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Torque Analysis of Perpendicular Magnetic Gear with High Gear Ratio

Prof.G.Muruganandam, Dr.K.S.Jayakumar, Mr.Hariharan.S, Mr.Joshua.E

Abstract - This paper presents design and analysis of torque and flux density in perpendicular magnetic gear with different magnetic materials, dimensions and air gap. The results were compared to each other. This type of gear offers both high gear ratio and high torque. Moreover the low speed side is connected to prime mover and high speed side is connected to load after analysis, which is suitable for wind power, industrial (Group Drives) applications etc.

Finally, it is concluded that the result in this paper may help to initiate a shift from mechanical gears to magnetic gears. (Selection of magnetic gear for suitable applications).

Indexed Terms – High torque, Magnetic gear, Analytical modelling, Finite element analysis, Perpendicular Gear, NdFeB, Gear Ratio.

1 Introduction

Permanent magnets have fascinated and inspired many people throughout ages because a permanent magnet produces flux and magnetic force [2].

Recently, the concept of magnetic gears has been proposed. Because of physical isolation between the input and output shafts, it offers some distinct advantages namely: minimum acoustic noise, free from lubrication, extremely low vibration and noise-levels, freedom from maintenance, improved reliability, high efficiency and inherent overload protection they can operate through a separation wall, transmit torque without any physical contact and therefore it is quite suitable for using in any type of environment.

This torque from the magnetic coupling between perpendicular magnetic gears with different magnetic poles has been investigated experimentally. The torque of the magnetic gear depends upon magnetic material, air gap length and length of the magnet. For different multi pole magnetic couplings with the same magnetic field strength, the torque of magnetic coupling increases as the number of magnetic poles increases for distances similar to critical separation distance $l_{g,}$ but it is decreased as the separation distance becomes larger.

The purpose of the paper is to propose and implement a magnetic gear for various applications like wind power generation, industrial group drives, automobile and mills etc. This paper is divided into seven further sections. Section 2 deals with system design of perpendicular magnetic gear. Section 3 deals with Finite element analysis of the permanent magnet gear with high torque. Next in section 4, torque equation is derived. In section 5, determination of gear ratio is formulated. The comparison of different magnetic gear torque is made in section 6 and finally a conclusion is given in section 7.

- *Prof.G.Muruganandam, working as Associate Professor in Sona College of Technology, Salem, Tamilnadu, India.*
- *Dr.K.S.Jayakumar, working as Associate Professor in SSN College of Engineering, Chennai, Tamilnadu, India.*
- *Mr.Hariharan.S, studying Electrical and Electronics Engineering at Sona College of Technology, Salem, Tamilnadu, India.*
- *Mr.Joshua.E, studying Electrical and Electronics Engineering at Sona College of Technology, Salem, Tamilnadu, India.*

2 System Design

The Permanent magnet perpendicular gear shown in Fig.1 has 16 pairs of poles in low speed side (prime mover) and 4 pairs of poles in high speed side (load side).

The torque of magnetic coupling depends on the number of magnetic poles, the area of poles covered by magnets, the magnetic field strength and the separation distance between the gears. [1] Table I shows the particulars of various dimensions.

TABLE I

Description	Perpendicular Magnetic Gear
No of low speed rotor poles	16 pair
No of high speed rotor poles	4 pair
Outer radius of low speed rotor	240 mm
Inner radius of low speed rotor	61 mm
Outer radius of high speed rotor	240 mm
Inner radius of high speed rotor	61 mm
Length of rotor poles	100 mm
Air gap length	3mm to 5mm
Permanent magnet material	NdFeB & SM_2CO_{17}
Permeability of air region μ_0	$4\pi x10^{-7}$ Tm/A
Relative permeability of magnets $\mu_r = \mu / \mu_0$	1.0523

For better gear ratio to commutate the magnetic field from high speed side with few permanent magnetic poles into the low speed side with many poles [2].

3 Finite Element Analysis

The mentioned magnetic gears, shown in Fig.1, are used for finite element analysis. The parameters of the gears are listed in Table I. The flux density is shown in Fig.2, where the high and low speed rotors are placed in a position realisation to each other. Where, maximum torque is achieved. In Fig.3 the calculated torque versus time graph is shown. The curve is obtained by evaluating T_{HIGH} (7) Equations mentioned in torque equation. Maximum torque is 30.2 Nm. The above torques is calculated using the finite element analysis method.

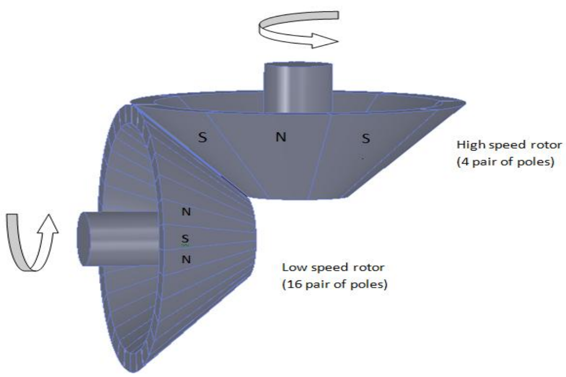
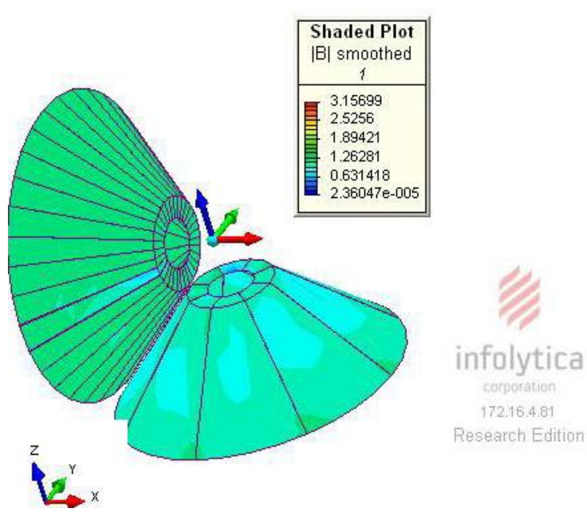
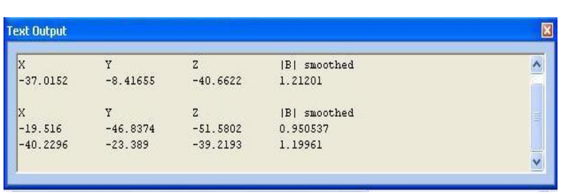


Fig.1. Perpendicular Magnetic Gear.

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X	Y	Z	|B| smoothed
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-40.2296	-23.389	-39.2193	1.19961

Fig. 2. Flux density in perpendicular Magnetic gear.

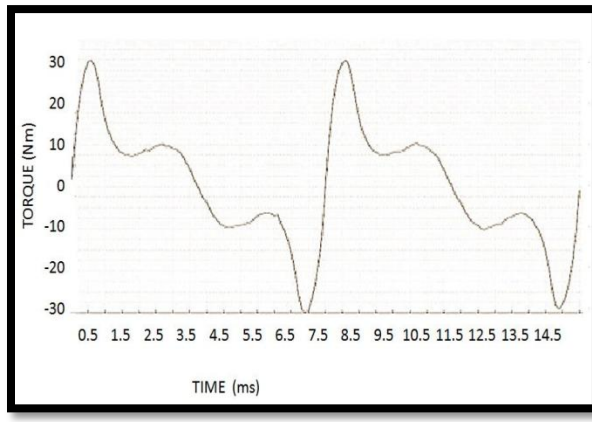


Fig.3. Torque Vs time of perpendicular magnetic gear.

4 Torque Equation

According to the principle of transformation of magnetic energy to mechanical energy the following equation can be obtained

$$T(\theta) = -\frac{\partial W(\theta)}{\partial(\theta)} \qquad \text{- (1)}$$

Where,

W(θ) – Magnetic energy.

Assuming that the magnetic energy is stored only in the air gap, *W(θ)* is expressed as,

$$W(\theta) = \frac{1}{2\mu_0}\oint_V B^2 dV \qquad \text{- (2)}$$

Where,

μ_0 - Permeability in vacuum.

V - Volume of the air gap.

B - Magnetic flux density in the air gap.

The initial rotor angle of the high speed rotor is assumed as $\theta = 0°$. Then, a rotor angle δ is given to the high speed rotor. Then, the equation (2) is transformed to (4) with volume difference of air gap Δv shown in (3)

$$\Delta v = L_S l_g \left(2 r_g \pi * \frac{d\delta}{2\pi} \right) = L_S l_g r_g d\delta \qquad - (3)$$

$$W(\theta) = \frac{L_S l_g r_g}{2\mu_0} \oint_V B^2 dV \qquad - (4)$$

Where,

L_S – Axial length of the air gap.

l_g – Air gap length between high speed rotor and Ferro pole pieces.

r_g – Average air gap radius.

Pull out torque on high speed side (load side)

$$T_{out}(\theta) = \frac{\partial \left[\frac{L_S l_g r_g}{2\pi} \oint_V B^2 d\delta \right]}{\partial(\theta)} \qquad - (5)$$

Where,

$T_{out}(\theta)$ - Pull out torque on high speed rotor.

r_g - Average air gap radius

l_g - Air gap length between the high speed rotor and Ferro pole pieces.

The instantaneous torque on low speed & high speed side,

$$T_{LOW} = T_{out}(\theta) \sin\left[\frac{N_S \beta_0 - p_2 \gamma_0 - p_1 \alpha_0}{p_2} \right] \qquad - (6)$$

$$T_{HIGH} = T_{out}(\theta) \sin\left[\frac{N_S \beta_0 - p_2 \gamma_0 - p_1 \alpha_0}{p_1} \right] \qquad - (7)$$

Where,

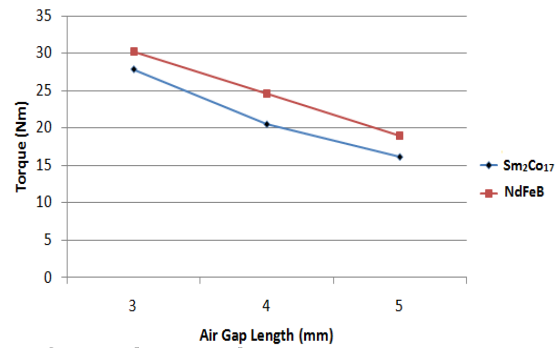
p_1 – pole pair on high speed rotor.

p_2 – pole pair on low speed rotor.

β_0 - Initial phase angle of the stator ring.

α_0 - Initial phase angle of the high speed rotor.

γ_0 -Initial phase angle of the low speed rotor.



5 Determination of Gearing Ratio

The gearing ratio is derived in [5] covers perpendicular magnetic gear operations. By defining p_1 and p_2 the pole pair number of high and low speed rotors respectively and N_s as the number of pole pairs in rotor. A large difference between pole pair p_1 and p_2 results in a higher gear ratio .

$$G_r = \frac{\omega_1}{\omega_2} = -\frac{p_2}{p_1} \qquad - (8)$$

Where,

ω_1 - Rotational speed of High speed rotor.

ω_2 - Rotational speed of Low speed rotor.

The minus sign indicates that the two rotors rotate in opposite direction.

Torque decreases rapidly with the increase of airgap length. Considering the complexity in manufacturing and installation process, the suggested air gap length is between 3mm to 5mm

Torque ripples are caused by the interaction of the rotor permanent magnets with ferromagnetic pole pieces i.e. cogging torque. Fig.3 shows the variation of the transmitted torque and the high speed rotor.

6 Comparison

Transmission torque of magnetic gear and magnetic materials are measured under different air gap width with same load. Fig.3 shows the torque of the perpendicular magnetic gear vs time. After comparison the torque of magnetic gear increases with decrease in the distance between the two rotors, magnetic materials and amount of useful flux involved between the two magnets are known.

Torque transmission under different air gap and different materials, are shown in Table II.

TABLE II.

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Magnetic material	Sm_2Co_{17}		
Air gap distance (in mm)	3	4	5
Torque (in Nm)	27.9	20.5	16.1
Magnetic material	**NdFeB**		
Air gap distance (in mm)	3	4	5
Torque (in Nm)	30.2	24.6	19.0

Fig.4. Torque vs air gap length.

7 Conclusion

A high performance magnetic gear topology has been presented and it has been shown that by employing rare earth magnets, a high torque density has been achieved. Rare earth magnets are very useful in different electromechanical devices, permanent magnet torque couplers and magnetic gears having many advantages in comparison with classical mechanical couplers and gears. Based on the finite element analysis result we understood that various types of gears with different magnetic materials are highly suitable for various applications like wind power generation, automobile applications and industrial (Group Drives) applications.

References

[1] Y. D. Yao, D. R. Huang, C. C. Hsieh, D. Y. Chiang, S. J. Wang, andT. IF. Ying, "The Radial Magnetic Coupling Studies of Perpendicular Magnetic Gears," IEEE Trans. Magn., vol 32, no.5, pp.5061- 5063, September 1996.

[2] Peter Omand Rasmussen, Torben Ole Andersen, Frank T. Jorgensen, and Orla Nielsen, "Development of a High-Performance Magnetic Gear," IEEE Trans. Ind. Appli., vol. 41, no. 3, pp.764-770, May/June 2005.

[3] K. T. Chau, Dong Zhang, J. Z. Jiang, Chunhua Liu, and Yuejin Zhang, "Design of a Magnetic-Geared Outer-Rotor Permanent-Magnet Brushless Motor for Electric Vehicles," IEEE Trans. Magn. Vol. 43, no. 6, pp.2504-2506, June 2007.

[4] Frank T. Jorgensen, Torben Ole Andersen, and Peter Omand Rasmussen, "The Cycloid Permanent Magnetic Gear," IEEE Trans. Ind. Appli., vol 44, no. 6, pp.1659-1665, November/December 2008.

[5] Linni Jian, *Student Member*, *IEEE*, K. T. Chau, *Senior Member*, *IEEE*, and J. Z. Jiang,"A Magnetic-Geared Outer-Rotor Permanent-Magnet Brushless Machine for Wind Power Generation," IEEE Trans. Ind. Appli., vol. 45, no. 3, pp. 954-962, May/June 2009.

[6] Linni Jian, K. T. Chau, Yu Gong, J. Z. Jiang, Chuang Yu, and Wenlong Li, "Comparison of Coaxial Magnetic Gears With Different Topologies," IEEE Trans. Magn., vol. 45, no. 10, pp. 4526-4529, October 2009.

[7] L. L. Wang, J. X. Shen, P. C. K. Luk_, W. Z. Fei_, C. F. Wang, and H. Hao, "Development of a Magnetic-Geared Permanent-Magnet Brushless Motor," IEEE Trans. Magn., vol. 45, no. 10, pp. 4578-4581, October 2009.