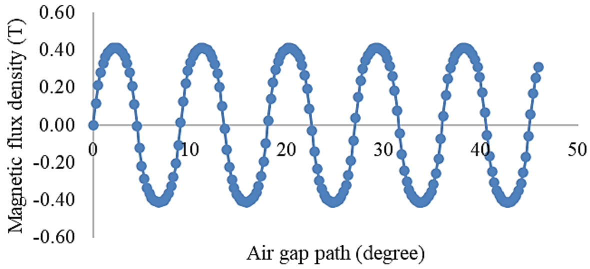

Figure 4. Magnetic flux density around outer air gap measured from open-slot shape

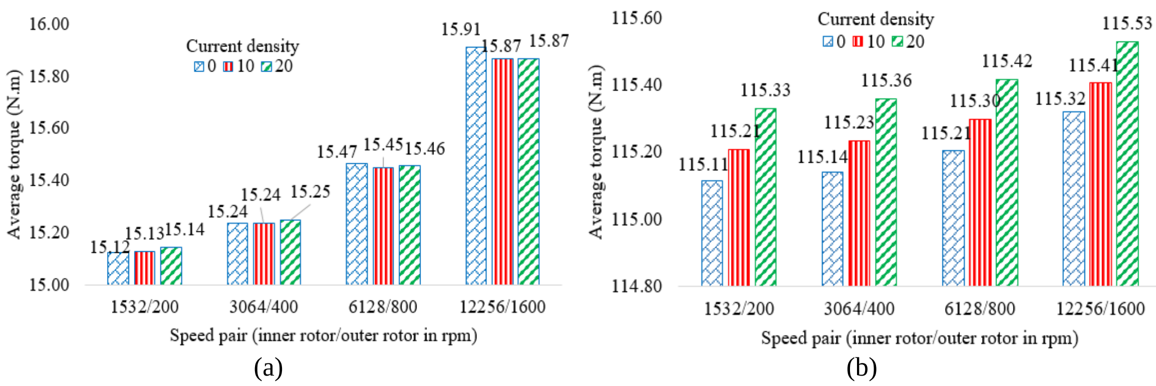

Figure 5. Torque of RPMG employing closed-slot shape at three current density values: (a) inner rotor and (b) outer rotor

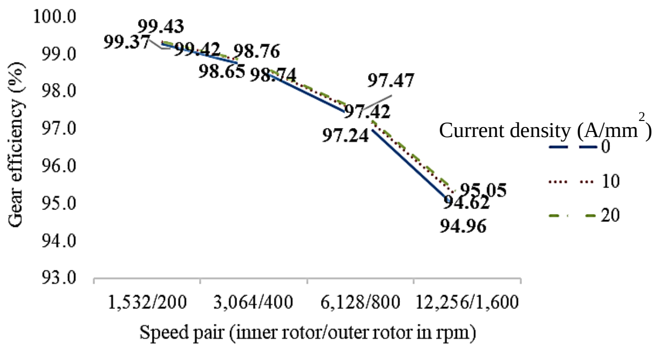

Figure 6. η_G at different current density levels at increasing speed pair for closed-slot shape

Table 4. Stator tooth shapes result at highest speed pair condition of 12,256/1,600 rpm for 0 A/mm^2 and 20 A/mm^2

Current density	Shapes	Outer air gap magnetic flux density (RMS) (T)	Average inner rotor torque (N.m)	Average outer rotor torque (N.m)	Average gear efficiency (%)
0A/mm^2	Open slot	0.3238	15.78	114.59	94.75
	Closed slot	0.3255	15.91	115.32	94.62
	Partially closed slot	0.3247	15.8	114.79	94.82
20 A/mm^2	Open slot	0.3272	15.87	115.7	95.17
	Closed slot	0.3257	15.87	115.53	95.05
	Partially closed slot	0.3263	15.83	115.64	95.34

4. CONCLUSION

Two topologies that produce high torque density in magnetic gear are CMG and RPMG. Yet, both suffer high losses when operated in high-speed condition. This loss is mainly contributed by eddy current loss. To overcome this issue, a second flux source is added to the RPMG to compensate the loss from the eddy current which transform it into HMG. From the result, it was found that when a second flux source was introduced to the stator, the gear efficiency was improved, especially on the partially closed structure. However, the improvement achieved from the partially closed structure was only 0.525%. Due to the lack of slot space and narrow tooth path, high flux leakage was observed around the tooth area. The flux leakage caused the flux which was provided by the second flux source became ineffective. To provide a wider tooth, the author suggests selecting a lower pole pair combination such as 3, 23, and 26 for inner pole pair, ferromagnetic pole piece and outer pole pair respectively. If an RPMG uses this pole pair combination, the area of the slot will increase, and thus the effectiveness of the second flux source is expected to be more significant. This study will be pursued further in the future.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Higher Education Malaysia (MOHE), Universiti Teknikal Malaysia Melaka (UTeM), Universiti Tun Hussein Onn Malaysia (UTHM), and UTeM Short Term Research Grant Scheme (PJP/2022/FTKEE/S01880) for the financial support of this research.

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