Design and Analysis of an Integrated Halbach-magnetic-geared Permanent-magnet Motor for Electric Vehicles

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Abstract

This paper proposes an integrated Halbach-magnetic-geared permanent-magnet (PM) motor to meet the new demands arising from electric vehicles. It can offer the advantages of lightweight, compact size and low-speed high-torque operation. The key is to newly incorporate the Halbach arrays into the coaxial magnetic gear (MG) in such a way that the PM motor field and the MG field are decoupled. In addition, because the adoption of Halbach arrays can enhance the effective harmonic components as well as suppress the useless harmonic components of the magnetic field, the torque transmission performance of the outside MG can be improved. Moreover, the iron losses can also been reduced. Simulation results based on the time-stepping finite element method are given to verify the validity of the proposal.

Keywords

magnetic gear, permanent magnet, halbach array, torque transmission

1. INTRODUCTION

With ever increasing concerns on fossil energy shortage and global warming, there is fast growing interest in electric vehicles (EVs) [Chau and Chan, 2007]. Up to now, EVs can be classified as three main types: battery EVs (BEVs), fuel cell EVs (FCEVs) and hybrid EVs (HEVs) [Chan and Chau, 2001; Wong et al., 2005; Wong et al., 2006]. No matter in which type of EVs, electrical motor is fully or partially substituted for internal combustion engine to drive the vehicles. Thus high performance driving motor has become a core technology for EVs. Generally, such motors are demanded to offer high-torque low-speed (around 1000 rpm) operation as well as lightweight and compact design [Chau et al., 2008].

In early days, induction motors were preferred for EVs due to their high reliability, manufacturing facilitation and low cost [Jiang et al., 2003]. Recently, switched reluctance (SR) motor has also been recognized to have considerable potential for EVs because of its simple construction and outstanding torquespeed characteristics [Rahman et al., 2000]. With the advent of high-energy permanent magnets (PM), some kinds of PM motors have been developed to offer higher power density and operating efficiency, such as PM brushless dc motor [Gan et al., 2000], PM axial flux motor [Eastham et al., 2002], PM doublesalient motor [Chau et al., 2006; Fan and Chau, 2005], PM Transverse-flux motor [Wang et al., 2008] and so on. It is well known that for certain power rating, higher rated speed implies smaller motor size as well as lighter weight. Thus, in most EV systems, the driving motors are designed to be rated at very high speed (4000 rpm or above), and mechanical gearboxes are engaged to match the high speed motor and the relatively low speed wheel. Figure 1 shows the scheme of the mechanical-geared motor system. The sun gear shaft of the planetary gear is connected to the shaft of the driving motor for scaling down its rotational speed. The wheel tire is directly mounted on the rim of the ring gear.



Fig. 1 Scheme of the mechanical-geared motor system

Mechanical gearbox can help to improve the power density of the driving system. However, because of its contact mechanisms, the associate transmission loss, noise, vibration, and regular lubrication are inevitable. Recently, the concept of non-contact torque transmission through the interaction between PMs has been attracting increasing attentions, and the gearboxes designed to follow such concept are entitled as magnetic gear (MG) [Furlani, 1997]. By adopting coaxial topology, the utilization of PMs in magnetic gear has been significantly improved [Atallah et al., 2001; Chau et al., 2006; Liu et al., 2009]. Thus it can offer very high torque density comparable to mechanical gearboxes, and some distinct advantages, namely, minimum acoustic noise, free from maintenance, improved reliability, inherent overload protection, and physical isolation between input and output shafts.

Most recently, the MG has been incorporated into a PM brushless motor to achieve low-speed high-torque operation [Chau et al., 2007]. As shown in Figure 2, the inner stator is artfully inserted into the MG to share the same high speed rotor with the MG. Also the wheel tire is directly mounted on the low speed rotor. Such in-wheel motor can get rid of the shortcomings arising from mechanical gearbox. Moreover, the highly-integrated design can dramatically reduce the overall size and weight. However, with further investigation, some disadvantages of such driving motor have been unveiled. Firstly, most of the flux lines go through all three airgaps. Such stout electromagnetic coupling between the inside motor field and the outside gear field will definitely deteriorate the speed control of the motor. Secondly, the torque ripples arising from the stator slots as well as the ferromagnetic segments will impact the dynamic performance of the EV.

Halbach arrays hold the merits of sinusoidal field distribution magnetization, strong field intensity and self-shielding magnetization [Xia et al., 2004]. The purpose of this paper is to propose an integrated Halbach-magnetic-geared PM motor which can exert the advantage of Halbach arrays mentioned above to achieve the field decoupling, reduce the cogging torques and improve the torque transmission capacity. Moreover, the iron losses can be reduced with the improvement of the magnetic field distribution.



Fig. 2 Integrated magnetic-geared in-wheel motor

2. PROPOSED CONFIGURATION

Figure 3 (a) shows the topology of the proposed integrated Halbach-magnetic-geared PM motor in which an outer-rotor PM motor is artfully integrated into a



(b) Arrangement of Halbach PM arrays

Fig. 3 Proposed motor

coaxial MG. It consists of four main parts: the motor stator, the motor outer rotor which is also the gear inner rotor, the stationary ring and the gear outer rotor. Three airgaps are formed to separate them from each other. The gear inner rotor is designed like a cup with PMs mounted on its inside and outside surfaces. In addition, PMs are employed on the inside surface of the gear outer rotor. The key difference from the existing magnetic-geared motor is that Halbach arrays are engaged instead of the radial magnetized PMs on both the inner-rotor and outer-rotor to constitute magnetic poles. As shown in Figure 3 (b), the pole-pair numbers of the Halbach arrays on the motor outer-rotor, the gear inner-rotor and the gear outer-rotor equal 3, 3 and 16, respectively. Correspondingly, the numbers of PM segment per pole are 4, 4 and 2. The magnetization direction in each segment can be given by:

$$M = M_x + jM_y$$

= $M \cos \left((1 \pm p) \theta \right) + jM \sin \left((1 \pm p) \theta \right)$ (1)

where the minus case is for the gear inner-rotor, the positive case is for the motor outer-rotor and the gear outer-rotor, p is the number of pole-pairs, θ is the angle between the x axis and the centre line of each PM segment, $M = B_r/\mu_0$ is the amplitude of remnant intrinsic magnetization, and B_r is the remanence of the PM. Since the Halbach PM arrays provide the definite advantage of self-shielding magnetic fields, the gear outer-rotor can adopt nonmagnetic materials, such as stainless steel or even high-strength plastic, hence of-

fering the desired lightweight, compact structure and reduced iron losses. Also, the stationary ring is built of laminated ferromagnetic pole-pieces which can further reduce iron losses.

The torque transmission between the gear inner-rotor and gear outer-rotor is based on the modulation of the airgap flux density distributions due to the stationary ring. By defining P_1 and P_2 as the pole-pair numbers of the gear inner-rotor and gear outer-rotor, respectively, and n_s as the number of ferromagnetic pole-pieces on the stationary ring, it yields $n_s = P_1 + P_2$. Hence, the speed relationship [Atallah et al., 2001] is given by:

$$G_r = -\omega_1 / \omega_2 = P_2 / P_1 \tag{2}$$

where G_r is so-called the gear ratio, and ω_1 , ω_2 are the speeds of the gear inner-rotor and gear outer-rotor respectively. The minus sign denotes that the rotors rotate in opposite direction. So, when $P_1 = 3$, $P_2 = 16$ and $n_s = 19$, $G_r = -16/3$ is resulted.

3. PERFORMANCE ANALYSIS

The validity of the existing integrated motor has already been verified [Chau et al., 2007]. In order to illustrate the merits of the proposed integrated motor, it is directly compared with the existing one in terms of performances. Thus, based on the same specification as listed in Table 1, both the proposed and existing ones are analyzed by using the finite element method. Figure 4 gives the magnetic field distributions in two integrated motors. It can be seen that most flux lines in the existing one pass through 3 airgaps, indicating that the coupling between the PM motor field and the MG field is strong; whereas most flux lines in the proposed one are self-contained by the Halbach PM arrays, indicating that the two magnetic fields are virtually decoupled. In the presence of magnetic coupling, the

 Table 1 Specification of proposed motor

2 kW
42 V
220 Hz
4000 rpm
750 rpm



Fig. 4 Magnetic field distributions

flux control of the motor will be sluggish, hence deteriorating its dynamic performance.

Figure 5 gives the radial flux density waveforms in the inner airgaps of two integrated motors, and Figure 6 shows their harmonic spectra. Due to the absence of magnetic coupling, the proposed one can drastically suppress the undesirable pole-pairs (p = 9, 15, 21, 33) though there is a slight decrease in the synchronous pole-pair (p = 3) for torque transmission. The suppression of asynchronous pole-pairs can effectively reduce the cogging torque of the motor outer-rotor from 1.2 Nm to 0.5 Nm as depicted in Figure 7.



Fig. 5 Radial flux density waveforms in inner airgap



Fig. 6 Harmonic spectra of radial flux density in inner airgap



Fig. 7 Cogging torque due to stator slots

In order to fairly assess the MG of the proposed integrated motor as compared with other MGs, the PM motor is removed so that its coupling effect on the MG is absent. The candidates for comparison are the radially magnetized MG with iron outer-rotor (RI), the radially magnetized MG with nonmagnetic outerrotor (RN), the Halbach MG with iron outer-rotor (HI) and the Halbach MG with nonmagnetic outer-rotor (HN). Figures 8 and 9 show the radial flux density waveforms and their harmonic spectra in the middle airgap of four MGs, respectively. Similarly, Figures 10 and 11 show the waveforms and spectra in the outer airgap. It can be found that the Halbach candidates (HI and HN) can offer significant improvements in the effective pole-pair in the middle airgap (p = 3) and that in the outer airgap (p = 16) as compared with their counterparts (RI and RN). Also, both HI and HN can greatly suppress the undesirable pole-pairs in the middle airgap (p = 9, 15, 21, 28, 29) and those in the outer airgap (p = 24, 29, 48). The improvement of those synchronous pole-pairs functions to increase the torque transmission capability of the MG, while the suppression of those undesirable pole-pairs functions to reduce the cogging torques and iron losses of the



Fig. 8 Flux density waveforms in middle airgap



Fig. 9 Flux density harmonic spectra in middle airgap.



Fig. 10 Flux density waveforms in outer airgap



Fig. 11 Flux density harmonic spectra in outer airgap

MG.

Table 2 gives a quantitative comparison of the synchronous pole-pairs which govern the torque transmission. Focusing on the two Halbach candidates, it can be observed that the HN offers a slightly lower magnitude in the outer airgap than the HI. This slight sacrifice is worthy and acceptable, since the use of nonmagnetic outer-rotor not only reduces the weight and size, but also eliminates the associated iron losses.

Table 2 Comparison of synchronous pole-pairs in dif-ferent MGs

	Middle airgap ($p = 3$)		Outer airg	ap (<i>p</i> = 16)			
	Magnitude	Percentage	Magnitude	Percentage			
RI	0.468 T	74.7 %	0.844 T	85.3 %			
RN	0.346 T	62.8 %	0.554 T	82.2 %			
HI	0.632 T	90.7 %	1.022 T	90.8 %			
HN	0.438 T	85.1 %	0.965 T	93.1 %			

Table 3 Comparison of torques on different MGs

	Gear driving torques		Gear cogg	ing torques				
	Inner-rotor	Outer-rotor	Inner-rotor	Outer-rotor				
RI	24.4 Nm	129.8 Nm	1.48 Nm	2.53 Nm				
RN	17.1 Nm	90.7 Nm	1.48 Nm	2.42 Nm				
HI	28.1 Nm	149.5 Nm	0.29 Nm	1.58 Nm				
HN	27.3 Nm	145.1 Nm	0.28 Nm	1.53 Nm				

Moreover, the corresponding torque-angle relationships on the inner-rotor and outer-rotor are shown in Figure 12. Table 3 gives their quantitative comparison. Both illustrate that the HN has only a slight reduction of torque transmission capability compared with the HI. Therefore, the proposed integrated motor with the MG having a nonmagnetic outer-rotor offers better performances than its counterparts.



Fig. 12 Torque-angle curves of MGs

4. CONCLUSION

In this paper, an integrated Halbach- magnetic-geared PM motor has been proposed and analyzed. The proposed motor exerts the full merits of Halbach PM arrays so that the PM motor field and the MG field are decoupled. Thus, the MG can adopt a nonmagnetic outer-rotor, hence significantly improving the power density and virtually eliminating the associated iron losses. Also, the associated cogging torques can be significantly reduced.

Acknowledgements

This work is funded by a grant (HKU 7105/07E) from the Research Grants Council, Hong Kong Special Administrative Region, China.

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(Received February 27, 2009; accepted April 3, 2009)