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DEVELOPMENT OF A SHUTTER TYPE MAGNETIC GEAR

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Abstract. Magnetic gears offer significant advantages over traditional mechanical gears, such as the ability to increase as well as decrease the input speed, contactless power transfer, high gear ratios, oil free operation, inherent overload protection, high torque density, potential for high efficiency and little or no maintenance. This paper reports the design, construction and experimental evaluation of a shutter-type magnetic gear. The experimental results show that the gear could be an alternative to mechanical gears especially in applications where the advantages of magnetic gears are essential.

Key Words. Permanent magnet; gear; finite element method; torque density; magnetic design.

1. INTRODUCTION

It is usually more cost and size effective to use a high speed electrical machine together with a mechanical gearbox to achieve the required load torque and speed. The downside of using a mechanical gear is that the gear lubrication and cooling are often required, while noise, vibration and reliability can also be significant issues. In renewable energy generation it is often necessary to increase the speed of the input with a gear system, which implies an oversized mechanical gearbox to handle up-speed power flow. Magnetic gear is an attractive alternative technology, which offers significant advantages over conventional mechanical gear such as bi-directional and contactless power transfer, oil-free operation, inherent overload protection, high torque density, potential for high efficiency and little or no maintenance. Despite these advantages, magnetic gears have received little attention from both research institutions and industry, due to the relative complexity of magnetic gears and the shortcomings of earlier permanent magnet (PM).

The basic concept of magnetic gearing can be tracked down to the beginning of the 20th century. An early U.S. patent [1] described the electromagnetic gear consisting of two rotational shafts with salient steel poles. The two shafts are magnetically connected with stationary electromagnetic poles. Even though the idea in the patent seemed quite effective, apparently nothing was done to utilize the idea in commercial applications. Another interesting patent [2] described two discs with different diameters and different number of PMs on the two disks. The gearing topology proposed in the patent was also weak in the utilisation of PMs as only one magnet on each disk contributes to torque transfer. In the mid 1900s only ferrite magnets were available, which is only about one tenth of the field strength of modern neodymium magnets. This limited the force transfer capabilities of magnetic gearing and also the development and progress of the magnetic gearing technology.

There are a few publications where magnetic spur gears were considered [3]. Spur-like magnetic gears could work very well in applications where contactless power transfer is necessary, where space is not a problem and where relatively simple designs are essential. The main disadvantage is that only a limited amount of magnets transfer torque at any given moment, which lowers the maximum torque per volume (or torque density) that can be transferred. These simple magnetic gears are feasible but they have poor torque density and lower gear ratios, which makes them ineffective.

Another interesting topology is shown in Fig. 1, in which two rotating discs are coupled with magnets axially. The advantages of using axially placed magnets rather than radially placed magnets are that the two shafts can be separate from each other and the gap between two discs can be more easily observed; also two or more high speed output or input shafts can be used. These discs are relatively easy to manufacture and the torque density is relatively high when compared to spur-like magnetic gears.

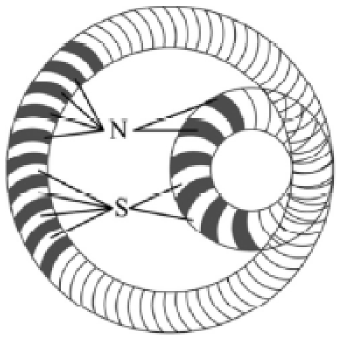

Fig. 1: Magnetic disk gear schematic.

The magnetic worm gear was proposed in [4], the topology of which is illustrated in Fig. 2. The gearbox is of a gear ratio of 1:33, with a maximum torque of 11.5 Nm and an approximate torque density of 0.1 kNm/m³. This example illustrates that magnetic worm gears have very low torque densities but relatively high gear ratios. This topology could be used in applications where the worm configuration is necessary.

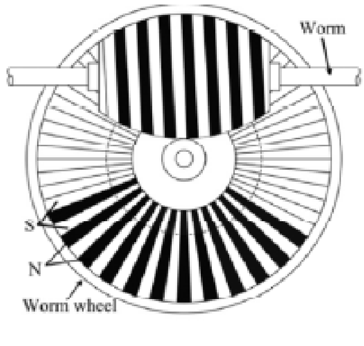

Fig. 2: Magnetic worm gear schematic [4]

Literature [5] reported the development of a magnetic planetary gearbox and an illustration can be seen in Fig. 3. The advantage of using a planetary gearbox is that it has three transmission modes and a high gear ratio. The gearbox exhibited a torque density of nearly 100 kNm/m³ and a gear ratio of 3:1. By adding more planet gears the transmission torque can be increased, but adding more planet gears also increases the cogging torque. The magnetic planetary gear exhibits a relatively high torque density and a high gear ratio, but the planet arrangement makes it unnecessarily complicated.

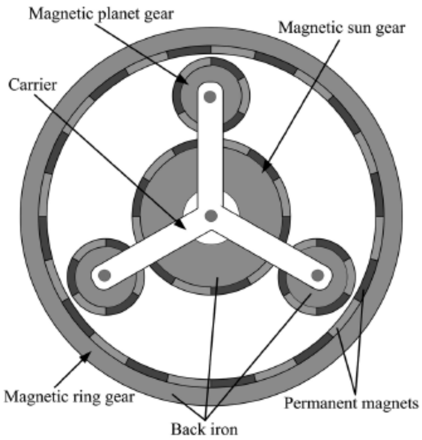

Fig. 3: Magnetic planetary gear schematic [5]

In [6] a novel magnetic gear configuration was introduced, which is relatively simple in design. The gear consists of a high speed inner rotor, a low speed outer rotor and stationary pole pieces (see Fig. 4). The gear topology is known as a shutter-type magnetic gear. The shutter magnetic gear may attain a torque density exceeding 100 kNm/m³, which is comparable to that of two- to three-stage helical gearboxes (50-150 kNm/m³). Normally the pole pieces are kept stationary and the high speed rotor and low speed rotor are rotated. However, alternative configuration may also be used; for example, the high speed rotor and the pole pieces rotate while the low speed rotor (outer rotor) is stationary. This arrangement is sometimes preferred as it simplifies the mechanical design. The main advantage that the shutter-type gear has over the other above described magnetic gear topologies is that almost all the magnets are involved in transmitting torque at a given moment, which greatly increases its torque density.

There are also more complex topologies for example the cycloid magnetic gear [7]. The cycloid magnetic gear works on the same principle as a mechanical harmonic gear. Andersen et al [7] designed and built an experimental cycloid gear with two gear sets to balance the unbalanced magnetic force, which is able to reach a maximum torque of 33 Nm, a gear ratio of 1:22 and a torque density of 183 kNm/m³. The problem with this type of gearbox is that it needs 12 needle roller bearings just to counter the cycloid motion. But with all these extra complications they still measured an efficiency of 94% at 500 rpm.

For this specific study, the shutter-type magnetic gear is selected as the suitable topology for a prototype. The shutter-type topology shows potential for high torque density, high gearing ratios and it is relatively simple in design. In this paper the shutter-type magnetic gear is examined. The first step is to complete the magnetic and mechanical designs. Next the construction and assembly of the prototype are discussed. The testing and performance evaluation are then looked at and finally the recommendations and conclusion are considered.

2. PRINCIPLE OF OPERATION

The coupling between magnets is a function of several variables including the number of poles, the material properties, dimensions and separation.

Fundamental to the operation of a magnetic shutter gear is the magnetic fields produced by the PMs on either the high- or low-speed rotors modulated by the steel pole pieces, which results in space harmonics having the same number of poles as the related magnet rotor. Fig. 4 illustrates the schematic of a shutter-type magnetic gear. It has been showed in [8] that the number of pole pairs in the space harmonic flux density distribution produced by either the high or low speed rotor PMs is given by:

$$\begin{aligned} p_{m,k} &= |mp + kn_s| \\ m &= 1, 3, 5, \cdots, \infty \\ k &= 0, \pm 1, \pm 2, \pm 3, \cdots, \pm \infty \end{aligned} \tag{1}$$

where p is the number of pole-pairs on the PM rotor and n_s the number of stationary pole-pieces. Furthermore, the gear ratio is given as:

$$G_r = \frac{n_s - p}{p} \tag{2}$$

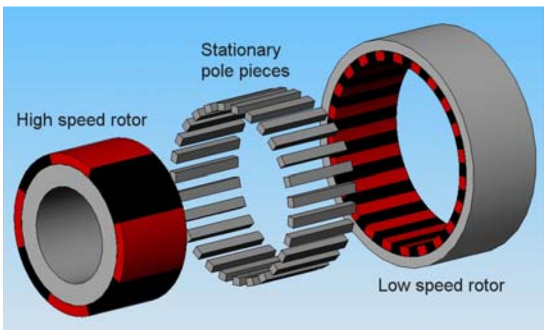

Fig. 4: Magnetic shutter gear schematic

Keeping the outer rotor stationary may be a preferred operating arrangement since it may simplify the overall mechanical design. The torque will then be transmitted to the pole pieces instead of the outer rotor, the gear ratio then becomes:

$$G_r = \frac{n_s}{p} \tag{3}$$

3. DESIGN OF THE PROTOTYPE

The design of the magnetic gear involves both magnetic and mechanical design.

3.1 *Magnetic Design*

Similar to PM machine design, one has to pay attention to the torque quality when designing a magnetic gear. To minimize the cogging torque a cogging factor defined in [9] is used for selecting suitable PM poles and modulator pole-pieces combinations, i.e.

$$f_c = \frac{2pn_s}{N_c} \tag{4}$$

where N_c is the smallest common multiple between the number of poles on one of the PM rotors (p) and the number of stator pole-pieces (n_s). The factor gives a good estimate of the severity of the cogging torque. The lower the cogging torque factor the lower the cogging torque is likely to be. From the cogging torque factor it is clear that the larger the smallest common multiple and the lower the number of poles, the smaller the cogging torque factor will be and thus the cogging torque. To keep a reasonable number of total magnets, the number of pole-pairs on the high speed rotor was chosen to be two (p_h=2). Figure 5 shows the number of pole-pieces and number of PM poles on the low speed rotor against the gear ratio. The graph also shows the cogging torque factors. To obtain the lowest cogging torque the cogging torque factor was chosen as one (f_c=1). With a cogging torque factor of one, from the graph, gear ratios of 1.5 to 11.5 could be selected. A gear ratio of 10.5 (G_r=10.5) was chosen to simplify calculations and to demonstrate the high gear ratios obtainable by magnetic gears. With this the rest of the parameters can be calculated as n_s=23 and p_l=21 by using Eqns (1) and (2).

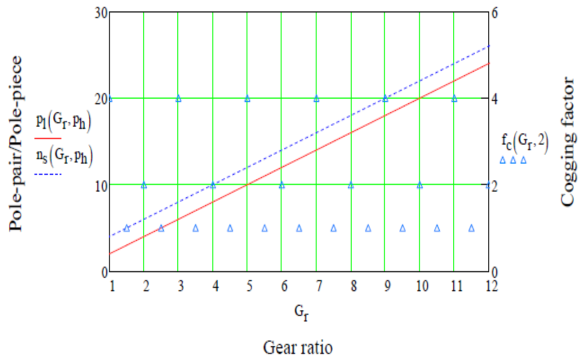

Fig. 5: Cogging torque vs. gear ratio graph.

3.1.1 *Simulation Studies*

Two-dimensional (2D) finite element (FE) analysis method was used for the simulation studies, the program used was Maxwell 2D. Fig. 6 shows the 2D FE model of the magnetic gear. Since there is no magnetic symmetry, the whole device has to be modeled. To minimize the iron losses the stationary pole-pieces were chosen to be laminated steel. These small parts make the mechanical design very difficult. It was proposed in [6] that the stator pole-pieces may be connected by a very thin steel strip at the outer diameter and after all the laminations were stacked together the outer ring would then be machined away leaving just the small squares (or pole-pieces). To simplify the mechanical design even further it was realized that the pole pieces could be connected at the inner radius rather than the outer radius by thin steel strip. It has been shown that the presence of the thin steel strip makes relatively little impact on the performance of the gear and strengthens the already weak structure of the stator laminations significantly.

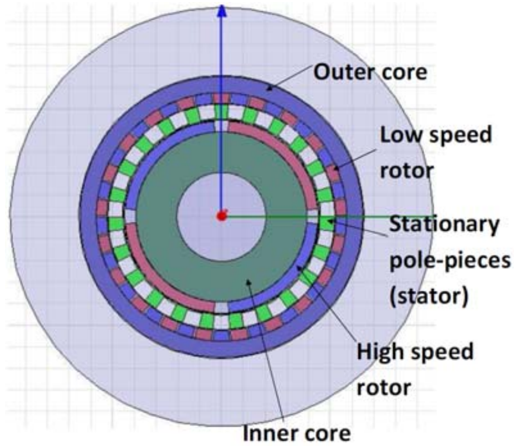

Fig. 6: 2D finite element model of shutter-type magnetic gear.

Fig. 7: Maxwell 2D transient analysis of solid inner- and outer-yoke magnetic losses

To minimize core losses the yoke of rotating PM rotors would normally need to be laminated steel. Analyses are carried out to determine if the inner- or outer- yoke could be solid- or needs to be laminated-steel. Fig. 7 shows an FE transient analysis of core losses when both the inner- and outer-yoke are solid steel. It can be seen that almost 250 W of energy is lost if both the inner- and outer-yokes are made of solid steel.

The next graph (Fig. 8) shows the losses when both the inner- and outer-yokes are laminated steel, the losses is only about 500 mW, which is much lower than the case when both yokes are solid-steel. Fig. 9 shows the losses where the inner yoke is solid steel and the outer-yoke laminated steel. The losses from Fig. 9 is about 3 W, which is a lot better than when both yokes are solid-steel and comparable with when both yokes were laminated-steel. From these results it is clear that the outer-yoke must be made of laminated steel and the inner yoke can be solid steel without causing major core losses. The final parameters for the magnetic shutter gear are given in Table 1.

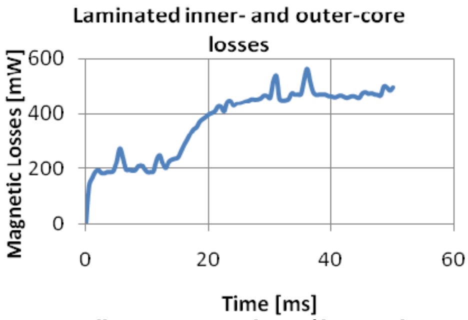

Fig. 8: Maxwell 2D transient analysis of laminated inner- and outer-yoke magnetic losses

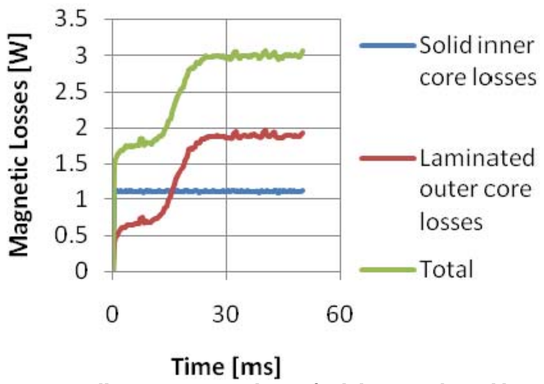

Fig. 9: Maxwell 2D transient analysis of solid inner yoke and laminated outer yoke magnetic losses

Table 1: Final Parameters for Magnetic Gear Prototype

Pole pairs on high speed rotor (p_h)	2
Pole pairs on low speed rotor (p_l)	21
Number of stator segments or pole-pieces (n_s)	23
Outer radius of low speed yoke, mm	57.5
Inner radius of low speed yoke, mm	52.5
Outer radius of stator segments, mm	52
Inner radius of stator segments, mm	45
Outer radius of the high speed rotor, mm	44.3
Stack length, mm	39.3
Permanent magnet thickness, mm	5
Permanent magnet length, mm	40
Permanent magnet grade	N35

3.2 *Mechanical Design*

In the magnetic design the main dimensions are determined and can be seen in Table 1. One of the biggest difficulties in the design was the small clearances between the inner- and outer-rotors and the stationary pole-pieces. The air gaps between the inner rotor and the stationary pole pieces and between the pole pieces and the outer rotor are 0.7 mm and 0.5 mm respectively. The design was further complicated by the fact that the stationary pole-pieces and the outer-rotor's yoke needs to be laminated steel to minimize magnetic losses. The housing of the gearbox was also carefully designed to minimize magnetic losses from the moving PMs in the rotors. Another difficulty was how to support the two rotating rotors without compromising the structural integrity of the stationary pole-pieces in between them. In most mechanical machines the shafts of the machine (or rotors) are supported by two bearings at each end of the shaft, in the case of the magnetic gearbox this is not practical because the two rotors are on different shafts and the stationary pole-pieces also needs to be supported. Figs. 10 and 11 show the finished low speed rotor assembly and the high speed rotor assembly respectively.

Fig. 10: Finished low speed rotor assembly

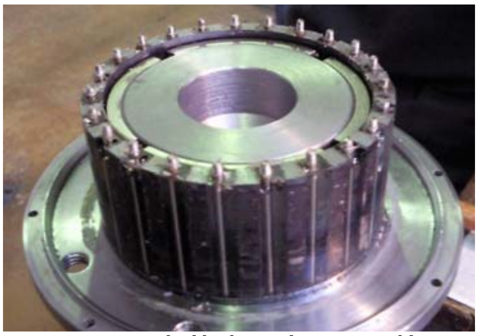

Fig. 11: Finished high speed rotor assembly

4. TESTING AND PERFORMANCE EVALUATION

To evaluate the performance of the gearbox a test bench needs to be setup. The test bench consists of an induction machine to drive the gearbox, a direct-drive low speed PM generator to act as a load to the gearbox, two torque sensors to measure the input and output torque of the gearbox, a stand and fittings to connect all the parts involved.

The first test conducted was a no-load test. This test was done to determine the losses of the gearbox at different speeds. The test was done by starting the induction machine at a low speed and measuring the torque and losses of the gearbox at speed increments of around 50 rpm. Fig. 12 shows a graph of the results from the no-load test. It can be seen that at the design speed of 1000 rpm, the losses are almost 70 watts, which is far greater than the predicted losses which were only about 3 watts. From this test it is clear that the magnetic gearbox has additional losses that the analytical model did not account for. Next a load test was done where the load resistors, connected to the PM generator, were incrementally changed to keep the load at a constant of 20 Nm; this was to determine if the efficiency will change at different speeds. The constant load of 20 Nm was chosen as 20 Nm is near the maximum load before the gearbox starts to slip. The results of the constant load-test are shown in Fig. 13. From this test it can be seen that the efficiency decreases when the speed increases. At a speed of 1000 rpm the efficiency is just above 70 %.

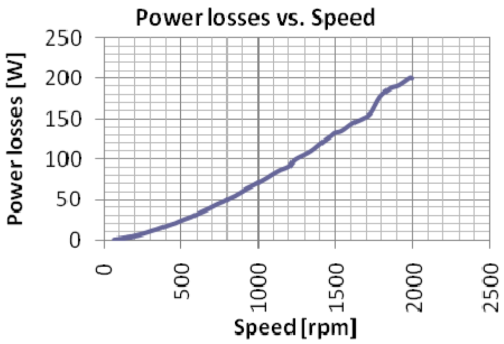

Fig. 12: Experimental results of the no-load test

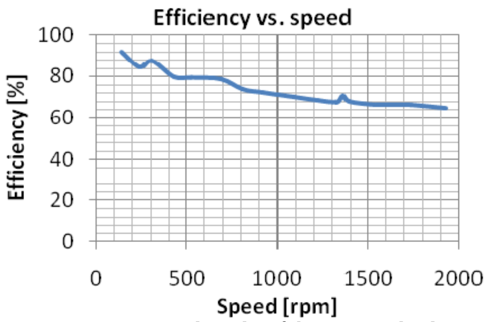

Fig. 13: Experimental results of the constant load test

Table 2 shows a comparison of the magnetic gear that was developed against different mechanical gear topologies. All comparisons are done at 1000 rpm input speed. As can be seen from the table the magnetic gear is comparable to the mechanical gears in most parameters. The magnetic gear's efficiency is not as good as the mechanical gears, but the magnetic gear is still in the beginning phase of development. With continuous research and development the construction difficulties of the magnetic gear can be overcome and the performance can be further improved.

Table 2: Gearbox Comparison

Manufacturer	Rino	Rino	Iron horse	PGC	Magnetic gear
Gear type	Single stage spur gear	Bevel gear	Worm gear	Planetary gear	Shutter gear
Gear ratio	7:1	12:1	10:1	10:1	10.5:1 or 1:10.5
Torque, Nm	25.1	19.1	58.195	35	33
Efficiency, %	93	88	88	90	70
Volume, m^3	0.00237	0.00085	-	-	0.00358
Weight, kg	5.5	-	10.43	1.4	9.552

5. CONCLUSION

This paper describes the development and testing of a shutter-type magnetic gear. A topology is chosen from literature to investigate. The parameters of the gearbox are optimised using two dimensional finite element modelling. A prototype was constructed and tested. The results showed that the magnetic gearbox is comparable with its mechanical counterparts, but it still lacked in areas especially efficiency. The unique advantages of the magnetic gear compared to mechanical gears are very beneficial especially in renewable energy applications. Further studies will be focusing on improving the efficiency, the mechanical design and the investigation of other topologies.

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