Finite-Element Analysis of Magnetic-Gear Composite Motor Based on EasiMotor

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Abstract. The magnetic gear composite motor, which combines permanent magnet motor with magnetic gear together, can be used to reduce mechanical losses and thus obtain a high motor torque under the non-mechanical contact. By using the 2-dimensional finite-element analysis (2-D FEA) carried by using the FEA software EasiMotor, the motor distribution of magnetic field lines, the flux density and the corresponding Fourier analysis, the induced electromotive force, steady-state operation torque, cogging torque characteristics were analyzed respectively. The 2-D FEA is a valid tool used for analyzing the magnetic field and optimally designing the composite magnetic gear. The simulation results confirm the correctness and effectiveness of the proposed motor model.

1. Introduction

Gears can be found a wide utilization in industrial field, but the traditional mechanical gears have some inherent drawbacks of friction, mechanical impact, as well as induced noise and vibration. In order to overcome such drawbacks, the magnetic gears with high-performance permanent magnets have been rapidly developed. The non-contact magnetic gears can offer more advantages, such as having low mechanical, loss fatigue and low acoustic noise, the abilities of overload protection, maximum torque generation and misaligning tolerance [1], which can greatly improve lots of performances for the traditional mechanical-gears. Most magnetic gears are configured with external/internal meshed structures [2, 3, 4]. The main disadvantage of such design is that the poorer torque density can be obtained, which influences the practical applications of high power for magnetic gears. Atallah and Howe proposed a new type of magnetic-gear device with a coaxial structure in 2001[5], for the coaxial magnetic-gear device, all permanent magnets are uniformly arranged for torque generation, so the generated torque is greatly improved. In this paper, the static magnetic-field of the above proposed coaxial magnetic-gear device was analysed by using the finite-element method. The structural design and the reduction gear ratio of the coaxial magnetic-gear device were presented, and how the number of magnetic poles affects the static magnetic field distribution was also analysed.

2. Operational Principle

2.1. The principle of magnetic-gear

The concentric magnetic gear is divided into three parts, from the outside to the inside: the low-speed rotor, the stator magnetizer and the high-speed rotor. The magnetic field flowing through the stator magnetizer located in the middle can generate spatial harmonics in the air gap, and then interact with the magnetic field on the other side to transfer the required torque.
According to the operational principle of the magnetic gear, there is an equivalent relation between the pole-pairs \( p_1, p_2 \) and the poles of the stator magnetizer \( n_p \):

\[
p_1 + p_2 = n_p
\]  

(1)

When the magnetizer is at the static state, the rotating speed ratio of the inner and outer rotors is equal to:

\[
r = \frac{\omega_1}{\omega_2} = -\frac{p_2}{p_1}
\]  

(2)

2.2. The principle of the magnetic-gear motor

There are many applications of magnetic-gear motor, such as PM synchronous wind generator, hub motor used for electric vehicle, etc. Figure 1 shows the structure model of an improved PM synchronous motor [6]. The main features are as follows:

1. Replacing the high-speed internal rotor of general magnetic-gear with the stator of PM motor, and using the rotating magnetic field of the stator winding to replace the high-speed rotating magnetic field generated by the original inner rotor rotation.

2. The magnetic steel of the outer rotor is embedded in the iron core and all the magnets are magnetized in the same direction, instead of a positive-inverse spacing arrangement normally adopted by the PM motor.

Because the inner rotor of the magnetic-gear is ignored, the structure is relatively simple. And also half of the permanent magnet material can be saved due to the magnetic steel of the rotor is arranged in the same direction of magnetization. The working principle of the motor is that the control mode of brushless PM DC motor or PM motor is used to electrify in the stator winding, and an internal rotating magnetic field is produced. According to the principle of the magnetic gear, the rotating magnetic field, which is acted by a magnetizer, will drive the external rotor to rotate in reverse, and the ration of the reverse rotation velocity to the internal rotation velocity is inversely proportional to the pole-pairs. Since the speed of the outer rotor is reduced, the large torque output can be obtained.

![Figure 1. The structure model of an improved PM synchronous motor.](image)

3. 2-D Model of Magnetic-Gear Motor

The structural parameters of such motor are listed in Table 1. The 2-dimensional structural model of such motor is built in software EasiMotor (from which the dxf model file can be downloaded). The 2-D model is set up by the following steps: 1) Set the magnetizing direction of the PM, the magnetizing core is at the location (0,0); 2) Add the moving body, the rotor part is designated as the moving area; 3) Add the outer circle to zero boundary; 4) Add three-phase winding excitation; 5) Specify that the pole-pairs of the finite-element is the stator pole-pairs.
Table 1. The structure parameters of the composite motor.

| Parameter                        | Value | Parameter                        | Value               |
|----------------------------------|-------|----------------------------------|---------------------|
| Poles of rotor                   | 23    | Slot number                      | 18                  |
| Poles of magnetizer              | 27    | Winding form                     | Fractional slot/double layers |
| Poles of stator                  | 4     | Pitch                            | 2                   |
| Rotor outer diameter (mm)        | 149   | Space width (mm)                 | 8                   |
| Rotor inner diameter (mm)        | 128   | Slot width (mm)                  | 3.3                 |
| Magnetic steel thickness (mm)    | 4.5   | Slot height (mm)                 | 1                   |
| Stator outer diameter (mm)       | 112.6 | Slot shoulder height (mm)        | 1.6                 |
| Stator inner diameter (mm)       | 30    | Slot body height (mm)            | 27.3                |
| Magnetizer thickness (mm)        | 6.5   | Number of conductors per slot    | 180                 |
| Air gap of stator (mm)           | 1     | Pole arc coefficient of magnetic steel | 1.2                |
| Air gap of rotor (mm)            | 1     | Pole arc coefficient of magnetizer | 0.9                 |
| Axial length (mm)                | 32    | Iron core material               | 50W470              |

4. Finite-Element Analysis

4.1. Static magnetic field analysis

The magnetic field distribution and the magnetic field lines obtained by the analysis of the above-mentioned finite element model under no-load static magnetic field are shown in Figure 3. From the distribution diagram, it can be seen that the same magnetizing direction is 23 pieces of magnetic steel. The magnetic field of 23 pairs of poles is generated on the motor, and the magnetic field of the rotor with 4 pole-pairs is generated in the stator by the magnetizer.
Figure 3. The distribution diagram of static magnetic field.
At the same time, the air gap flux density curves at the stator and rotor air gap are drawn and analyzed by FFT respectively, the simulation results are shown in Figure 4.

(a) Air gap flux density of stator  
(b) FFT of air gap flux density of stator

(c) Air gap flux density of rotor  
(d) FFT of air gap flux density of rotor

Figure 4. The distribution diagram of static magnetic field.

4.2. Cogging torque analysis
By applying the transient field finite-element method and setting the rotor constant speed to run an electric period (the angle of a polar distance), the cogging torque of the motor can be obtained, as shown in Figure 5(a), and it can be found that the amplitude of the cogging torque is less than 0.4Nm. At the same time, the results of flux linkage in the three-phase stator windings are shown in Figure 5(b). From the results, we can see that the flux linkages of three-phase stator windings are very close to sinusoidal waveform.
4.3. Transient performance analysis
The same control strategy of PM motor can be used to drive such magnetic-gear composite motor. However, it should be noted that there are some differences in the operation of the magnetic-gear composite motor, so there are differences in control. In this paper, three-phase star full-bridge inverter for brushless dc motor (BLDC) and vector control algorithm ($I_d=0$) for Permanent magnet synchronous motor (PMSM) are used respectively to simulate. The power supply voltage is 310V, the speed ratio of speed change to magnetic gear is -5.75.

Firstly, no-load simulation analysis is carried out, the rotor is to free movement, the moment of inertia is 0.008kg.m$^2$, the load torque is 0N.m, and the initial position of the rotor is determined from Figure 5(b) according to the value of the stator flux, the transient simulation is performed, and the results are shown in Figure 6.

Then the load torque of the rotor is set to -20Nm, which is linear to the speed, and the transient segregation of the rotor is carried out, the simulation results are shown in Figure 7.
From the above simulation results, it can be seen that the stator current waveforms obtained by the vector control algorithm (PMSM with $I_d=0$) are more sinusoidal than those of obtained by three-phase star full-bridge inverter (BLDC), correspondingly, the torque ripple is less, and also the operation is more stable.

5. Conclusion
In this paper, the working principle of magnetic-gear composite motor is introduced, the finite-element method, implemented by using the FEA software EasiMotor, is presented to analyse the performance of magnetic-gear composite motor. The steady and dynamic responses of the compound motor can be obtained by using different methods of static and transient magnetic fields. According to the above simulation results, it can be seen that the magnetic-gear composite motor can satisfy the requirement of low speed and high torque for motor design and control at the same time. It can used to in electric vehicle driving, machine driving, wind power generation and other industry applications.

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