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Torque Analysis of Magnetic Spur Gear with Different Configurations

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Abstract

This paper presents design and torque analysis in various types of magnetic gear with different magnetic materials and air gap. This type of gear offer both high speed and high torque required for drive applications. In the proposed gear analysis the low speed side is connected to prime mover and high speed side is connected to load, suitable for wind power, automobile applications and group drive applications etc. The torque of the radial magnetic coupling between magnetic gears with different magnetic materials and different air gap length has been simulated usin MagNet software and the gear performances are compared. Finally, it is concluded that the result in this paper may help to initiate a shift from mechanical gears to magnetic gears.

Indexed Terms – Analytical modeling, Finite element analysis, High torque, Magnetic gear.

Nomenclature

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

$T_1(\theta)$ - Pull out torque on low speed rotor

$T_2(\theta)$ - Pull out torque on high speed rotor

p_1 - Pole pair of high speed rotor.

p_2 - Pole pair of low speed rotor.
ω_1 - Rotational speed of high speed rotor.
ω_2 - Rotational speed of Low speed rotor.

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 the 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; transmit torque without any physical contact. Therefore, it is quite suitable for using in any type of (all the) environments.

The literature survey made with different papers concludes that magnetic gears are highly efficient with better torque by eliminating frictional losses. But the constraint is that the above statements were not validated through any mathematical proof.

The torque of magnetic coupling decreases with increasing the distance between the magnetic gears. 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 smaller than a critical separation distance l_g, but it is reversed as the separation distance becomes larger.

The objective of this paper is to propose and implement a magnetic gear for various applications like wind power generation, automobile and mills etc. For all the mathematical 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 7 sections. Section 2 deals with design of various type of magnetic gear. Section 3 deals with Finite Element Analysis of the permanent magnetic gear with high torque. In section 4 torque equations are developed. In section 5 Determination of gearing ratio are formulated. After that simulation results and analysis is made in section 6 and finally the conclusion is given in section 7.

Magnetic Gear Design

Fig 1 shows the permanent magnet spur gear with 4 pair of poles in low speed side (prime mover side) and 2 pair of poles in high speed side (load side). But in this type of arrangement, lots of the magnets are inactive and cannot generate useful torque in load side [2-3]. Also it takes more space between two gear rings because two gear rings are separated. In order to improve the useful flux in the magnet and also to reduce the space between two gear rings, Inner type spur gear arrangement is being used which is shown in fig.2. Further to improve the load torque the high speed rotor is fixed at the centre of the prime mover rotor (outer rotor). The no of poles in the load side (High speed side) is 2 pair and prime mover (low speed side) side is 4 pair which is shown in fig.2. So the gear ratio is 1: 2. Optimum utilization of magnet modified spur gear to salient pole type spur gear with same poles and gear ratio specifications which is shown in fig 3.

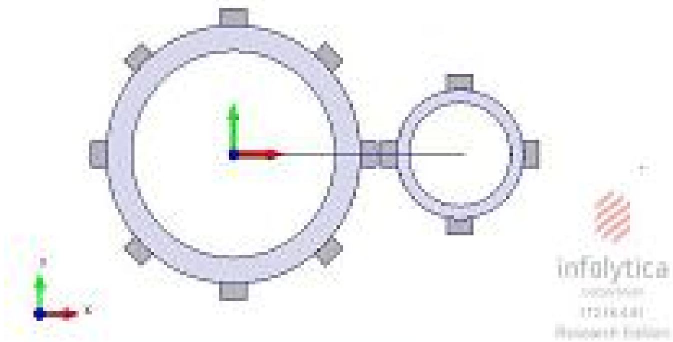

Figure 1 . Permanent magnet spur gear

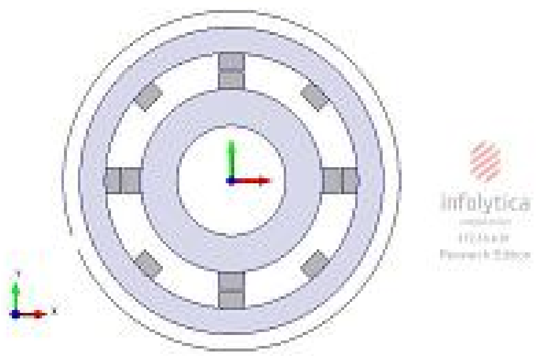

Figure 2. Inner type spur gear

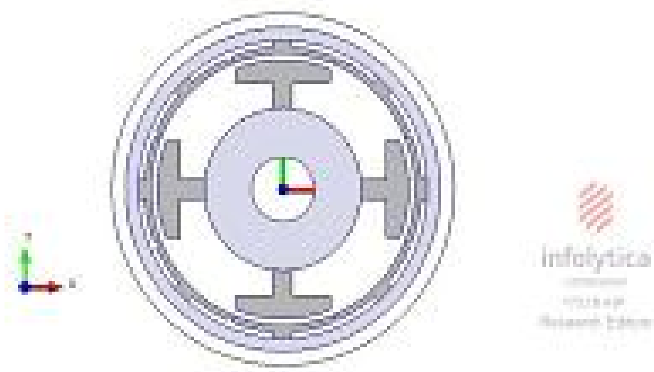

Figure 3 Salient pole type spur gear

The torque of magnetic coupling depends on the number of magnetic poles, the area of poles covered by the magnets, the magnetic field strength of magnets and the separation distance between the magnetic gears [4].

Table 1 shows the particulars of various dimensions.

TABLE I

Description	Units	Spur Gear	Inner type spur Gear	Salient pole type spur Gear
No of low speed rotor poles	-	8	8	8
Outer radius of low speed rotor	mm	28	30	25
Inner radius of low speed rotor	mm	20	21.75	21
No of high speed rotor poles	-	4	4	4
Outer radius of high speed rotor	mm	15.5	10	20
Inner radius of high speed rotor	mm	10	12.5	12.5
Length of the magnetic material	mm	100	100	100
Air gap length	mm	1	1	1
Permanent Magnet material	-	NdFeB & Sm_2CO_{17}		
Permeability of air region (μ_0)	Tm/A	$4\pi x 10^{-7}$		
Relative permeability of magnets $\mu_r = \mu / \mu_0$	-	1.0523		
Max torque	N.m	6	22.5	30

To maintain better gear ratio we design more poles on the low speed side and fewer poles on the high speed side.

Finite Element Analysis

The mentioned magnetic gears shown in Fig1, 2, and 3 are used for FEM to analyze the performance of magnetic gears. The parameters of the gears are listed in table I, the flux lnes are shown in figure 5,8 and 11, while the flux density are shown in figures 4,7 and 10. The calculated torque versus time curve is shown in fig 6, 9 &12. The curve is obtained by evaluating torque mentioned in torque equation (8) [5-11].

For the Spur gear, the maximum Torque obtained is 6 Nm, for Inner type spur gear, the max.torque is 22.5Nm and for salient pole type spur gear the max. Torque is 30.0 Nm (as per Table II).The above torques is calculated with the help of finite element method (FEM).

Torque equation

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

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

Where,

$W(\theta)$ – Magnetic energy.

Assuming that the magnetic energy is stored only in the air gap, $W(\theta)$ is expressed as,

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

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, equation (2) is transformed to (4), with the volume difference of the air gap Δv shown in (3)

$$\Delta v = L_S l_{g1}\left(2 r_{g1}\pi\frac{d\delta}{2\pi}\right) = L_S l_{g1} r_{g1} d\delta \qquad - (3)$$

$$W(\theta) = \frac{L_S l_{g1} r_{g1}}{2\mu_0}\oint_V B^2 d\delta \qquad - (4)$$

Where,
L_S – Axial length of the air gap.
l_{g1} – Air gap length between Low speed rotor & stationary pole pieces.
r_{g1} – Average air gap radius.

The Pull out torque is obtained as

$$T_1(\theta) = \frac{-\partial\left[\frac{L_S l_{g1} r_{g1}}{2\mu_0}\oint_V B^2 d\delta\right]}{\partial(\theta)} \qquad - (5)$$

Where,
$T_1(\theta)$ - Pull out torque on low speed rotor.

And similarly for the high speed rotor,

$$T_2(\theta) = \frac{-\partial\left[\frac{L_S l_{g2} r_{g2}}{2\mu_0}\oint_V B^2 d\delta\right]}{\partial(\theta)} \qquad - (6)$$

Where,
$T_2(\theta)$ - Pull out torque on high speed rotor.
r_{g2} - Average air gap radius
l_{g2} - Air gap length between the high speed rotor and stationary pole pieces.

The stable torque developed on the low and high speed rotor can be expressed as

$$T_{LOW} = T_1(\theta)\sin\left[\frac{N_S\beta_0 - p_2\gamma_0 - p_1\alpha_0}{p_2}\right] \quad - (7)$$

$$T_{HIGH} = T_2(\theta)\sin\left[\frac{N_S\beta_0 - p_2\gamma_0 - p_1\alpha_0}{p_1}\right] \quad - (8)$$

Where,

p_1 – pole pair of high speed rotor.
P_2 – pole pair of 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.
$N_s = p_1 + p_2$

Torque decreas rapidly with the increase of the air gap length. Considering the limitation of manufacturer and installation the suggested air gap length is between 0.5mm to 0.7mm.

Torque ripples are caused by the interaction of the rotor permanent magnets with the ferromagnetic pole pieces i.e. cogging torque Fig. 6, 9 &12 shows the variation of the transmitted torque on the high speed rotor.

Determination of Gearing Ratio

The gearing ratio is derived in [5] covers all the types of magnetic gear operations. By defining p1 and p2 as the pole pair number of the outer and inner rotors respectively and Ns as the number of Ferro magnetic pole pair of rotors. A large difference between pole pair p1 and p2 in (9) results in a higher gear ratio.

$$G_r = \frac{\omega_1}{\omega_2} = -\frac{p_2}{p_1} \quad - (9)$$

Where,

ω_1 - Rotational speed of high speed rotor.
ω_2 - Rotational speed of Low speed rotor.
The minus indicates that the two rotors rotate in opposite direction.

Simulation results and Analysis

Transmission torque of different type of 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.

Table 2 Torque transmission under different air gap, different materials and different types of gears.

Table 2

Types of Magnetic Gear	Sm2Co17			NdFeB		
Air gap distance	1mm	2mm	3mm	1mm	2mm	3mm
Torque in Spur Gear (Nm)	5.3	4.3	3.2	6	4.8	3.9
Torque in Inner type spur Gear (Nm)	21.7	20.1	17.9	22.5	20.5	18.7
Torque in Salient pole type spur Gear (Nm)	28.8	25.7	24.2	30.0	26.9	25.3

6 a Spur Gear Results

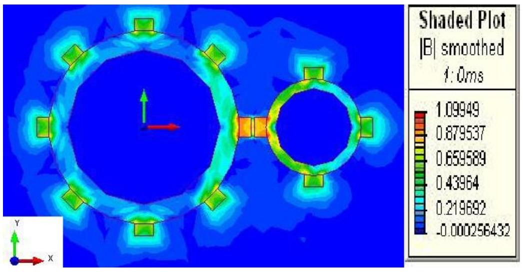

Figure4 Flux density distibution in spur gear (airgap 1mm, NdFeB)

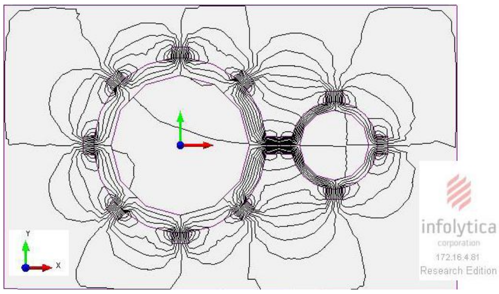

Figure 5. Flux line in spur gear (airgap 1mm, NdFeB)

Figure4 shows the simulation result for Torque versus Time for spur gear from the waveforms the max torque is 6 Nm.

Figure 6. Torque vs time for spur gear (airgap 1mm, NdFeB)

6 b. Inner type Spur Gear Results

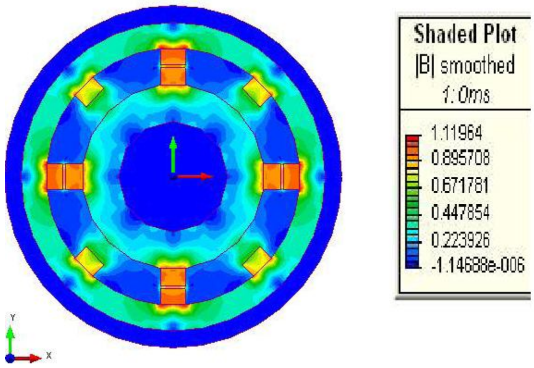

Figure 7 Flux density distribution in Inner type spur gear (airgap 1mm, NdFeB)

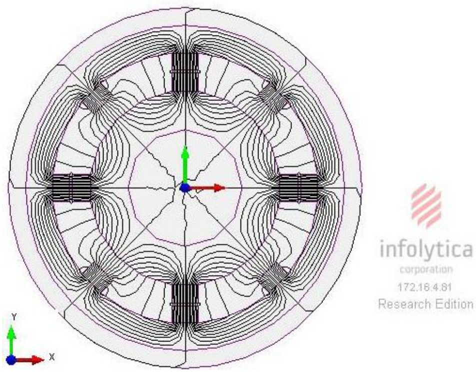

Figure 8. Flux line in Inner type spur gear (airgap 1mm, NdFeB)

Figure 8 shows the simulation result for Torque versus Time for inner type spur gear from the waveforms the max torque is 22.5Nm.

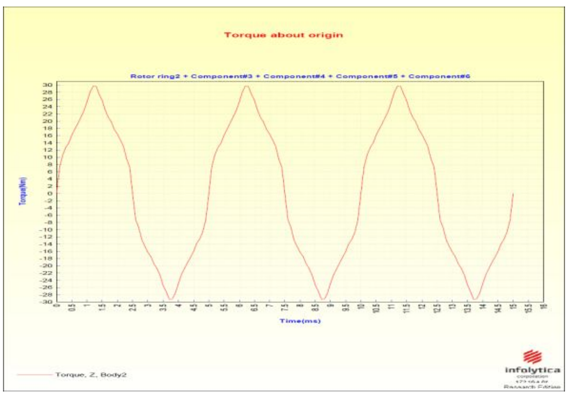

Figure 9. Torque vs time Inner type spur gear (airgap 1mm, NdFeB)

6 c Salient pole type Spur Gear Results

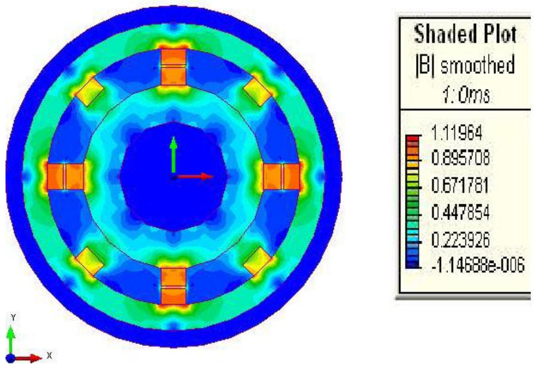

Figure10 Flux density distribution in salient pole type spur gear (airgap 1mm, NdFeB)

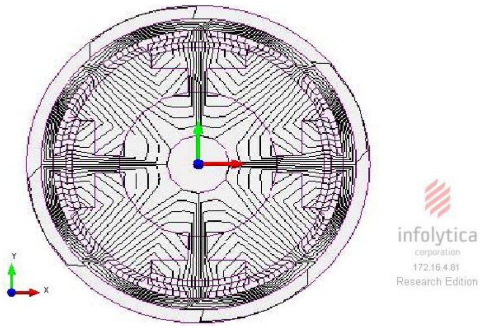

Figure11. Flux line in salient pole type spur gear (airgap 1mm, NdFeB)

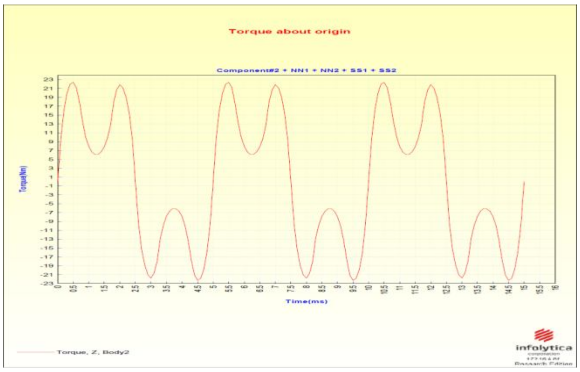

Figure 12 Torque vs time for salient pole type spur gear (airgap 1mm, NdFeB)

Figure12 shows the simulation result for Torque versus Time for salient pole type spur gear from the waveforms the max torque is 30 Nm.

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 can be achieved. Rare earth magnets are very useful in different electromechanical devices, permanent magnetic torque couplers and magnetic gears having many advantages in comparison with classical mechanical couplers and gears. Based on the finite element analysis results of various types of gears with different magnetic materials, it is proved they are best suitable for various applications like wind power, automobile applications, group drive applications etc.

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