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A Comparative Study of the Performance Capabilities of Magnetic Gears

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Abstract -- **This article is a literature review and comparison of the performance capabilities of magnetic gears. The purpose of this paper was to determine the validity of further attempts at implementing magnetic gear technology into large scale applications such as wind turbines. It was determined that mechanical gears still carry an advantage over magnetic gears in terms of performance; magnetic gears have only reached a peak torque performance of 731 Nm. The highest torque density for a magnetic gear is 239 Nm/L. Improvements in magnetic gears, such as, the types of magnets used, and improved topologies of the gears have been significant factors in improving the performance of magnetic gears. Such improvements signify that there is potential in magnetic gear technology, and that further research in designing high performing magnetic gears could potentially lead to a viable replacement for mechanical gears.**

Index Terms-- **gear-box, magnetic gears, mechanical gears, direct drive machines, torque density, magnetic shear stress.**

I. Introduction

THIS paper compares the performance between magnetic gears, electric machines and mechanical gears, by comparing torque, torque density, and shear stress.
Mechanical gears are typically used in large scale applications such as wind turbines; and though they are an efficient option, they often have reliability issues [1]. One solution, has been to design or repurpose a magnetic gear, which is much more reliable due to its contactless operation and inherit overload capability. The first magnetic gear was introduced in 1916 by Armstrong, C. G as a U.S patent “Power Transmitting Device” [2] , and was developed further in 1941, by H.T Faus [3]. These early designs had poor performance due to their poor use of the magnetic material and the low energy magnetic material available. Since the introduction of rare earth magnets, there have been several publications that describe significantly higher performing magnetic gear topologies [4-19]; the progression from lower to higher performing gears is described in Figures 1-3. The history of magnetic gear development has been well recorded, and allows one to look at their limitations, and their potential. The potential that magnetic gears have could make renewable energies such as wind power more cost effective in the long run due to their reliability, and the only obstacle in the field is to build a high performing magnetic gear, comparable to a mechanical gear. Some papers have focused on the improvements that magnetic gears offer in large scale applications such as wind turbines, [4], [5], [11], as well as oceanic powered generators [20].

To build a prototype of a magnetic gear, large enough to run a wind turbine, to test is extremely expensive. However, a few papers have been published recently that describe magnetic gears with relatively large torque densities.

As mechanical gears have high torque performances, they have been the most obvious option for use in wind turbines, however surges often cause mechanical issues which are very expensive to fix [1]. This issue is ever growing as wind turbines move off-shore, where wind speeds are higher, and service becomes far costlier. By using magnetic gears, the reliability of gears used in wind turbines can be increased, and therefore the cost of using wind as a source of renewable energy decreases.

A. Math and Equations

The outer rotor volumetric torque density, T_{DO}, is defined as,

$$T_{DO} = \frac{T_M}{\pi r_o^2 d} \tag{1}$$

where T_M is the measured peak torque, r_o is the outer radius of the outer rotor, and d is the active region stack length of the gear. The inner rotor volumetric torque density is defined as,

$$T_{Di} = \frac{T_M}{\pi r_i^2 d} \tag{2}$$

where r_i is the outer radius of the inner rotor. The magnetic shear stress, σ_D, is defined as,

$$\sigma_D = \frac{F}{2\pi r_{air} d} \tag{3}$$

where r_{air}, is the radius of the outer air gap. By comparing (1) and (2) and noting that torque and force are related by, T=Fr, the magnetic shear stress can be related to the torque density as follows,

$$2\sigma_D = T_{Di} \tag{4}$$

where T_{Di} is the inner rotor volumetric torque density in Nm/m^3, and σ_D is the magnetic shear stress in kN/m^2.
The mass torque density was also determined in Nm/kg with the following conversion;

$$T_D = \frac{T_M}{\pi r_o^2 d\rho} \tag{6}$$

where ρ is the density of steel, or 7.85 kg/L. this equation was applied in determining the upper bound of the mass torque density in Nm/kg when the mass or weight was not already given.

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B. Methods

This study will be conducted in the form of a literature review. By using primary data from studies done on magnetic gears, mechanical gears, and direct drive generators. The experimental, and calculated results were then placed in tables, which describe the performance of the different magnetic and mechanical gear models. The torque density was calculated using (1), and the shear stress was calculated using (3). The time line, and the amount of models that will be described will provide a comprehensive perspective on the magnetic and mechanical gear performances. In order to compare the different gears without causing bias, the mechanical gears selected followed similar parameters of the magnetic gears that have been developed.

Magnetic and mechanical gears were compared in this study by calculating torque densities, using the given parameters, and torque ratings, of each gear. These values as well as the magnetic shear stress of the magnetic gears were then described in Figures 2-5. The performances of the magnetic and mechanical gears will also be compared with the performance of electric machines. The following figure describes a common topology of the magnetic gears that were reviewed in this study.

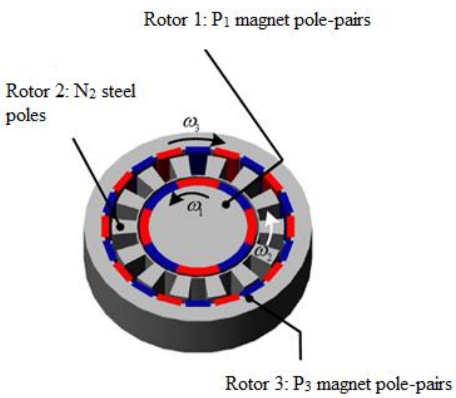

Fig. 1. General layout of a coaxial magnetic gear [15].

C. Comparative Tables.

Table I shows torque density and shear stress for the magnetic gears. Table II shows the torque and torque density for mechanical gears [21], [22] and Table III shows torque, torque density and shear stress for direct drive machines. There are several trends to be acknowledged; for one, the shear stress and torque densities for the magnetic gear is higher than for the direct drive motors, also there are larger improvements in magnetic gears, in the last twenty years, and that magnetic gears are catching up to mechanical gears in performance ratings in terms of torque density. There is still room to improve, further testing, and prototype evaluations could potentially offer further improvements especially at larger radii.

D. Magnetic Gears

TABLE I
DATA COLLECTED AND CALCULATED FROM THE DIMENSIONS AND EXPERIMENTAL RESULTS FROM MAGNETIC GEARS

Author	**Outer Radius (m)**	**Measured Torque (Nm)**	**Torque Density (Nm/L)**	**Torque Density**	**Shear stress**
[4]	0.11	731	239	30	168
[5]	0.10	146	123	16	80
[6]	0.04	64	111	14	13
[7]	0.11	156	108	14	-
[8]	0.10	140	99	13	-
[9]	0.07	169	98	12	84
[10]	0.12	220	92	10	32
[11]	0.09	96	90	11	51
[12]	0.10	100	85	11	54
[13]	0.06	33	81	10	48
[14]	0.07	62	80	10	50
[15]	0.07	60	78	10	60
[14]	0.07	59	76	10	58
[16]	0.12	600	68	9	39
[20]	0.06	93	64	8	60
[18]	0.07	13	63	8	44
[19]	0.06	16	54	7	32
[23]	0.11	73	53	7	41
[24]	0.07	40	52	7	40
[25]	0.06	12	42	5.33	27
[26]	0.25	1066	41	2	21
[27]	0.08	75	34	4	30
[28]	0.05	5	29	4	24
[29]	0.07	33	29	4	19
[30]	0.26	716	27	3	14
[31]	0.18	475	23	3	15
[32]	0.09	15	15	2	12
[33]	0.18	100	13	2	-

E. Mechanical Gears

TABLE II
DATA COLLECTED FROM MECHANICAL GEARS

Model	**Outer Radius [m]**	**Torque [Nm]**	**Torque Density [Nm/L]**	**Torque Density [Nm/kg]**
Atlas	0.28	3163	47	18
Venus	0.16	1808	82	11
Polaris	0.20	5875	122	15
Neptune	0.28	9039	124	17
Earth	0.21	4971	125	19
Orion Plus	0.28	16269	141	16
Luna	0.16	4519	204	26
Neptune plus	0.28	16043	219	26
GBPN-1601-005	0.07	450	281	25
GBPN-0401-005	0.02	14	286	38
GBPN-0601-005	0.03	40	301	44
GBPH-0601-NP-005	0.03	48	340	41
GBPN-0801-005	0.04	110	362	53
GBPH-0901-NS-005	0.05	155	366	44
GBPH-0901-NP-005	0.05	180	475	56
GBPH0601-NS-005	0.03	55	486	45
GBPN-1201-005	0.06	390	507	65
GBPH-1501-NP-005	0.07	536	513	41
GBPH-1801-NP-005	0.09	1248	545	35
GBPH-0601-CS-005	0.03	47	573	43
GBPH-1201-NP-005	0.06	292	584	64
GBPH-0901-CS-005	0.05	155	607	44

F. *Direct Drive Machines*

TABLE III
DATA COLLECTED FROM THE DIMENSIONS AND EXPERIMENTAL RESULTS FOR DIRECT DRIVE MACHINES

Author/Model	Outer Radius [m]	Peak Torque [Nm]	Torque Density [Nm/L]	Torque Density [Nm/kg]	Magnetic Shear Stress [kN/m^2]
[34]	0.36	153	2.6	0.3	1.3
AC-75[35]	0.15	122	6.7	3.6	3.3
AC-150[35]	0.15	225	9.5	4.5	4.8
[36]F	0.21	720	10.0	1.3	5.0
[36]B	0.04	8	13.6	1.7	6.8
[36] A	0.04	9	25.7	3.3	12.8
[36]E	0.11	220	26.3	3.4	13.2
[36]D	0.09	91	29.8	3.8	14.9
[36] C	0.05	19	33.7	4.3	16.8
[37]	0.07	60	52.6	6.7	26.3

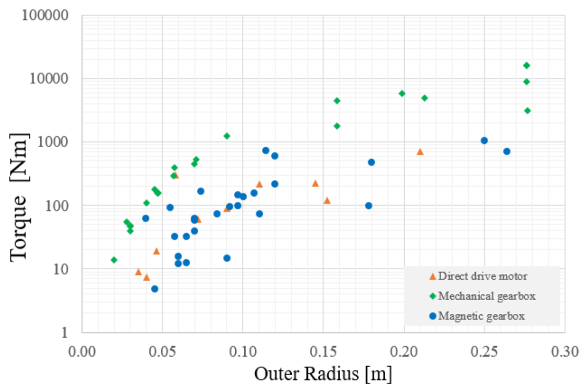

Fig. 2. Torque as a function of the outer radius of the outer rotor for mechanical gears, magnetic gears, and direct drive machines for comparison.

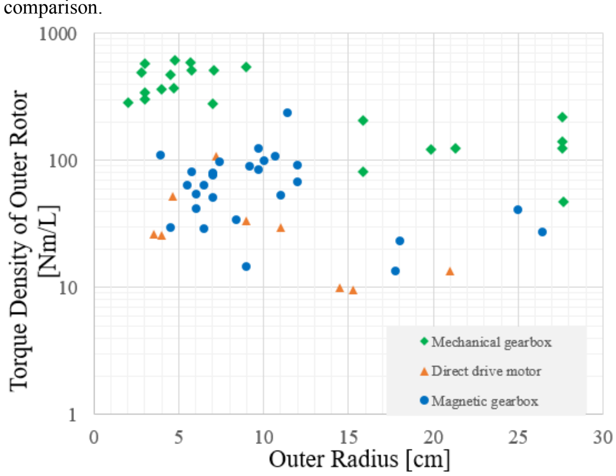

Fig. 3. Torque density as a function of the outer radius of the outer rotor for mechanical gears, magnetic gears, and direct drive machines for comparison.

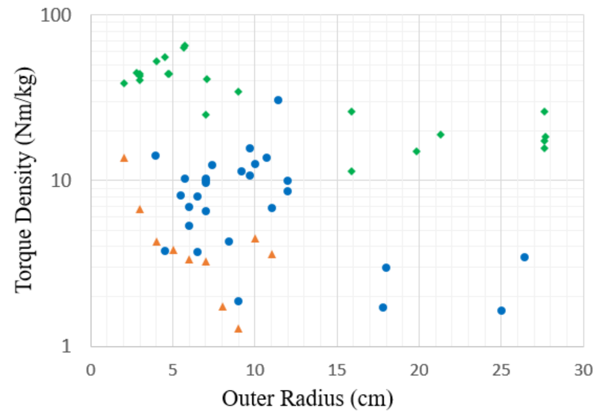

Fig. 4. Torque density in (Nm/kg) as a function of the outer radius of the outer rotor for mechanical gears, magnetic gears, and direct drive machines for comparison.

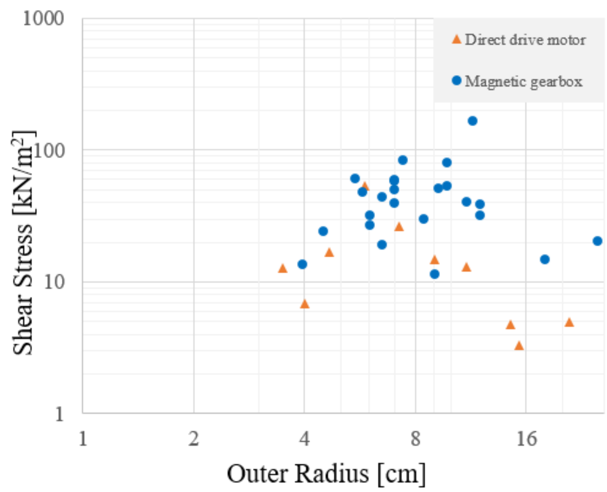

Fig. 5. Magnetic Shear Stress in (kN/m^2), using properties of (2), as a function of the outer radius of the outer rotor for, magnetic gears, and direct drive machines for comparison.

II. CONCLUSION

Based on the models of gears explored in this research, there is evidence suggesting that magnetic gears have the potential to achieve relatively high torque densities when compared with mechanical gears; this is particularly so for large diameter magnetic gears. This paper has tried to illustrate what many have suggested in the past, that when looking at mechanical and magnetic gear performances, magnetic gears have to further catch up to mechanical gears when it comes to performance, however a lot of progress has been made fairly quickly in the last few decades. The highest torque density this study found was 239 Nm/L [4], which is significant. This study suggests that magnetic gears are not only more reliable, and therefore more cost effective, they also could potentially be a viable substitution for mechanical gears, at higher torque values.

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