Design and Implementation of a Novel Magnetic Bevel Gear

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Abstract: A magnetic gear offers several advantages compared to the mechanical gear due to the reduced maintenance, higher efficiency than conventional gears and physical isolation between input and output shafts. This paper presents a novel design of magnetic bevel gear that achieves high torque transfer to the load. The proposed gear design provides higher load torque under various gear configurations. The various configurations include different air gap length, different pole pairs with the same gear ratio and gear dimensions.

A practical prototype magnetic gear model is developed and its torque performance is analysed and compared with finite element analysis simulation method under various configurations. Also, the performance of the proposed magnetic bevel gear is compared to mechanical bevel gear. Finally, it is concluded that the results in this paper may help to initiate a shift from mechanical bevel gears to magnetic bevel gears.

Keywords: magnetic bevel gear; finite element analysis (FEA); torque transmission; gear ratio.

1. INTRODUCTION

In a bevel gear, the axes of the two shafts intersect and the tooth bearing faces are conically shaped. The bevel gears are conventionally mounted on the shafts that are displaced by 90° as shown in Fig. 1. At the same time, they can be designed to work at any other angle as shown in Fig. 1.

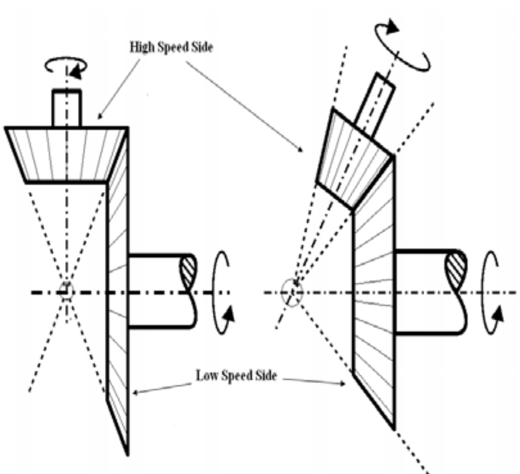


Fig. 1. Perpendicular Bevel Gear and Bevel Gear at any angle.

The bevel gear is used in many of the applications such as group drives in textile mills, wind mill and for opening and closing of dam shutters of hydro electric power plant. However, it needs regular maintenance for avoiding corrosion and wear and tear of the system. Now a day, the magnetic gears play a vital role in rectifying this shortcoming. The faces of the tooth bearing can be replaced by permanent magnets which form the n orth and south poles as shown in Fig. 1. This type of gear can be used as a magnetic bevel gear in which the gear ratio depends upon the number of pole pairs. This type of magnetic gear does not need any maintenance.

Some of the important advantages of magnetic gear are reduced maintenance, improved reliability, free lubrication, higher efficiency than conventional gears, inherent overload protection, physical isolation between input and output shafts, Inherent anti-jamming transmission significantly reduces the harmful drive train pulsations, very low acoustic noise and vibration.

A U.S. patent (Neuland, 1916) has proposed a two revolving shafts with electromagnets placed on the rims to achieve a maximum torque. In this US patent system, the transmit torque and the speed of the system can be altered to the convenience using the magnetized shafts and poles. Even though the gearing topology is adopted, this method has the limitation of lower efficiency and design complexity. So, it is not used in commercial applications.

Another U.S. patent has been filed (Faus, 1940) in which the magnetic gear and the different number of teeth on the two discs are used. In this approach, it is very difficult to achieve the required torque density due to the usage of ferrite material type magnets available at that time. Since the availability of rare earth magnets has become very popular since 1980s, the above topics have attracted people's attention and the disadvantage of using electromagnet is eliminated (Lee *et al*., 1985). The rare-earth permanent magnets have the ability to produce very strong magnetic field without continuous exterior excitement. This can help to get rid of the drawbacks of electromagnets. However, the usage of super conductive magnet demands the cooling system which costs very high (Hesmondhalgh and Tipping 1980). In the recent years, the rare earth magnet has become very popular in the research field. But the current environment demands the systems to work in all the directions.

(Yao *et al*., 1996) have proposed a magnetic gear system where the torque analysis has been made. In this approach, the torque achieved is in the range of 2.8Kgm – 5.8Kgm which is considered to be low. The magnetic field of the machine is also computed using Finite Element Analysis (FEA).

(Ramsden *et al*., 2000) have used the FEA based analysis when an outer rotor directs the drive permanent magnet generator. In this approach, the mechanical deformation of the machine happens even in the case of time harmonic magnetic fields.

(Ando *et al*., 2012) have developed a cylindrical magnetic gear with 1:2 gear ratio. In this paper, the driving torque of gear is analysed and compared with the developed proto type model. Further, the driving torque is analysed due to the implication of revolving speed, distance between the magnetic gear (air gap) and rotational load.

(Siavash Pakdelian *et al*., 2013) have designed a Trans - rotary magnetic gear. This gear consists of a rotor and a translator with air gap in between. The rotary magnetic field creates a linear motion, or vice versa. This magnetic device can be used to convert the low speed and high force linear motion of the translator to high speed and low torque rotation of the rotor suitable for driving a compact rotary generator. Such designs result in poor force densities.

The mechanical bevel gears used in various applications suffer from problems like frequent gear oil change, maintenance problems, reduced gear life, etc. In order to overcome the drawbacks encountered in the conventional mechanical gears, a novel magnetic bevel gear design is proposed and its performance is simulated and tested practically under various design configurations. At present, the existing magnetic gear is acting in an axial direction mechanical power flow only. This paper proposes a novel system of magnetic gear which has a freedom to operate over any angle so that the power flow can be in any direction. The proposed magnetic bevel gear shows better performance comparatively and can be implemented in various applications.

2. GEAR DESIGN

The main principle of the designed magnetic bevel gear is a radial magnetic circuit which is employed to realise the magnetic coupling of high speed and low speed rotors. As shown in Fig. 2, the magnetic bevel gear has 16 pairs of poles in the low speed side (prime mover) and 4 pairs of poles in the high speed side (load). The high speed and low speed rotors have different pole pairs of permanent magnets designed to be two separate sections sharing a two Ferro pole pieces in radial directions. The surfaces of the permanent magnets are mounted on the two rotors. The separated rotor cores (Ferro pole pieces) are evenly distributed around the circumference and inserted into a non magneto permeability shell. In order to increase the mechanical support of the rotor system, there is an additional support mechanical ball bearing between the two rotors. The specifications of the magnetic bevel gear are shown in Table 1.

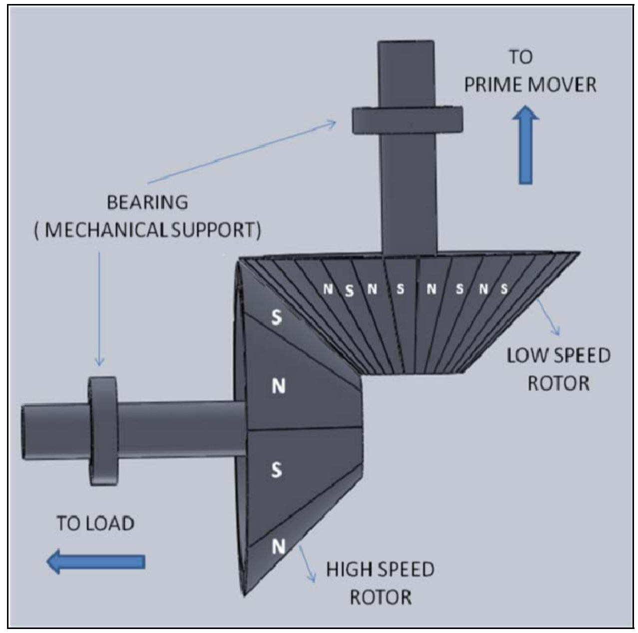


Fig. 2. A Magnetic Bevel Gear

Table1. Magnetic Bevel Gear Specifications.

Description	Magnetic bevel gear
Pole pair configuration	N_P= 8 N_L= 2, N_P= 16 N_L= 4 & N_P= 32 N_L= 8
Radius of low speed rotor	Bottom = 61mm & Top = 240 mm
Radius of high speed rotor	Bottom = 61 mm & Top = 240 mm
Length of rotor poles	100 mm
Pole thickness	10 mm
Air gap length (l_g)	0.5 mm, 1 mm, 1.5 mm & 2 mm
Permanent magnet material	NdFeB
Permeability of air region μ_0	$4\pi x 10^{-7}$ Tm/A
Relative permeability of magnets $\mu_r = \mu / \mu_0$	1.0523

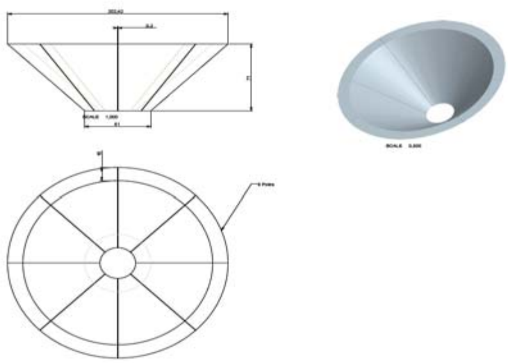


Fig. 3. A high speed rotor with 4 pole pairs and its dimensions.

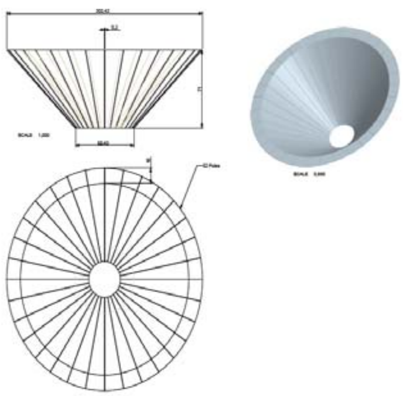


Fig. 4. A low speed rotor with 16 pole pairs and its dimensions.

The size of the low and high speed rotors are apportioned for the given overall dimension constraints. The rotor assembly consists of high energy permanent magnet and magnetic stainless steel ring to house the magnets and to carry the flux. Fig. 3 and Fig. 5 show the high speed rotor with 4 pole pairs and one pole piece dimensions respectively. Similarly Fig. 4 and Fig. 6 shows the low speed rotor with 16 pole pairs and one pole piece dimensions respectively.

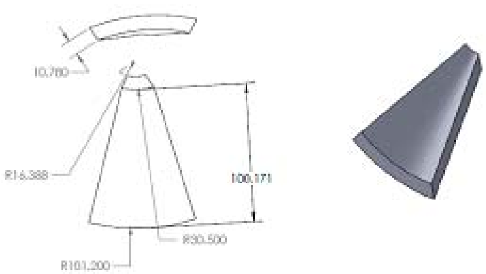


Fig. 5. One pole piece dimensions – High Speed Rotor.

According to the principle of transformation of magnetic energy to mechanical energy, the following equation can be obtained (Vijasyashankar *et al*., 2011; Muruganandam *et al*., 2012a; Muruganandam *et al*., 2012b).

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

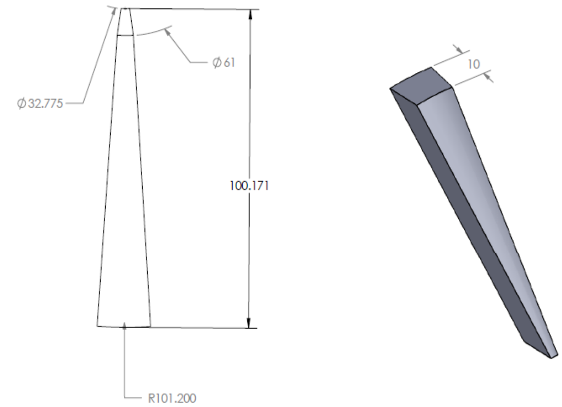


Fig. 6. One pole piece dimensions – Low Speed Rotor.

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

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

where μ_0 is permeability in vacuum, V is volume of the air gap and B is magnetic flux density in the air gap. Also

$$P = T\omega \tag{3}$$

where, P is mechanical power developed, ω is angular velocity.

$$T\omega = \frac{1}{2\mu_0}\oint_V B^2 dV \tag{4}$$

$$T = \frac{1}{2\omega\mu_0}\oint_V B^2 dV \tag{5}$$

$$T_L = TG_r \tag{6}$$

where Gr is the gear ratio and TL is the load torque.

2.1 Determination of a Gear Ratio

The gearing ratio is derived by (Jorgensen *et al*., 2008; Jian *et al*., 2009) which covers all types of magnetic gear operations by defining N_P and N_L, the number pole pairs of prime mover and load side rotors respectively. A large difference between pole pairs N_P and N_L results in a higher gear ratio.

$$G_r = \frac{\omega_P}{\omega_L} = -\frac{N_L}{N_P} \tag{7}$$

where ω_P is rotational speed of prime mover rotor, ω_L is rotational speed of load side rotor, N_L is number of pole pair in load side rotor and $N_P$is number of pole pair in prime mover side rotor.

The minus sign indicates that the two rotors rotate in opposite directions. In order to get better gear ratio, commutate the magnetic field in the high speed side with few permanent magnetic poles and low speed side with many poles.

3. A MATHEMATICAL MODEL OF THE MAGNETIC BEVEL GEAR

The primary objective of this modeling is to compute the transfer function relating the load torque (T_L) and the prime mover torque (T_P) of the proposed magnetic bevel gear. The magnetic bevel gears are the matching devices for achieving maximum power transfer between the prime movers and the load. The gears are frequently used by a servo system in industrial and automobile control. These change the speed to torque compatibility with various desired levels of speed. Usually, the gears are used for torque magnification and reduction of speeds. Thus in mechanical systems, a gear acts as the matching device like the transformer in electrical system. Fig. 7 shows the equivalent model of a magnetic bevel gear.

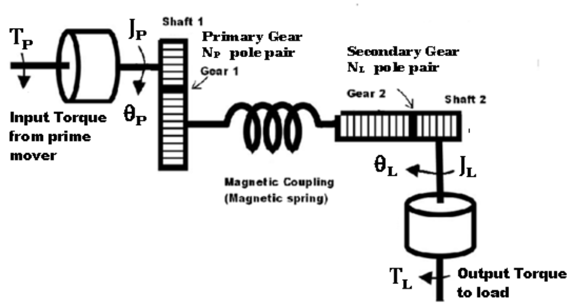


Fig. 7. Equivalent model of magnetic bevel gear.

The mechanical rotational power available at prime mover P_P is proportional to θ_P T_P. Similarly, the rotational power delivered to load P_L is proportional to θ_L T_L.

$$T_P = J_P \frac{d^2\theta_P}{dt^2} + B_P \frac{d\theta_P}{dt} + K_P\theta_P \tag{8}$$

where θ_P is angular displacement of prime mover shaft (degree), θ_L is angular displacement of load shaft (degree), J_P is moment of inertia of prime mover (Kg-m^2), J_L is moment of inertia of load (Kg-m^2), B_P is Co efficient of viscous (magnetic) friction of prime mover (Nm /rad/sec) and $B_L$is Co efficient of viscous (magnetic) friction of load (Nm /rad/sec).

Taking Laplace transformation of equations (8).

$$T_P = J_P s^2\theta_P + B_P s\theta_P + K_P\theta_P \tag{9}$$

$$T_P = \theta_P[J_P s^2 + B_P s + K_P] \tag{10}$$

where K_P is constant involved in modeling (prime mover).

$$\frac{\theta_P}{T_P} = \frac{1}{[J_P s^2 + B_P s + K_P]} \tag{11}$$

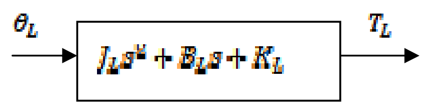
Similarly

$$T_L = \theta_L[J_L s^2 + B_L s + K_L] \tag{12}$$

where K_L is constant involved in modeling (load).

$$\frac{\theta_L}{TL} = \frac{1}{[J_L s^2 + B_L s + K_L]} \tag{13}$$

$$\theta_L = \left(\frac{N_L}{N_P}\right)\theta_P \tag{14}$$



$$\frac{T_L}{T_P} = \left(\frac{J_L s^2 + B_L s + K_L}{J_P s^2 + B_P s + K_P}\right)\left(\frac{N_P}{N_L}\right) \tag{15}$$

The transfer function of the system equation (15) is simulated for various pole pair using the MATLAB tool. It is observed that with the same gear ratio the settling time of the system gets decrease by increasing the number of pole pair which is shown in Fig.8, Fig. 9 and Fig. 10.

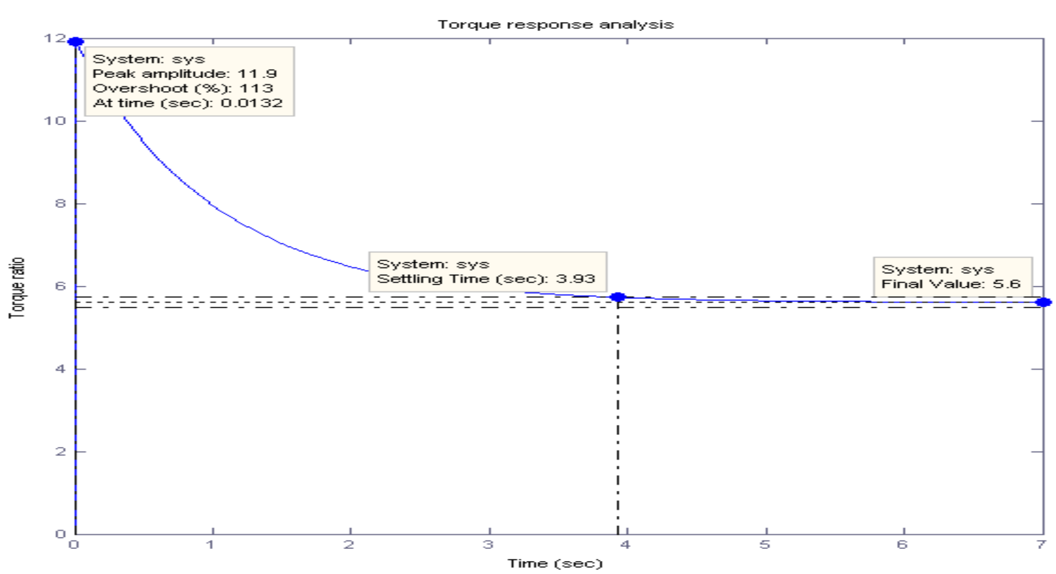


Fig. 8. Torque ratio analysis for N_p=8 & N_L=2.

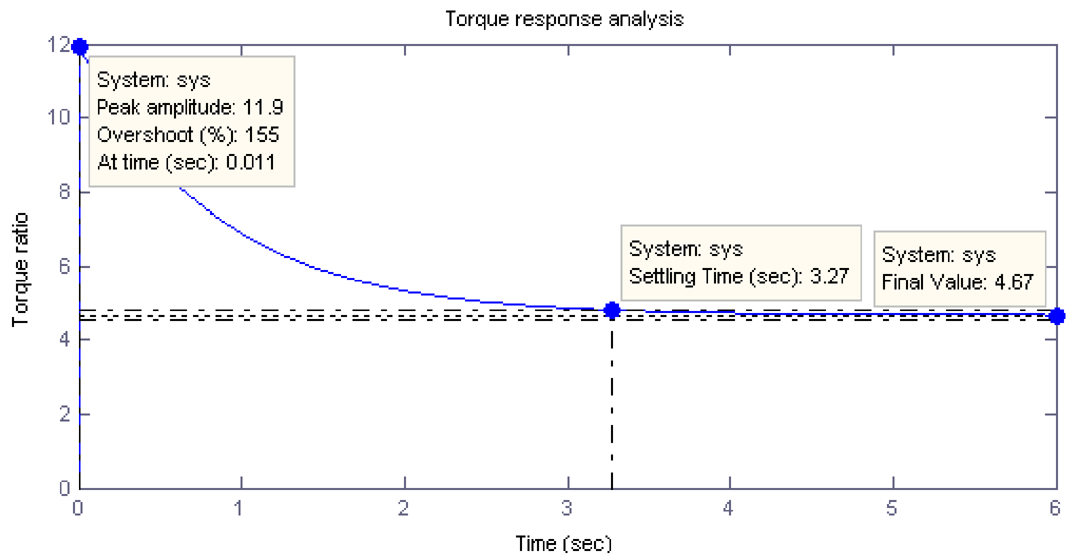


Fig. 9. Torque ratio analysis for Np=16 & NL=4.

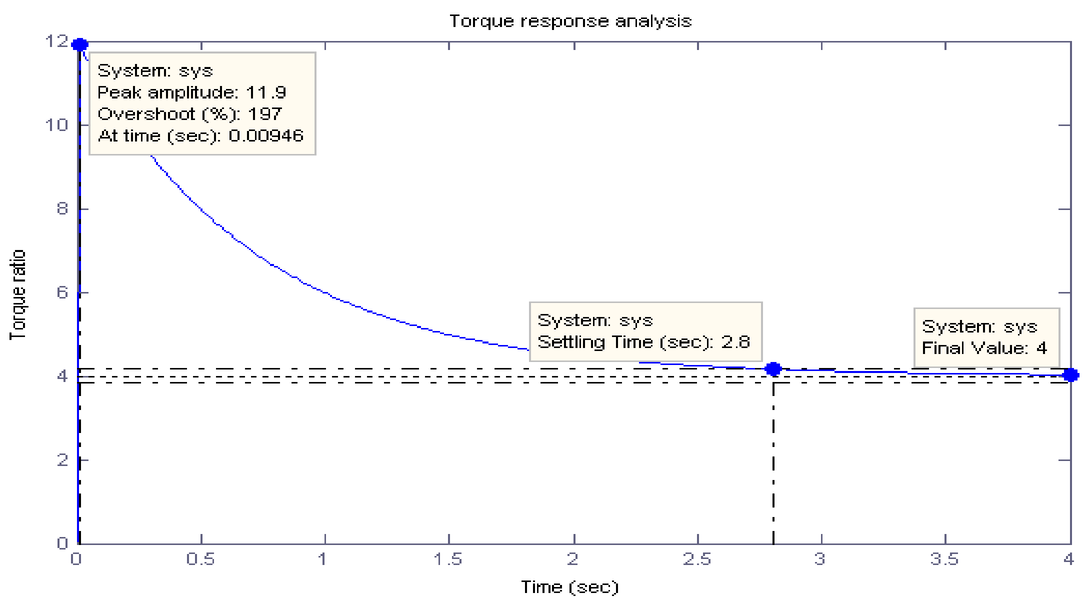


Fig. 10. Torque ratio analysis for Np=32 & NL=8.

4. THE FINITE ELEMENT ANALYSIS

FEA gives the nearby solution of partial differential equations and integral equations. The solution may be obtained by eliminating the differential equation or by submitting the partial differential equation to an approximating system of simple differential equation. The answers obtained from the above are integrated using Euler's method or Runge-Kutta method.

In order to predict the gear performance before designing an actual prototype, the analysis of the torque transferred to the load side is a major concern for gear designer. In general there are two major approaches for the torque design: the equivalent magnetic circuit's analysis and the finite element analysis. The magnetic circuit analysis provides the analytical relationship to the field distribution, magnetic material properties and gear dimensions. This analysis will be useful for gear design and optimisation.

The finite element analysis provides the most accurate estimation and improves the analytical design work.

The proposed magnetic bevel gear modeled using Pro/E tool based on the parameters is specified in Table 1. This design model is exported to the MagNet software for the further design enhancement and simulation.

The materials for the magnetic rotor are assigned as follows:

Magnets (North &South Poles)	:	NdFeB 30MGOe
Magnetic core	:	SS410 grade (stainless steel)
Shaft	:	Non magnetic (stainless steel)

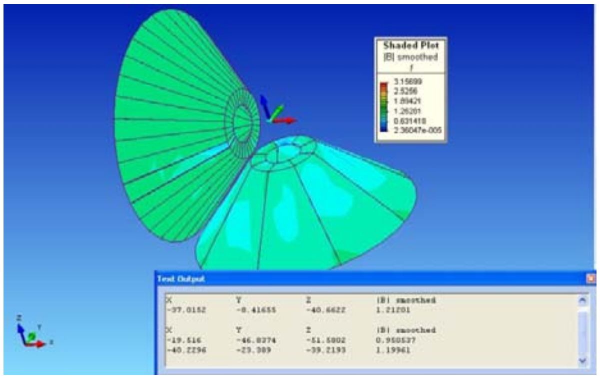


Fig. 11. Flux density in Magnetic bevel gear at N_P=16 & N_L=4.

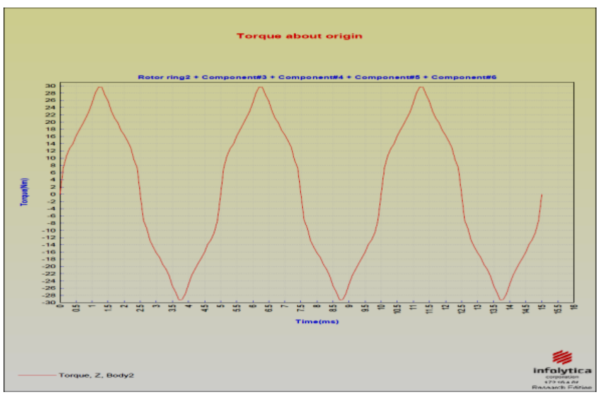


Fig.12. Torque vs time for magnetic bevel gear at N_P=16 & N_L=4.

The proposed design can be visualised in 3D with the help of a transient 3D solver tool in MagNet Software. It is observed that the flux density in the magnetic bevel gear as shown in Fig. 11 and maximum torque of 29 Nm is achieved in the simulation as shown in the Fig. 12.

5. THE MAGNETIC BEVEL GEAR PROTOTYPE

For realising a rotor in the proposed prototype, a stainless steel material (SS410 grade) is taken and cut into cone shape with the top radius of 240 mm and bottom radius of 61 mm. A provision is made on the outer part of the rotor to accommodate the pole that has the thickness of 10 mm and length of 100 mm. According to the pole pair configuration, the number of poles are chosen and placed in the created provision. During the placement, the north and south poles are fixed on the outer part of the rotor in the alternative fashion. The complete specification of the pole for the high speed rotor is shown in Fig. 5. A set of rotor is designed that act as a low speed and high speed rotor in the proposed prototype. A non magnetic material (stainless steel) based shaft is made and connected with the core part of the rotor. The other end of the shaft is connected with either the load (if high speed rotor) or prime mover (if the low speed rotor). A bearing component is added in the shaft to give a mechanical support for the proposed prototype that ensures the smooth rotation of the rotors. The Fig. 13 shows the complete design of the proposed prototype model with the N_P and N_L value as 16 and 4 respectively.

Fig. 13. Gear Structure of Prototype model at N_P=16 & N_L=4.

6. THE TORQUE MEASURING SYSTEM

For measuring a torque, a measuring system is designed as shown in Fig. 14. In this measuring system, the shaft end of the low speed rotor is connected to DC motor outputs that act as prime mover. Further, the shaft end of the high speed rotor is connected to the mechanical load input provided by a brake drum. Using the torque measuring system, a torque of magnetic bevel gear is measured by varying the load up to the slippage.

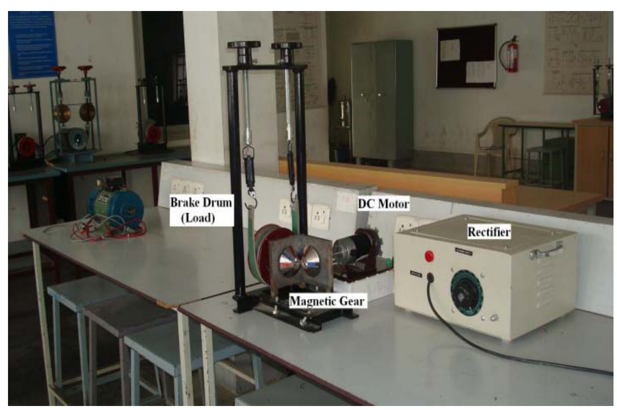


Fig..14. Torque measuring system.

7. THE PRACTICAL AND SIMULATION RESULT OF THE PROPOSED MAGNETIC BEVEL GEAER

For the value of table 1, a prototype model is made. It is practically checked and the results obtained are given in table 2. For the above model simulation, a study is also made with FEA analysis and those results are also given in Table 2.

Table 2. The Transmission torque under different air gap length for $N_P = 16$ and $N_L = 4$.

Air gap length	0.5mm	1 mm	1.5 mm	2 mm
Torque in FEA result	29.0 Nm	25.5 Nm	20.5 Nm	16.0 Nm
Torque in Proto type result	27.0 Nm	23.5 Nm	18.0 Nm	13.0 Nm

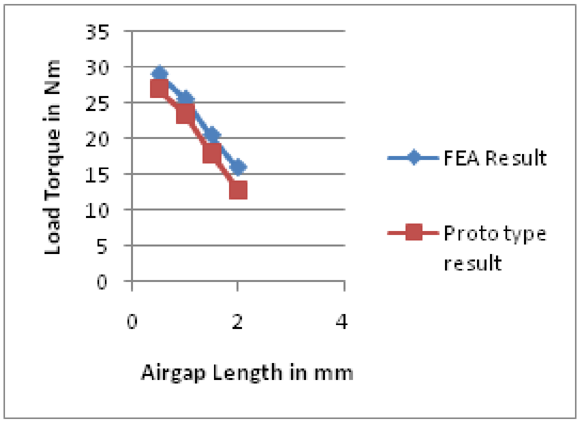


Fig. 15. Load torque Vs air gap length.

A graph is shown in Fig. 15 for which data are derived from table 2. From the Fig. 15 and Fig. 16 it is observed that as the air gap length decreases the torque gets increased.

Table 3. Magnetic bevel gear torque transferred different pole pair with the same gear ratio.

Air gap length	0.5mm	1 mm	1.5 mm	2 mm
$N_P = 8$, $N_L = 2$	28.0 Nm	24.0 Nm	19.5 Nm	15.0 Nm
$N_P = 16$, $N_L = 4$	29.0 Nm	25.5Nm	20.5Nm	16.0Nm
$N_P = 32$, $N_L = 8$	26.0 Nm	23.5 Nm	18.9 Nm	14.0 Nm

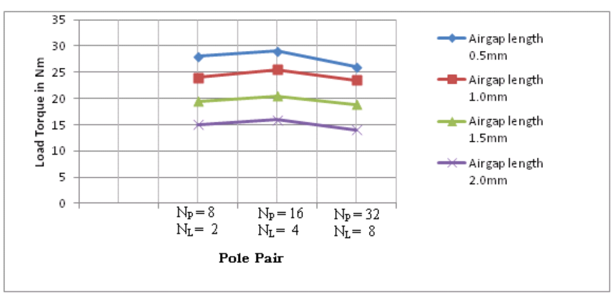


Fig. 16. Load torque Vs Pole pairs.

Based on Coulomb's law, increasing the number of pole pair increases the magnetic field strength but the surface area of each pole is getting smaller. Both these changes will lead to certain relationship between the maximum load torque and the pole pair. The transmission torque values obtained for four different air gap length variations are given in Fig. 13. From these results, it is clear that the gear with $N_P = 16$, $N_L = 4$ has a maximum load torque for all the four cases considered comparatively.

Table 4. A comparison of the magnetic bevel gear with commercial mechanical bevel gear

Gear parameters	Shanthi Gears (Mechanical Bevel gear)	Prototype Magnetic Bevel gear
Gear ratio	1:5.6	1:4
Load torque in Nm	25	27
Volume m^3	16.7×10^{-3}	13.8×10^{-3}
Weight in Kg	4.8 (Including Cooling Oil)	3.8
Application	Industrial	Industrial

In Table 4, a commercial mechanical bevel gear is compared to the prototype magnetic bevel gear.

For this comparison, the parameters like gear ratio, load torque, volume and weight are considered. However, the most general parameters like cost, analysing the performance of the system with the exceeded full load, noise and vibrations are ignored. Normally, the cost based comparison is performed in the mass production of the magnetic bevel gears.

Analysing the performance of the proposed system based on the exceeded full load is not feasible with a magnet and a mechanical system. With the magnetic bevel gear system, if the load exceeds the maximum limit, slippage happens. For the mechanical gear system, the same damages the gear tooth.

These results indicate that the magnetic bevel gear can be predominantly applicable for all the industrial applications to achieve a good torque transmission performance.

8. CONCLUSION

From the detailed literature survey from 1916 to 2013, it is found that many authors have proposed several novel magnetic gear but only (Yao *et al*., 1996) have given the idea of designing a magnetic gear that transfer the mechanical power in perpendicular direction but the other types of novel systems is focused on transferring the power flow only in the axial direction. In this paper, a magnetic bevel gear is designed with 1:4 gear ratio. In addition, a mathematical model is built for the proposed system and the settling time of the system has been determined using the MATLAB tool. Further, the gear design is simulated for various configurations which include different pole pairs and the air gap length with the same gear dimensions and constant gear ratio 1:4 using MagNet software. A prototype model has been developed based on the dimensions got from the simulation results.

A novel magnetic bevel gear which achieves the high gear ratio and torque has been successfully designed and analysed. Even though the proposed gear produces a torque of 27Nm, it is observed that the torque of the gear beyond 27Nm creates a slip in the gear. In future, a novel gear arrangement can be proposed to overcome the slip issue.

The magnetic bevel gear is also compared with commercial mechanism bevel gear. Here, it is seen that the magnetic bevel gear has a significantly improved volume, weight and full load torque in comparison with the commercial mechanical bevel gear.

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REFERENCES

Ando, Y., Awis, M., Nor Aziz, Q., Murakami, I., and Yamada, K. (2012). Analysis and Experiment of Cylindrical Magnetic Gear, *Materials Science Forum*, 721, 249-254 .

Faus, H.T., (1941). Magnet gearing. *U.S. Patent* 2 243 555.

Hesmondhalgh, D.E., Tipping, D. (1980). A multielement magnetic gear. *IEEE Proc. Elect. Power Appl.*, 127, 129–138.

Jian, L., Chau, K.T., and Jiang, I. Z. (2009). A Magnetic-Geared Outer-Rotor Permanent-Magnet Brushless Machine for Wind Power Generation",*IEEE Trans. Ind. Appli.*, 45(3), 954 - 962.

Jorgensen, F.T., Andersen, T.O., Rasmussen, P.O. (2008). The Cycloid Permanent Magnetic Gear. *IEEE Trans. Ind. Appli.,* 44(6) , 1659-1665.

Lee, R., Brewer, E., Schaffel, N. (1985). Processing of Neodymium-Iron-Boron melt-spun ribbons to fully dense magnets. *IEEE Transactions on Magnetics*,vol. 21, 5, 1958-1963.

Muruganandam, G and Jayakumar, K.S. (2012). Design and Simulation analysis of a Perpendicular Magnetic Gear, *International Journal of Electrical Engineering*, l5(3), 359-366.

Muruganandam, G. and Jayakumar, K.S. (2012). A Novel Perpendicular Magnetic Gear with High gear Ratio. *European Journal of Scientific Research*, 69(4), 593-598.

Neuland, H. (1916). Apparatus for transmitting power, *U.S. Patent* 1 171 351.

Ramsden, Wu.,W., Crawford, V.S. and Hill, T. (2000). A low speed, high-torque, direct-drive permanent magnet generator for wind turbines, *IEEE Industry Applications Conference*, 1, 147-154.

Siavash Pakdelian., Nicolas, W.F. and Toliyat, H.A. (2013) Principles of the Trans-Rotary Magnetic Gear, *IEEE Transactions On Magnetics*, 49, 883-889.

Vijasyashankar, S., Kannan, N. and Jayakumar, K.S. (2011). Design and Performance Analysis of Quadruple Winding Redundancy Brushless dc Torque Motor, *International Review of Electrical Engineering*, 6(5), 2361-2367.

Yao, Y.D., Huang, D.R., Hsieh, C.C., Chiang, D.Y., Wang, S.J., Ying, T.F., (1996). The Radial Magnetic Coupling Studies of Perpendicular Magnetic Gears. *IEEE Transactions On Magnetics*, 32(5), 5061-5063.