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The Effect of Variation in the Number of Pole and Air Gap on Torque Density on Radial Magnetic Spur Gear with Magnetic Block

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Abstract

Magnetic gear is an alternative to mechanical gear, where the magnetic gear has the advantages of no noise, minimum vibration, no maintenance required, increased reliability, overload protection capability, no physical contact between gears, and the resulting torque density is still below the mechanical gear torque density. In this research, the variation of the number of poles and air gap in the amount of torque density produced was carried out. The permanent magnet material used is Neodymium type with a gear ratio of 1:2. In the variation of the number of poles used by pairs of 4 and 8 poles, 8 and 16 poles, 10 and 20 poles, and 12 and 24 poles, in the variation of the air gap used, namely 1 mm, 1.2 mm, 1.3 mm, 1.4 mm and 1.5 mm. Magnetic gear performance can be seen through analysis simulation with the 3D finite element method using Finite Elements Software. The type of simulation used is the magnetostatic analysis method at the processing stage and the transient analysis method at the post-processing stage. From the simulation results, it is concluded that the greater the number of poles, the greater the torque density produced, and the closer the air gap distance will result in a greater torque density. The effect of the number of poles on the torque density is more significant than the effect of the air gap.

Keywords: Magnetic gear, spur gear, number of poles, air gap, torque density

1. Introduction

Mechanical gears are the most widely used transmission systems compared to other transmission systems, namely belt-pulleys and chain-sprockets, because they have large transmission capabilities and high efficiency [1–3]. However, high vibration and noise in mechanical gears are of concern to many researchers [4,5]. A growing environmental issue where noise is a serious concern led researchers to look for other transmission systems. Magnetic gears are the right choice by many researchers in terms of reducing noise because there is no direct contact between the two materials [6].

Radial Magnetized spur gear is one of the most commonly used magnetic gears. In this type of magnetic spur gear, the analytical analysis to obtain the torque equation has been described and compared numerically using the finite element method [7,8]. In its application, the shape of a permanent magnet is shown in Figure 1, where the shape of the magnet is the segmentation of a hollow pipe, and the arrangement of the orientation of the magnetic pole alternately without any gaps between them is difficult to make. Permanent magnets on the market are in the form of blocks. To be able to produce gears, the magnetic block is planted on the cylinder in a circular manner with a gap between it. Thus the formulation of the torque that has been generated cannot be used. Torque reduction in accordance with these conditions is also difficult and complex, so the finite element numerical method is used. Numerical modeling on radial magnetic conditions with the shape of a beam has been carried out by [9] with neodymium magnet material and completed with experiments. However, the research did not vary the gap and the number of magnets.

One of the factors to get high torque is the choice of the permanent magnet material. Important properties used to compare permanent magnets include curie temperature (Tc), residual induction (Br), coercivity (Hc), and maximum energy product [(BH) max] [10]. It is known that the greater the residual induction (Br) and coercivity (Hc), the better the properties of the object are to maintain the external magnetic field. However, until now, there are only four types of magnets that are commonly used as permanent magnet materials, namely AlNiCo [11], Feritte [12], SmCo5 [13], and the most recently discovered, NdFeB [14]. The properties of these materials is shown in Table 1.

Based on the literature study presented, this research was conducted with neodymium material because it has a large magnetic strength with variations in the number of magnets and the air gap width to obtain the characteristics of the torque density due to these variations.

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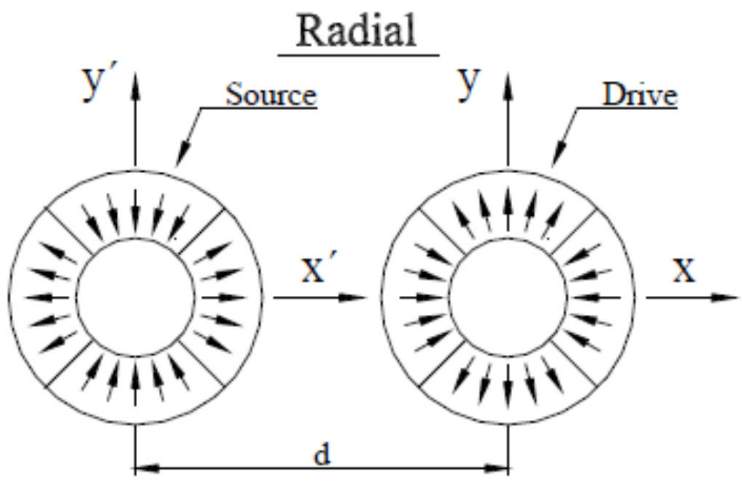

Figure 1. Radial Magnetized External Spur Gear

Table 1. Properties of permanent magnet materials

Magnet Type	Residual Induction, Br (T)	Coercivity, Hc (A/m)	Maximum Energy Product, (BH)max (MGOe)	Curie Temperature, Tc (°C)
Ferit	0.23 – 0.4	148.000 - 240.000	1.05 – 3.8	450 - 460
Alnico	0.7 – 1.3	40.000 - 139.000	1.5 – 9	740 - 860
SmCo	0.77 – 1.18	613.000 - 848.000	15 - 32	800 - 850
NdFeB	1.18 – 1.48	836.000 - 915.000	34 - 53	312 - 380

2. Numerical Method

The research method used is the finite element numerical method using software tools to analyze the torque on the magnetic spur gear with variations in the number of poles and air-gap. The torque data is used to determine the amount of torque density spur gear magnetic. One of the steps taken is verification, which is the stage of checking whether the simulation steps carried out are running correctly and accordingly or not. The verification process was compared with the results of the study in reference [15].

This research was conducted to determine the effect of air gap variations and the number of poles on the magnitude of the torque density magnetic gear. The torque density in each variation obtained will be compared with the torque density of mechanical gear at the same volume. The simulation model used in this study can be seen in Table 2.

The part design process was carried out using CAD software and then imported into Maxwell's Finite Element software. Figure 2 shows the bar magnet design that is used in this study.

This magnetic spur gear is arranged, as shown in Figure 3, which consists of a source as input and driven as an output. Each gear consists of poles whose number corresponds to the gear ratio. In this study, a 1:2 ratio was used so that the number of poles on the driven was always twice as many as the poles at the source. Between the source and driven, there is a distance called air gap.

In general, the stages carried out in this simulation process are divided into 3, namely the pre-processing, processing, and post-processing stages.

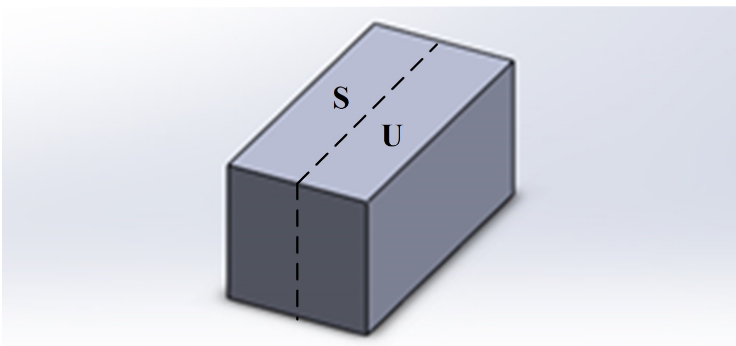

Figure 2. Neodymium bar magnet

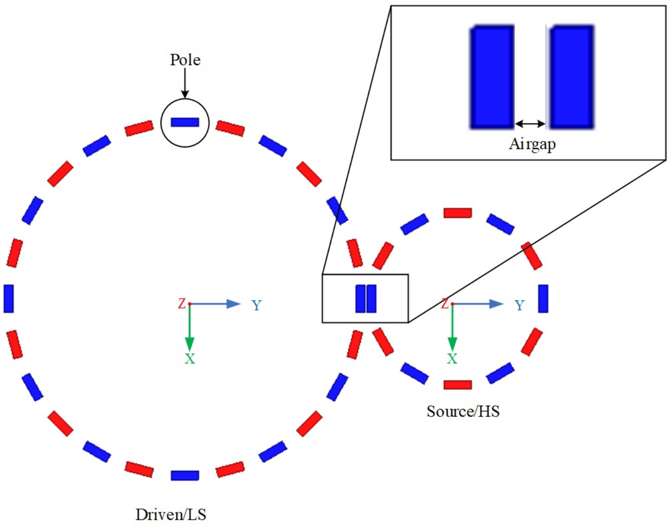

Figure 3. Magnetic gear design

Table 2. Magnetic gear simulation model

Bar magnet dimensions	Long	20		mm
	Wide	10		mm
	High	10		mm
Magnetic gear dimensions	Diameter gear 1	200		mm
	Diameter gear 2	400		mm
Magnetic gear condition	Number of poles	Test 1	6 & 8	Pole
		Test 2	8 & 16	Pole
		Test 3	10 & 20	Pole
		Test 4	12 & 24	Pole
	Magnetic gear distance	Test 1	1,5	mm
		Test 2	2	mm
		Test 3	2,5	mm
		Test 4	3	mm
Supporting conditions	Frame material	Neodynium Permanent Magnet		

2.1. The Pre-processing Stage

In determining the dimensions of the magnetic spur gear, the first step taken is determining the gear ratio to be made, namely 1:2. The ratio is then used to determine the number of poles and diameters that will be used in the HS (High Speed) and LS (Low Speed) gears. The determination of the number of poles refers to equation (1).

$$R_g = \frac{N_{pole2}}{N_{pole1}} \quad (1)$$

Where :

R_g = Gear ratio
N_{pole1} = The number of magnets in the HS gear
N_{pole2} = Number of magnets in the LS gear

In this research, a spur gear design will be made with 4 variations of the number of poles and 5 variations of the air gap. Variation of pole amount with 1 mm air gap as follows

1. Design 1 with the number of poles 6 and 12 poles.
2. Design 2 with the number of poles 8 and 16 poles.
3. Design 3 with the number of poles 10 and 20 poles.
4. Design 4 with the number of poles 12 and 24 poles.

Once simulated, the pair of poles is selected which produces the largest torque density to vary the air gap as follows.

1. Design 5 with an air gap of 1.0 mm
2. Design 6 with an air gap of 1.2 mm
3. Design 7 with an air gap of 1.3 mm

4. Design 8 with an air gap of 1.4 mm
5. Design 9 with an air gap of 1.5 mm

2.2. Processing Stage

At this stage, the simulation process includes importing a 3D model from CAD software to Maxwell's Finite Element Software, choosing a solver model, namely magnetostatic analysis, permanent magnet material input, region creation, meshing process, determining boundary conditions and excitation, initializing and continuing with the iteration process. After obtaining convergent data, the solver model is changed to transient analysis, input motion, determine output parameters, perform analysis setup and process analysis.

2.3. Post-processing Stage

The post-processing stage is the stage of taking the simulation results. These results are in the form of quantitative and qualitative data. Quantitative data is the distribution of torque values against time. Qualitative data is the appearance of the flux density distribution.

2.3.1. Torque (T) Magnetic Gear

To get torque data on lap time, setup is done on the Result icon on the Project Manager bar. Then the software will generate torque data on the HS gear and the LS gear in graphic form as shown in Figure 4.

2.3.2. Flux density (B) magnetic gear

After carrying out the transient analysis, the magnetostatic analysis was carried out again to obtain the flux density (B) value for each of the magnetic spur gear variants in all parts as shown in Figure 5. Previously the HS gear was rotated according to the angle which produced the maximum torque of Tmax to determine the value of flux density. (B) the maximum of each variation. These values are indicated by certain colors which indicate the minimum to maximum value ranges in the 3D spur gear magnetic model.

Based on the existing formula, the flux density (B) value will affect the amount of torque value and also the resulting torque density. Flux density itself has a direction to the x and y axes, so it is called Bxand By

2.4. Verification Stage

At this stage, the modeling result compared to another research of [15], for the same magnetic material and number of poles, but using different software. The results obtained are tabulated in Table 3.

Table 3. Comparison of results with Ref. [15]

Magnetic material	Number of poles	T_{max} (kNm/m^3)		Verification
		[15]	Researcher	Difference (%)
NdFeB	12	2.87	2.94	2.4

With the difference in the results of the torque density of 2.4%, the model made is accurate. So the next step is to change the dimensions and number of magnets according to the expected variations.

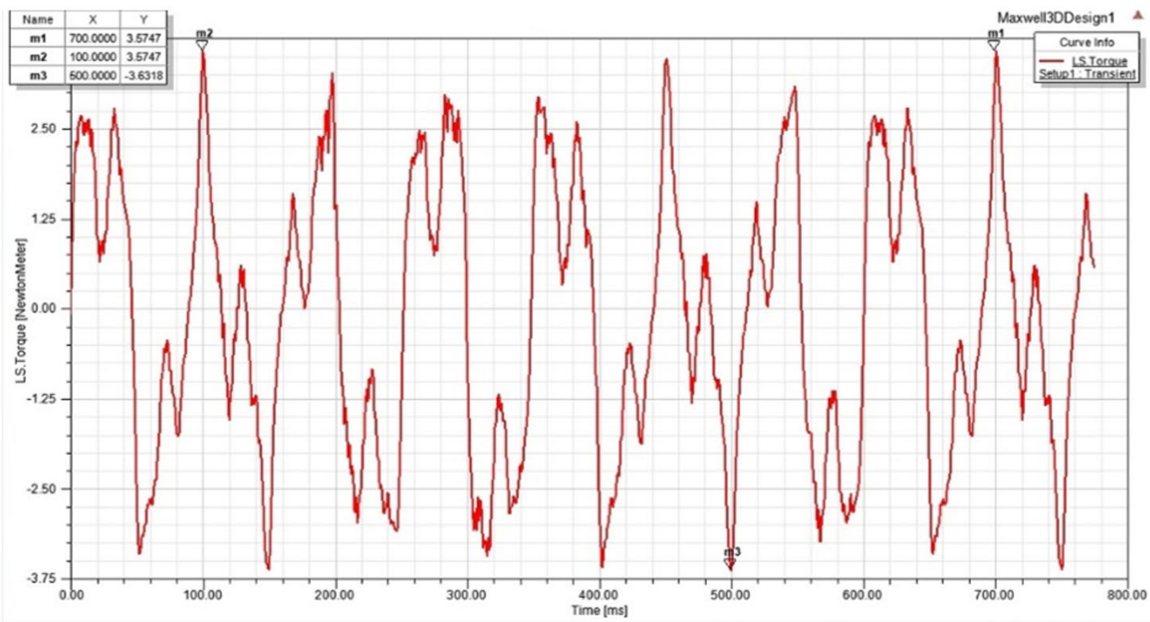

Figure 4. Torsion vs Time Graph

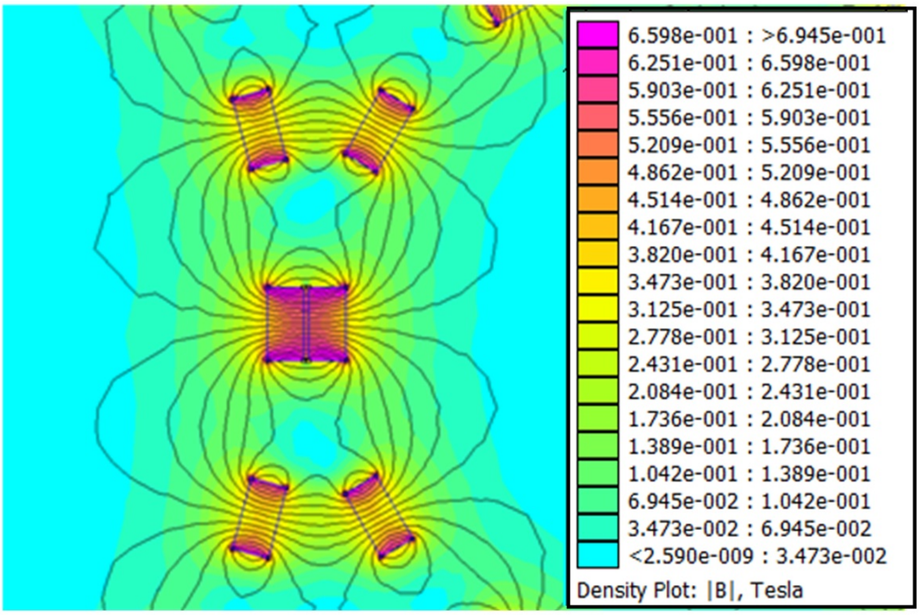

Figure 5. Examples of Flux density (B) values

3. Results and Discussion

From the simulation results obtained, a graph of the torque to the air gap and the number of poles of each geometric design, which is then analyzed on each graph. Furthermore, a comparison of the torque density generated by the magnetic spur gear and mechanical gear is carried out.

3.1. Analysis of the Effect of Number of Poles on Torque Density

From Figure 6, it can be seen that the lowest torque density occurs in pole pairs 6 and 12, which is 1.133 kNm/m_3. The torque density increases to 1.579 kNm/m_3 when the number of poles used is greater, namely 8 and 16 pole pairs. Furthermore, the torque density value increases when the number of poles is multiplied. The highest torque density value occurs in pole pairs 12 and 24, which is 2.234 kNm/m_3. The results obtained are in accordance with the hypothesis that with the increase in pole, the magnetic field increases so that the density torque also increases. The increase in torque density due to the increase in pole is quite significant linearly. If the reference is the least number of poles, the effect of the number of poles will increase by 39%, 47%, 97%.

The flux density value is influenced by the flux density in the x-direction and the y-direction (Figure 7 to Figure 10). The decrease in the flux density value will affect the amount of torque density generated. From all the flux density results obtained, it can be seen in the figures that the value of flux density By is more influential on the amount of maximum torque produced compared to Bx because flux density y-direction is the tangential direction corresponding to the direction of torque.

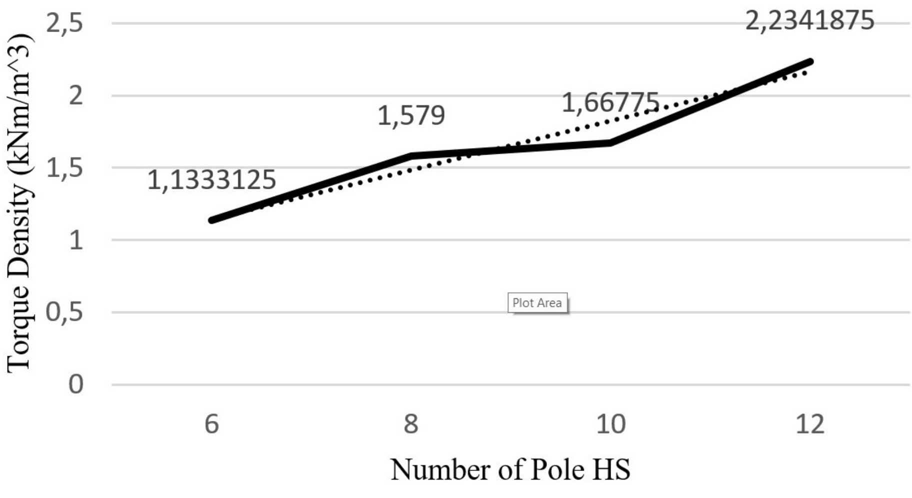

Figure 6. Graph of number of poles vs torque density on 1 mm air gap

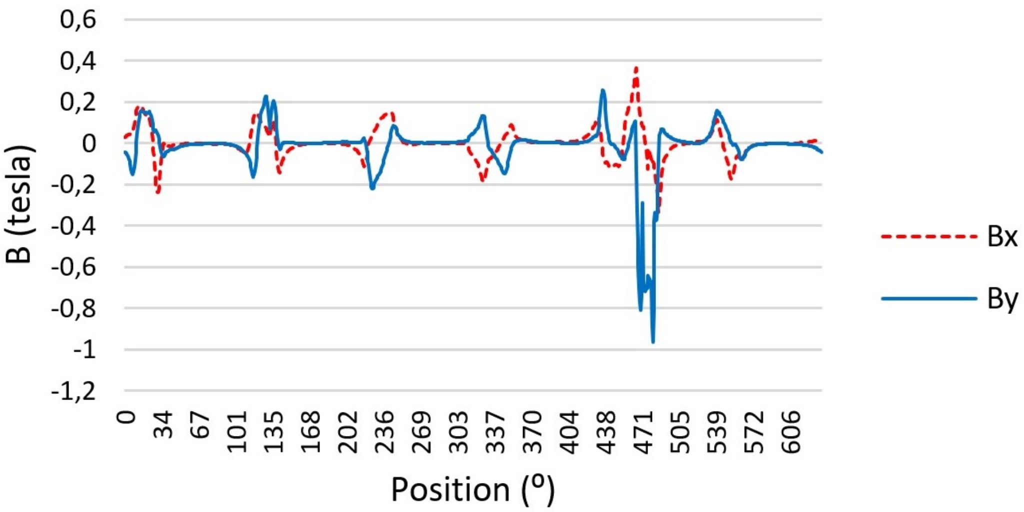

Figure 7. Flux Density on Number of Poles 6 (HS) and 12 (LS)

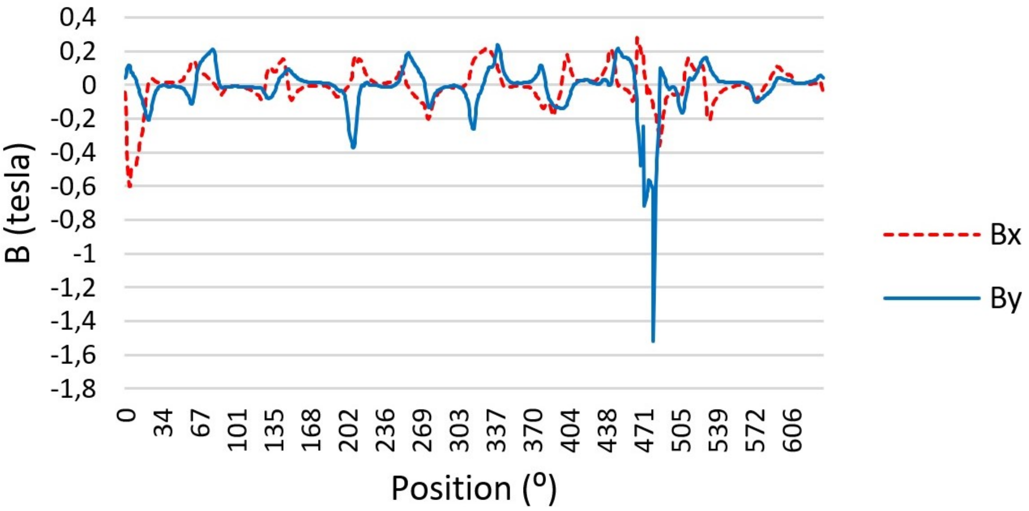

Figure 8. Flux Density on Number of Poles 8 (HS) and 16 (LS)

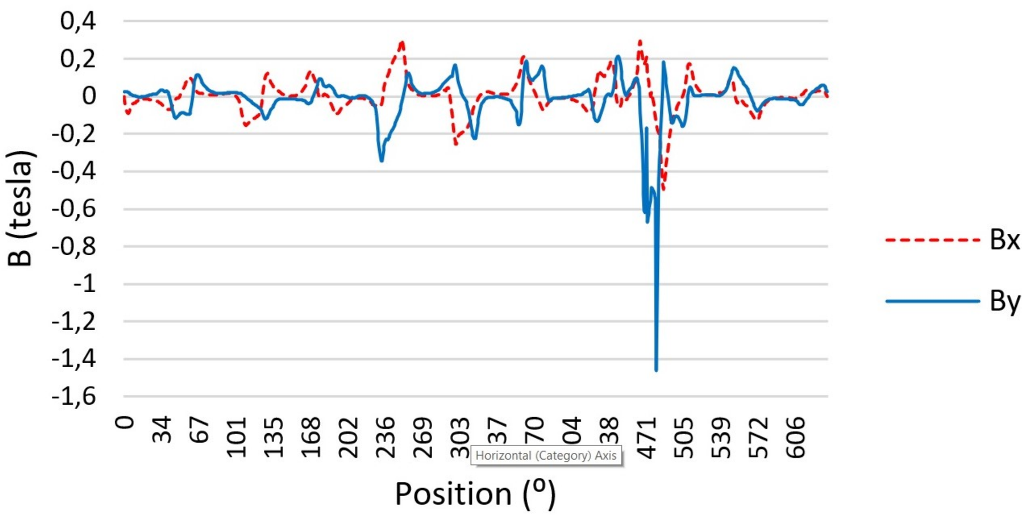

Figure 9. Flux Density on Number of Poles 10 (HS) and 20 (LS)

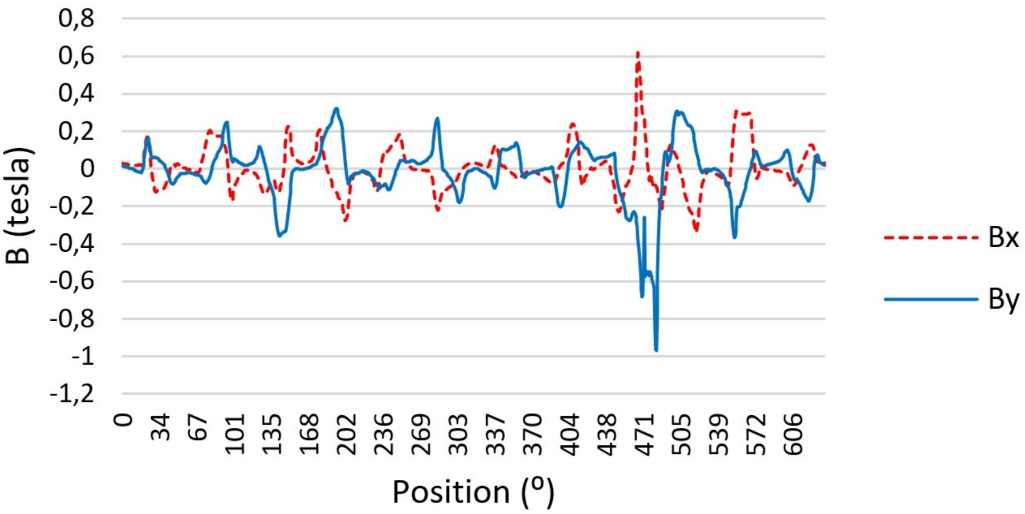

Figure 10. Flux Density on Number of Poles 12 (HS) and 24 (LS)

3.2. Analysis of the Effect of Air gap on Torque Density

From Figure 11, it can be seen that the greatest torque density value occurs at 1.0 mm air gap, which is 2.241 kN.m/m^3. However, the air gap of 1.2 mm, 1.3 mm, 1.4 mm and 1.5 mm respectively experienced decrease in torque density, namely 2.1833, 2.1163, 2.0883, and 2.0081 kN.m/m^3. The results obtained are in accordance with the theory that with the further away the air gap magnetic field is reduced, so that the torque density also decreases. The decrease in torque density due to increasing air gap is not so significant linearly because the air gap increase is quite small. If the reference is the torque at the farthest air gap, the smaller the air gap there is an increase in the torque density of 3.96%, 5.35%, 8.69%, 11.56%, respectively.

The flux density value is influenced by the flux density in the x direction and the y direction (Figure 12 - 16). The decrease in the flux density value cause of air gap will have an effect on the amount of torque density generated which has a big effect on the maximum torque value in the air gap variation is By. From all the results obtained, it can be seen that the value of flux density By is more influential on the amount of maximum torque produced compared to Bx because flux density in y direction is the tangential direction corresponding to the direction of torque.

3.3. Comparison of Magnetic Gear with Mechanical Gear

After knowing the maximum torque value of each spur gear magnetic geometry design, an analysis of the torque density of each design is carried out based on the volume occupied. The volume used in the mechanical and magnetic gears is the same, which is 16×105 mm^3. Mechanical gear data is obtained from manual calculations based on Lewis equations using ASTM 24 material. The number of poles on the magnetic gear is equal to the number of teeth on the mechanical gear.

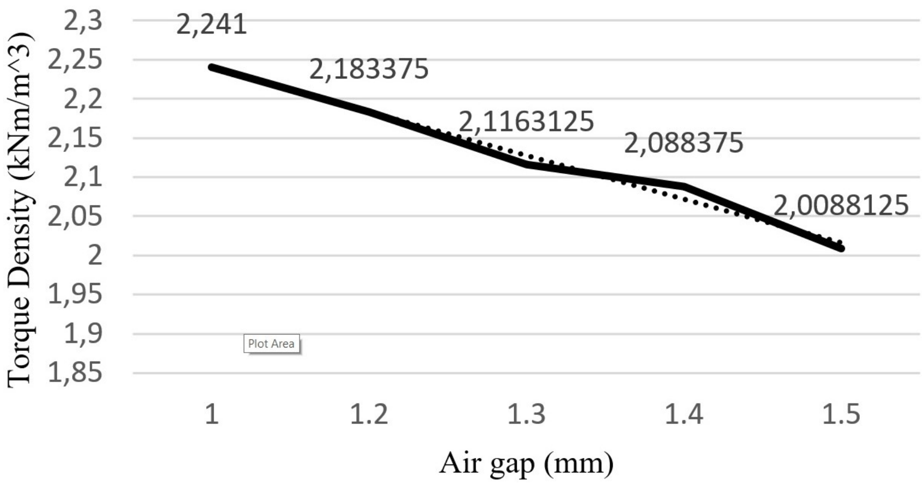

Figure 11. Graph of air gap vs torque density at Number of Poles 12 (HS) and 12 (LS)

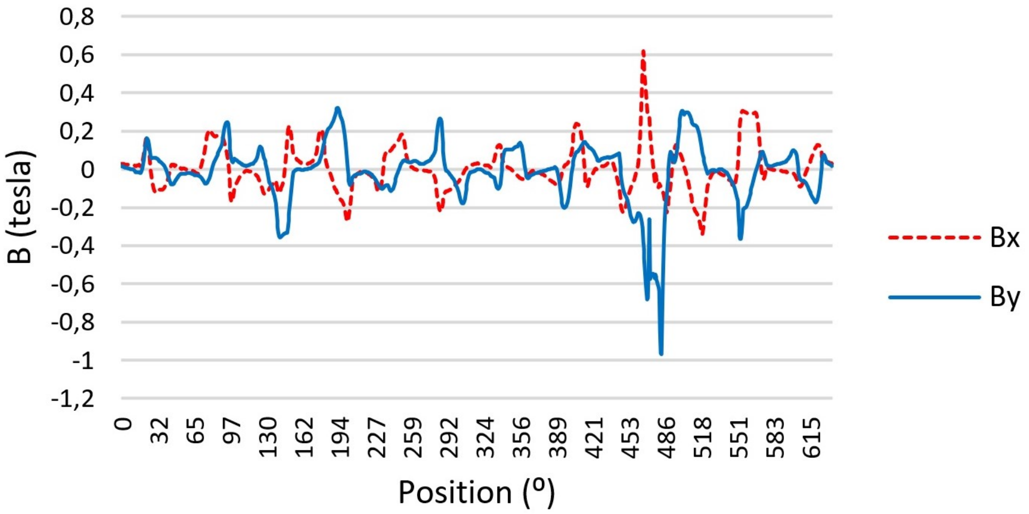

Figure 12. Flux Density vs Position with 1 mm Air Gap

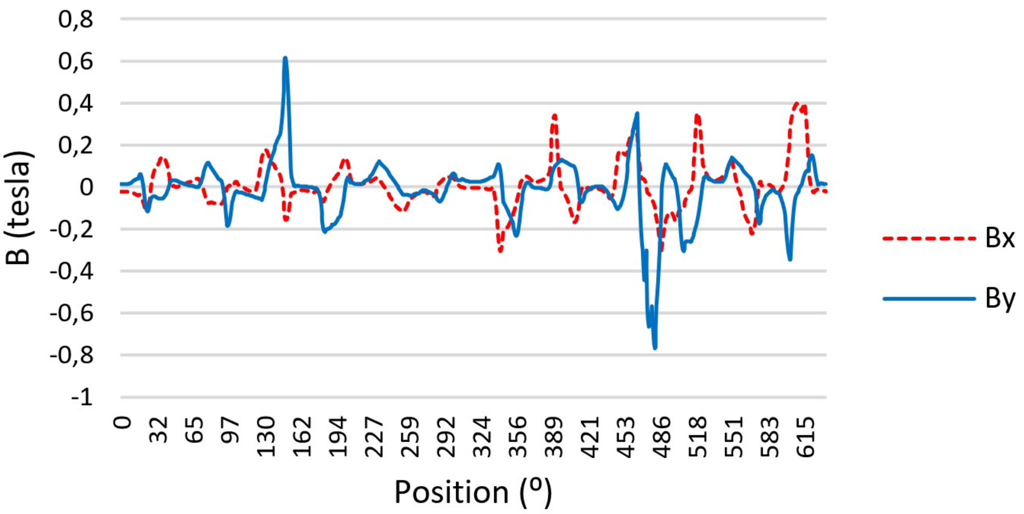

Figure 13. Flux Density vs Position with 1.2 mm Air Gap

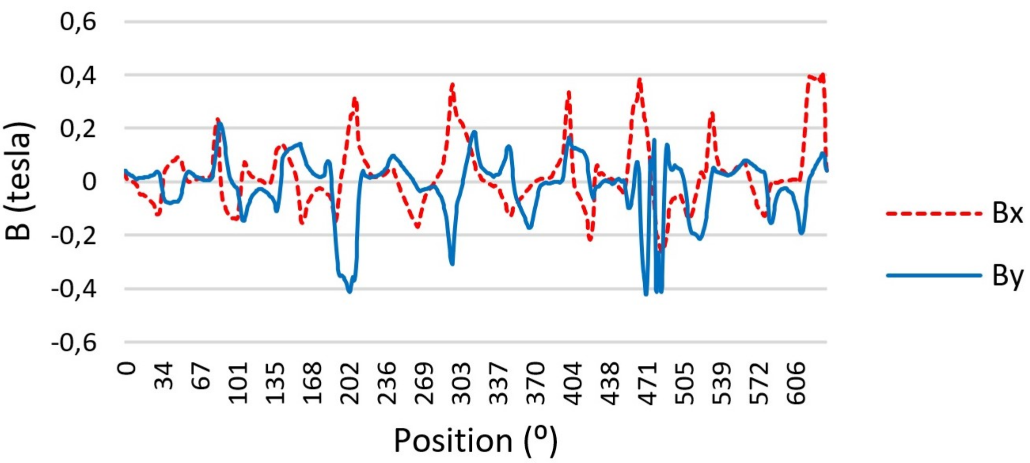

Figure 14. Flux Density vs Position with 1.3 mm Air Gap

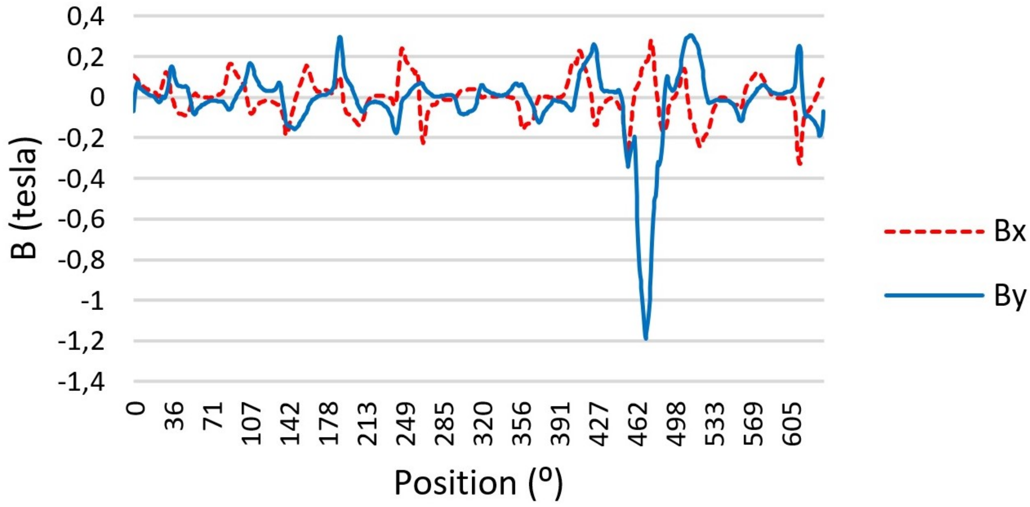

Figure 15. Flux Density vs Position with 1.4 mm Air Gap

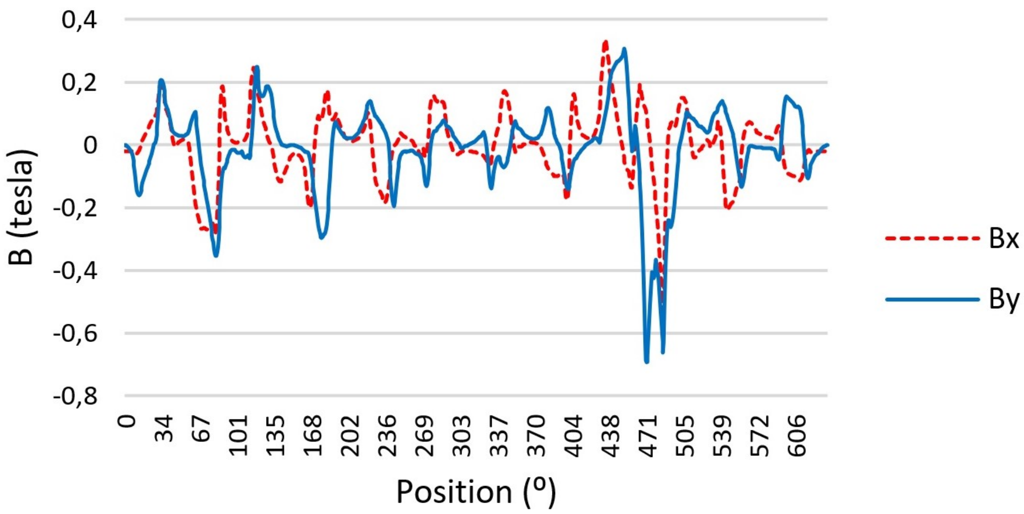

Figure 16. Flux Density vs Position with 1.5 mm Air Gap

The ratio between the torque density and the variation in the number of poles is shown in Figure 17. The torque density for mechanical gears decreases with increasing teeth. This is because the increasing number of teeth gears will reduce the size of the teeth. Thus the ability of the teeth to accept loads decreases. Conversely, in the magnetic gear, increasing the number of poles will reduce the gap between the poles and increase the volume of the magnet so that the magnetic flux becomes enlarged.

However, the difference in mechanical density torque is still much larger than the magnetic gear for all poles/teeth.

4. Conclusions

Based on the simulation and analysis data that has been carried out, it can be concluded that the greater the number of poles (N), the higher the torque density (ρ) for the same gear volume. The value of flux density By is more influential on the maximum torque generated compared to Bx. The value of the increase in torque density due to the variation in the number of poles is 39 %, 47 %, 97 %, respectively.

With smaller the air gap, the torque density is greater, because the closer the air gap distance is, the greater the flux density remanence (Br) produced. This causes the magnetization value to increase. The greater the magnetization value, the greater the maximum torque value (Tmax). The value of the increase in torque density due to the variation of air-gap from large air-gap to small air-gap is 3.96%, 5.35%, 8.69%, 11.56%.

The amount of torque density for the mechanical gear decreases with the increase in the number of teeth, while the torque density for the magnetic gear will be the opposite, which is greater. However, the torque density mechanical gear is still much greater than the torque density magnetic gear.

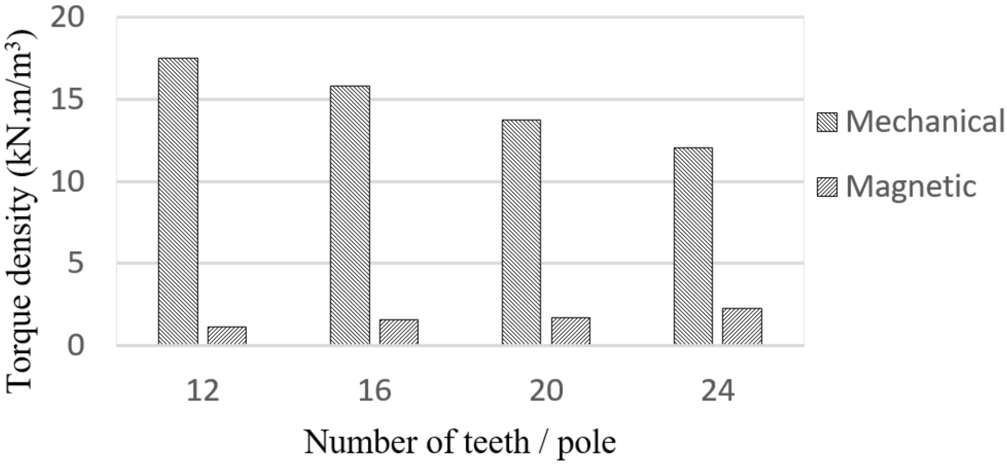

Figure 17. Graph of torque density variation of number of poles

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