Design and Analysis of Coaxial Magnetic Gear Mechanism with Halbach Permanent-Magnet Array

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Abstract. The disadvantages of mechanical gear can be replaced by the advantages of magnetic gear related to transferring torque without mechanical touch, no gear lubrication, low mechanical loss, low vibration, and intrinsic overload protection. From the types of magnetic gear, coaxial magnetic gear is the most developed type. Halbach permanent-magnet arrangement in coaxial magnetic gear mechanism can offer higher on transmitted torque and also capable of increasing the magnetic field compared to radially magnetized. Then this paper aims to carry out the characteristic of coaxial magnetic gear with Halbach magnetized in steady-state condition. Furthermore, magnetic field and transmitted torque were investigated by commercial software ANSYS/Maxwell. Finally, by using 2D finite element method, the result shows the maximum torque with 2150.76 Nm.

1. Introduction

Magnetic gear mechanism has advantages which able to replace mechanical gears mechanism. When mechanical gear is susceptible to damage by overload, magnetic gear is resistant to overload. When mechanical gear needs periodic maintenance, magnetic gear has no periodic maintenance. Moreover, magnetic gear does not produce noise and vibration because it has no physical contact. Nevertheless, magnetic gear can transmit torque well [1-3]. Using magnetic gear can produce a stably transmitted torque when the rotor rotates at different speeds [4]. The magnetic gear developed since 1941 by Fau [5]. At that time, the magnet has two gears, and the rotating axes are parallel to each other. Magnetic gear mechanism continues to be developed until now. Then, in 2001, Atallah and Howe discovered a new magnetic gear type. The magnetic gear has a low-speed rotor, high-speed rotor, permanent magnets and stationary steel pole-pieces [1]. Generally, the use of magnetic gear is to replace the functions of mechanical gear.

In the last ten years, industry and institution did research and development about magnetic gear technology and published it in a reputable journal [6]. The researcher institutions and industry develop magnetic gear by investigating its characteristic and potential application in the industrial field. The researches about magnetic gear characteristics, for example, investigates torque, torque density, torque ripple, flux density, eddy current, pole piece shapes, topologies, noise-vibration, and efficiency. The examples of magnetic gear potential application are for the transmission system, wind turbine, wave energy conversion, geared-motor, and so on. This topic is strongly possible to reach steps for commercial application [7-10].
There are various types of magnetic gear which are radial magnetic gear, transverse magnetic gear, worm magnetic gear, planetary magnetic gear, bevel gear, and harmonic gear [11-12]. The most popular type of magnetic gear is coaxial magnetic gear. This type is more accessible in the manufacturing process compared to another type. The example types of coaxial magnetic gear are radially magnetized, and Halbach magnetized. By using Halbach permanent-magnet arrangement, the magnetic gear can produce higher maximum torque, reduce torque ripple, reduce iron losses and also capable of increasing magnetic field [13-15]. It means that the Halbach arrangement is a good choice to be developed for transmitted torque demand. Finally, his paper aims to investigate the magnetic gear’s characteristic. Furthermore, magnetic field, flux density and torque characteristic of proposed coaxial magnetic gear were investigated by commercial software ANSYS/Maxwell.

2. Design Parameters

The Halbach permanent-magnet arrangement used in this paper shown in Figure 2(a). As shown in Figure 2(a), the permanent-magnet direction in the inner rotor arranged by outward-concentrated field while for the outer rotor arranged by inward-concentrated field.

Figure 2(b) shows the radial length of outer rotor iron part coded as A. B defines radial length of outer rotor permanent magnet. C and D in sequence define radial length of pole piece and radial length of inner rotor permanent magnet. The code E defines radial length of inner rotor iron part.

The proposed magnetic gear has one input and one output. Inner rotor set as an output while inner rotor as an input and the pole pieces held stationary. Under steady-state condition, the simulation of...
magnetic gear needs to be rotated in a reverse direction between input and output. The rotational speed of inner rotor \(w_1\) defined by gear ratio and the rotational speed of outer rotor \(w_2\) as presented in (1). In designing magnetic gear, the relation between the number of inner rotor’s permanent magnet pole pairs \(p_1\), the number of outer rotor’s permanent magnet \(p_2\) and pole pieces \(N_s\) needs to be considered as presented in (2). Then, this relation effected to the gear ratio which is defined by (3) [16]. If the gear ratio has a negative sign in front of the resulting number, it means that the inner rotor and the outer rotor rotate contrary direction [17].

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\begin{align*}
w_1 &= -Gr \cdot w_2 \quad (1) \\
N_s &= p_1 + p_2 \quad (2) \\
Gr &= p_2 / p_1 \quad (2)
\end{align*}
\]

In this research, the number of permanent magnet in the inner rotor is 4, and the number of permanent magnet in the outer rotor is 22. Therefore, the gear ratio is 5.5. This proposed magnetic gear has different radial length between inner and outer rotor permanent magnet as the optimization. The detail of magnetic gear parameters used in this research has parameters shown in Table 1.

| Table 1. Design parameters of a coaxial magnetic gear mechanism |
|--------------------------|----------|
| Parameter | Value |
| Number of outer rotor pole pairs \(P_1\) | 26 |
| Number of inner rotor pole pairs \(P_2\) | 4 |
| Number of pole piece \(N_s\) | 22 |
| Diameter of outer rotor | 140 mm |
| Diameter of inner rotor | 62 mm |
| Air-gap length | 1 mm |
| Radial length of outer rotor iron part \(A\) | 5 mm |
| Radial length of outer rotor Permanent Magnet \(B\) | 6 mm |
| Radial length of pole piece \(C\) | 4 mm |
| Radial length of inner rotor Permanent Magnet \(D\) | 7 mm |
| Radial length of inner rotor iron part \(E\) | 15 mm |

### 3. Analysis of Coaxial Magnetic Gear

The proposed design of magnetic gear developed in 2D finite element method using ANSYS/Maxwell software. During the simulation process, the iron material is used for inner and outer rotor while the material for pole pieces is Steel 1008. Furthermore, the permanent magnets material is NdFeB35. Because the model has one input and one output, then two motions set represent inner and outer rotor. By the aim of simulation which is to investigate the transmitted torque in a steady-state condition, the motion setup set to reverse. Inner rotor and outer rotor rotate in reverse direction with the rotational speed is 150 rpm and -27.27 rpm. The time range of simulation is from 0 ms to 50 ms. The result of the simulation is not only the torque but also magnetic field and flux density.

The maximum torque in the outer rotor has been obtained by 2261.55 Nm whereas the maximum torque in the inner rotor has been obtained by 420.15 Nm. As shown in figure 3, there are two lines which are represented outer torque in the upside (blue colour) and inner torque in downside (red colour). Therefore, the proposed design can produce a maximum torque by 2261.55 Nm.
Figure 3. Torque characteristic of the proposed magnetic gear

Figure 4. Magnetic flux density distribution at different angular position of magnetic gear

Figure 5. Magnetic field distribution at different angular position of magnetic gear

After the simulation, the flux density and magnetic field can be observed. The result is shown in Figure 4 and Figure 5. The distribution of magnetic flux density is presented in Figure 4. From three different angles, the colours indicate the alteration of distribution between permanent magnets. Figure 5 depicts the magnetic field distribution. The distribution of the lines is also indicating the alteration of the magnetic field. Different colour designates different value. The darker colours assign minimum values, while the lighter colours express maximum values of the magnetic distribution.
4. Conclusion
In this paper, the results for the magnetic gear characteristic are achieved. By using 2D finite element method with ANSYS/ Maxwell software, the modeling, simulation and the visualization of coaxial magnetic gear with Halbach permanent-magnet arrangement had been presented. The maximum transmitted torque is 2261.55 Nm. The magnetic flux density and the magnetic field have different value in different position, depend on the rotation of inner rotor and outer rotor permanent magnet. By knowing the value of transmitted torque and the magnetic field illustration, this research will be comparable with another magnetic gear types. Furthermore, this research will be a useful assistant tool for designing magnetic gear with transmitted torque demand. Future work related to this study will be aimed to investigating flux density, iron losses, torque ripple and efficiency of coaxial magnetic gear and solve the problem in manufacturing Halbach magnetized type.

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