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Design and Simulation Analysis of a Perpendicular Magnetic Gear

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Abstract

This paper presents design and analysis of flux density, torque and gear ratio in perpendicular magnetic gear. Permanenet magneic gear is a new type of non contact mechanical power transmission and high gear ratio system. This has unique advantages to be applied in the wind turbine and Industrial group drive applications etc. This type of gears offers both high speed and high torque required for drive applications. The flux density, torque and gear ratio of the perpendicular magnetic gear has been simulated using MagNet software (version 7.1.3). This novel gear arrangement will lead to many drive applications in industries, replacing the conventional mechanical gear.

Introduction

Permanent magnets have fascinated and inspired many people through the ages, because a permanent magnet produces a flux and magnetic force [1].

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 and extremely low vibration and noise-levels, free from maintenance, improved reliability, high efficiency and inherent overload protection. They can operate through a separation wall (i.e) transmit torque without any physical contact. Therefore, it is quite suitable for using in any type of environments [2-7]

This novel feature of perpendicular magnetic gear confiuration has not been implemented so far in drive applications. In this paper, a detailed mathemetical modeling and simulation of the perpendicular magnetic gear has been implemented.

The proposed magnetic gear provides better torque by eleminating frictional losses.

The objective of this paper is to propose and implement a magnetic gear for various applications like wind power generation and Industrial group drive applications etc. For all the mathemetical modeling, simulation and analysis, MagNet software (version 7.1.3) involving finite element analysis has been used in this paper.

This paper is divided into 9 sections. Section 2 deals with Perpendicular Magnetic Gear Design. Section 3 deals with Finite Element Analysis of the magnetic gear. Section 4 Magnetic fields in air gap equations are developed. In section 5 Torque equations are developed. In Section 6 Determination of gearing ratio are formulated. The simulation results and Discussion is made in section 7 and finally the conclusion is given in section 8.

Perpendicular Magnetic Gear Design

The principle of the designed perpendicular magnetic gear is that a radial magnetic circuit is employed to realize the magnetic coupling of high speed and low speed rotors and radial airgap length magnetic permieability modulation is used to realize the movement transform. The perpendicular magnetic gear shown in fig.1 has 32 pair of poles in low speed side (prime mover) and 4 pair of poles in high speed side (load). The high speed and lowspeed rotors have different pole pairs of permenent magnets, designed to be two separate sectios and sharing a two Ferro pole pieces in radial directions. Permanent magnets are surface mounted on the two rotors. The separated rotor cores (Ferro pole pieces) are evenly distributed arount the circumference and inserted into a non magneto permieability shell. Inorder to increase the mechancal support of the rotor system, there is an additional support mechanical ball bearings between the two rotors. Table 1 shows the particulars of various dimensions.

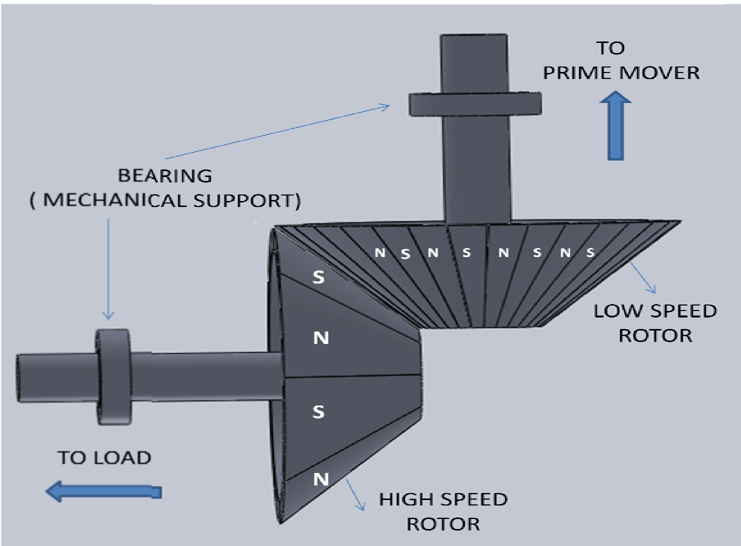

Figure 1: Perpendicular Magnetic Gear.

Table 1: Dimensions of gear

Description	Perpendicular Magnetic Gear
No of low speed rotor poles	32 pair
No of high speed rotor poles	4 pair
Outer radius of low speed rotor	240mm
Inner radius of low speed rotor	61mm
Outer radius of high speed rotor	240mm
Inner radius of high speed rotor	61mm
Length of rotor poles	100mm
Airgap length	0.5mm
Permanent magnet material	NdFeB
Permieability of air region μ_0	$4\pi x 10^{-7}$ Tm/A
Relative permieability 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.

Finite Element Analysis

The magnetic gear shown in Fig.1 is used for finite element analysis. The parameters of the gears are listed in Table.1. 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 is shown. The curve is obtained by evaluating T_{HIGH} (11) Equations mentioned in torque equation.The Max torque obtained is 30 Nm. The above torque is calculated using the finite element analysis [8-12].

Equation of Magnetic Field in Air Gap

The radial component of flux density in the airgap at high speed rotor side is

$$B_r(r,\tau) = \sum_{m=1,3,5...} b_{rm}(r)\cos(mp_h(\tau - \omega_h t) + mp_h\tau_0) \tag{1}$$

Where,
r – radial distance
τ - Angle of high spped rotor
ω_h - Rotational speed of high speed rotor
τ_0 - the initial angle of the high speed rotor
$b_{rm}(r)$ - Fourier co efficient for the radial component of the flux density.

When the ferro pole pieces exist the magnetic lines of flux will only distribute along the pole pieces because there are no other magnetic medium around.

The Fourier form of the permiability modulations is given by

$$\lambda = \lambda_{ro} + \sum_{n=1}^{\infty} \lambda_n \cos(n_s \tau) \tag{2}$$

Where n_s - the numberof Ferro pole pieces.

Through the modulation of the pole pieces, the flux density in the air gap adjustment to the low speed rotor then will be

$$B_r(r,\tau) = \Big(\sum_{m=1,3,5...} b_{rm}(r)\cos(mp(\tau-\omega_r t)+mp\tau_0)\Big)\Big((\lambda_{r0}(r) \quad (3)$$

$$+\sum_{j=1,2,3...} \lambda_{rj}(r)\cos(jn_s(\tau-\omega_s t))\Big)$$

$$= \lambda_{r0}(r) \sum_{m=1,3,5...} b_{rm}(r)\cos(mp(\tau-\omega_r t)+mp\tau_0)+$$

$$\frac{1}{2}\sum_{m=1,3,5...}\sum_{j=1,2,3...}(b_{rm}(r)\lambda_{rj}(r)\cos(mp+jn_s)(\tau-\frac{mp\omega_r+jn_s\omega_s}{mp+jn_s}t+mp\tau_0)+$$

$$\frac{1}{2}\sum_{m=1,3,5...}\sum_{j=1,2,3..}(b_{rm}(r)\lambda_{rj}(r)\cos(mp-jn_s)(\tau-\frac{mp\omega_r-jn_s\omega_s}{mp-jn_s}t+mp\tau_0) \tag{4}$$

It should be noted that ω_r reperesent the average angular velocity of the low speed rotor, since the individual mangnets rotate at different instantaneous speed as a result of their different relative radial position around the sinusoidally shaped outer surface of the low speed rotor.

Torque Equation

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

$$T(\theta) = -\frac{\partial W(\theta)}{\partial(\theta)} \tag{5}$$

Where,

W(θ) – Magnetic energy.

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

$$W(\theta) = \frac{1}{2\mu_0}\oint_V B^2 dV \tag{6}$$

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 (6) is transformed to (8) with volume difference of airgap Δv shown in (7)

$$\Delta v = L_S l_g \left(2 r_g \pi * \frac{d\delta}{2\pi} \right) = L_S l_g r_g d\delta \tag{7}$$

$$W(\theta) = \frac{L_S l_g r_g}{2\mu_0} \oint_V B^2 dV \tag{8}$$

Where,
L_S – Axial length of the air gap.
l_g – Air gap length between Low & High speed rotor
r_g – Average air gap radius.

Pull out torque on high speed side (load side)

$$T_{out}(\theta) = \frac{\partial \left[\frac{L_S l_g r_g}{2\pi} \oint_V B^2 d\delta \right]}{\partial(\theta)} \tag{9}$$

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,

$$T_{LOW} = T_{out}(\theta) \sin\left[\frac{N_S\beta_0 - p_2\gamma_0 - p_1\alpha_0}{p_2} \right] \tag{10}$$

$$T_{HIGH} = T_{out}(\theta) \sin\left[\frac{N_S\beta_0 - p_2\gamma_0 - p_1\alpha_0}{p_1} \right] \quad 11)$$

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.
Numbe of Pole pairs $Ns = p_1 + p_2$

Determination of Gear Ratio

The gearing ratio is derived in [5] covers all types of magnetic gear operations. By defining p_1 and the pole pair number of outer and inner 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

$$G_r = \frac{\omega_1}{\omega_2} = -\frac{p_2}{p_1} \qquad (12)$$

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 airgap length is between 0.5mm to 0.7mm.Torque ripple 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.

Simulation Results and Discussion

Transmission torque of perpendicular magnetic gear and different magnetic materials are measured under different air gap with the same load. After comparison the torque of magnetic gear increases with decreasing the distance between the two rotors, magnetic materials and amount of useful flux involved between the two magnets.

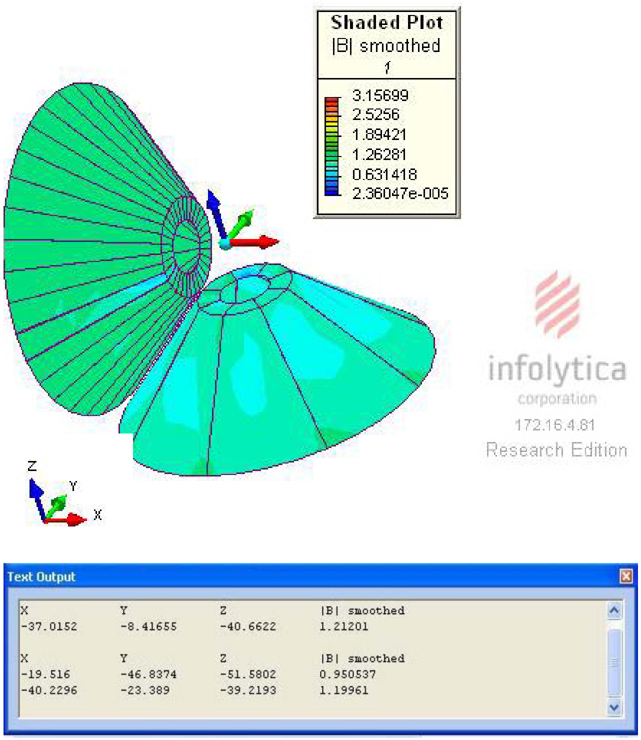

Figure 2: Flux density distibution in Perpendicular magnetic gear

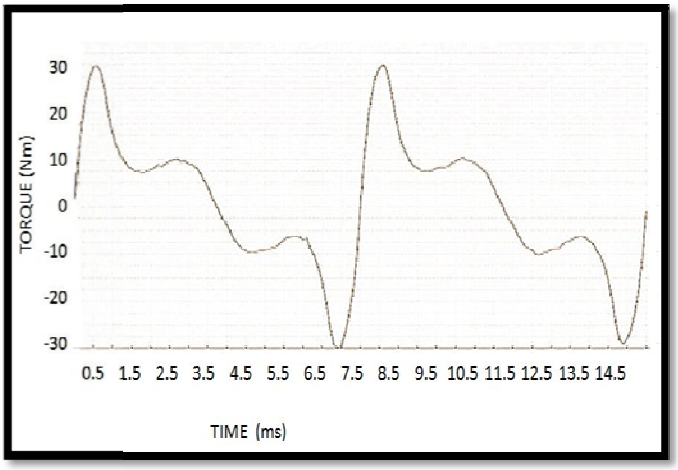

Figure 3: Torque vs time for perendicular magnetic gear.

The most important charecteristics of perpendicular magnetic gear is its ability to transmit the torque both from high speed and low speed side.

The torque devoloped by the low and high speed rotor depends upon magnetic material, airgap length, length of the gear, thickness of the magnets and thickness of ferro pole pieces.

Table 2: Optimum range of perpendicular magnetic gear

Magnetic material	Airgap length	Thickness of low speed side rotor magnet	Thickness of high speed side rotor magnet	Thickness of ferro pole pieces both low and high speed rotor	Maximum Torque Produced
NdFeB or SM_2CO_{17}	0.2 to 0.5mm	0.5 mm to 0.7mm	0.5 mm to 0.7mm	0.5 mm to 0.7mm	28 to 30 Nm.

The optimum range of values to produce maximum torque from a perpendicular magnerid gear is 30 Nm, as represented in Table2.

Conclusion

A high torque perpendicular magnetic gear was designed, simulated and analysed with the help of MagNet software (version 7.1.3) involving FEA. The calculations have shown that the magnetic gear with gearing ratio of 1:8 and a maximum torque of 30 Nm. The maximum achievable torque of this gear was calculated by analytical expressions derived in [12] and the torque transferred equation (11). These proposed configurations might also be used in wind turbine, automobile or Industrial group drive applications.

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