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The Study of Magnetic Gear

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ABSTRACT

This project explores the design, development, and analysis of magnetic gears as an innovative alternative to traditional mechanical gears. Magnetic gears utilize magnetic fields for torque transmission, offering advantages such as reduced wear, noise, and maintenance due to the absence of physical contact. The study focuses on optimizing gear performance through material selection, magnet arrangement, and gear geometry. A TORSIONAL TEST was conducted to evaluate slipping torque, efficiency, and load capacity under various operating conditions. The findings demonstrate the feasibility of magnetic gears in applications requiring high precision, reliability, and durability. This research contributes to advancing gear technology and highlights the potential for implementing magnetic gears in industries such as robotics, automotive, and renewable energy systems.

INTRODUCTION

Introduction to Magnetic gear

Magnetic gear:

A **magnetic gear** is a type of gear system that transmits torque through magnetic forces instead of mechanical contact between teeth. Unlike traditional mechanical gears, magnetic gears use the attraction and repulsion of magnetic fields, typically generated by permanent magnets, to transfer motion. This non-contact interaction eliminates friction, wear, and the need for lubrication, making them highly efficient and requiring less maintenance.

Magnetic gear overview

A MG (magnetic gear), shown in Figure ,1 consists of p1 pole-pair permanent magnets, referred to as PMs, that can rotate at $\omega 1$, a middle rotor with n2 ferromagnetic steel poles that are able to rotate at $\omega 2$, and p3 pole-pair PMs that rotate at $\omega 3$. The inner and outer rotors contain ferromagnetic pieces along with permanent magnets. On these rotors there are usually a large difference between the number of poles on the inner (high speed) and outer rotor (fixed/low speed). The magnets on these rotors are commonly surface-mounted magnets for many of the configurations that have been proposed. Surface-mounted magnets are expensive and as such, the MG being studied uses rectangular magnets that are less costly. In general, the layouts of MGs are borrowed directly from layouts intended for mechanical gears

Objective:

MGs could offer a much longer service life due to their contactless torque transfer capability and only requiring bearing lubrication. Another possible application for MGs is under uncertain loading circumstances that can arise from highly variable loads, such as shock loading. MGs have greater resilience in these 5 conditions than mechanical gearboxes, again due to the contactless torque transfer, which allows the poles to slip without causing any mechanical failures. However, control approaches need to be utilized in order to allow the gearbox to recover from one pole slippage condition. In a planetary gearbox there are limiting factors, for example, gear ratio limitations in planetary gears, such as having a maximum and minimum number of teeth that are able to be used. There are also few options for overload protection when using a mechanical gearbox; typically, the mechanical gearbox is either oversized or has another mechanical system to govern the torque being input into the gearbox. This leads to inefficiencies, an increase in cost, and reliability issues

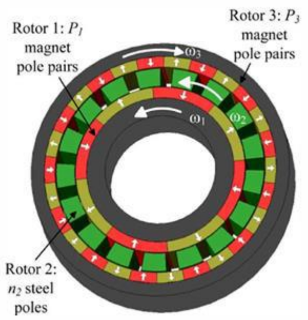


Figure 1: Surface-mounted radial MG layout(V. M. Acharya et al., 2013)

Key Features of Magnetic Gears:

1. **Contactless Operation**: Magnetic gears transmit torque without physical contact, reducing wear and tear.
2. **High Efficiency**: Reduced friction improves overall energy efficiency.
3. **Overload Protection**: The magnetic field limits torque transmission, preventing mechanical damage under excessive loads.
4. **Silent Performance**: No direct contact leads to minimal noise during operation.

LITERATURREVIEW:

Historically, mechanical gearboxes are considered the standard in torque transfer and industry has been content in using the mechanical planetary or epicyclical gears for torque transfer. There have been significant advances in power production, but little done to improve the method for the transfer of torque. The oversizing of mechanical gearboxes for shock loading increases the mass and volume that has to be incorporated into the overall design, which can become a large hindrance for producing large scale energy production equipment such as wind turbines and current turbines. In horizontal wind turbines it is advantageous to have a gearbox that has less mass due to the difficulty of having a large mass at a high elevation being supported by a thin beam. As stated previously, a MG has an inherent overload capability; this capability does not require a magnetic gearbox to be oversized to be able to handle the overload conditions. Magnetic gears require less maintenance than their mechanical gearbox counterparts, which is advantageous for ocean energy current turbines due to the difficulty for maintenance on current turbines being deep under water. MGs have typically used large quantities of rare earth magnets, with the emerging technology of adding ferromagnetic pole pieces uses flux-focusing arrangements Magnetic Gearbox History,

Neuland filed a patent in 1916 for an electromagnetic geared system similar to Figure 1; the main difference from that figure is that only one member contained a magnetized winding, the fixed rotor (K. K. Uppalapati, Bird, Dan, Garner, & Zhou, 2012) The concept of a gearbox using permanent magnets dates back as early as the 1940's with a US patent by Faus shown in Figure 6 (Frank, 2011). These early MGs used ferrite magnets in a spur gear configuration and yielded poor torque densities when compared to a mechanical gear (Frank, 2011). The early MGs yielded low torque capabilities due to the topology of the magnets; Faus's a topology resembles a mechanical gear pair. This design did not have overload capability due to the magnets meshing like the teeth of a gearbox.

Radial magnetic gear:

Radial MGs are more commonly known as coaxial MGs, this research refers to radial MG as such due to the flux flow. Radial MGs have been studied more thoroughly than their axial MG counterpart. The radial MG publications dating as far back as 1916 with one of the first by Neuland, as stated previo Radial MGs are more commonly known as coaxial MGs, this research refers to radial MG as such due to the flux flow. Radial MGs have been studied more thoroughly than their axial MG counterpart. The radial MG publications dating as far back as 1916 with one of the first by Neuland, as stated previously (Neuland, 1916). In 1967 Resse created a similar design to Neuland only the inner rotor contained permanent magnets. In Resse's design the outer rotor was kept stationary while the middle rotor and inner rotor were allowed to rotate. The inner rotor was the high-speed side and the middle rotor was the low-speed side; this configuration is shown in Figure 7 (Reese, 1967)usly (Neuland, 1916). In 1967 Resse created a similar design to Neuland only the inner rotor contained permanent magnets. In Resse's design the outer rotor was kept stationary while the middle rotor and inner rotor were allowed to rotate. The inner rotor was the high-speed side and the middle rotor was the low-speed side; this configuration is shown in Figure 7 (Reese, 1967)

Martin designed a similar MG in 1968, shown in Figure 8. Martin's design differed only by replacing the outer and inner rotor with permanent magnets while leaving the middle rotor having flux modulation pieces, labelled 28, this is shown in Figure 8 (Bronn, 2012).

In 1972 Laing was granted a patent for a MG that operated in a similar way to Martins shown in Figure 9, it differed only in the shape of flux modulators and also that every second pole on the rotor contained permanent magnets (Bronn, 2012)

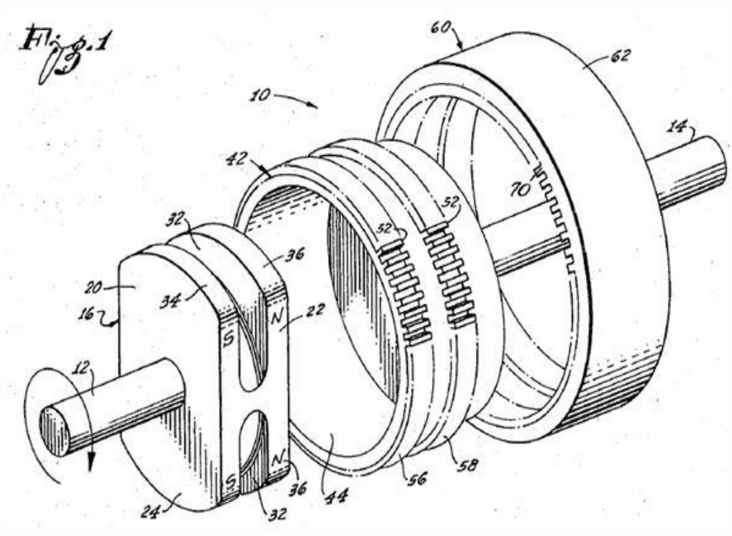


Figure 7:Reese coaxial design (Reese, 1967)

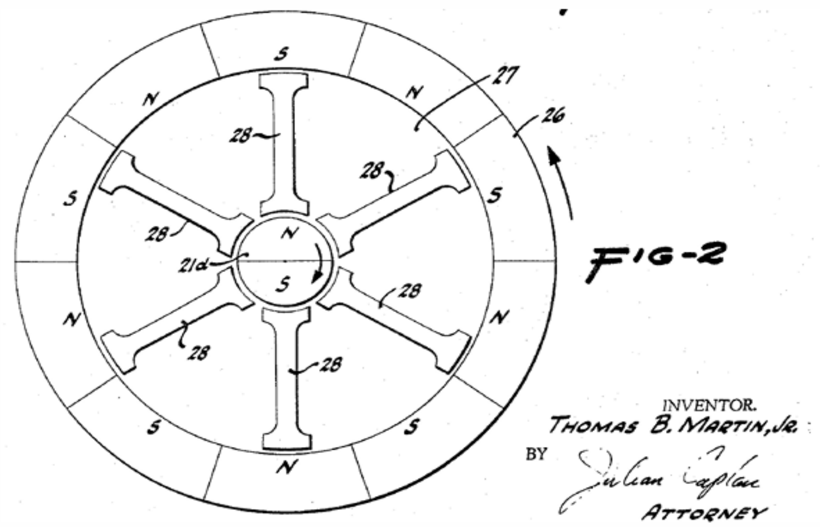
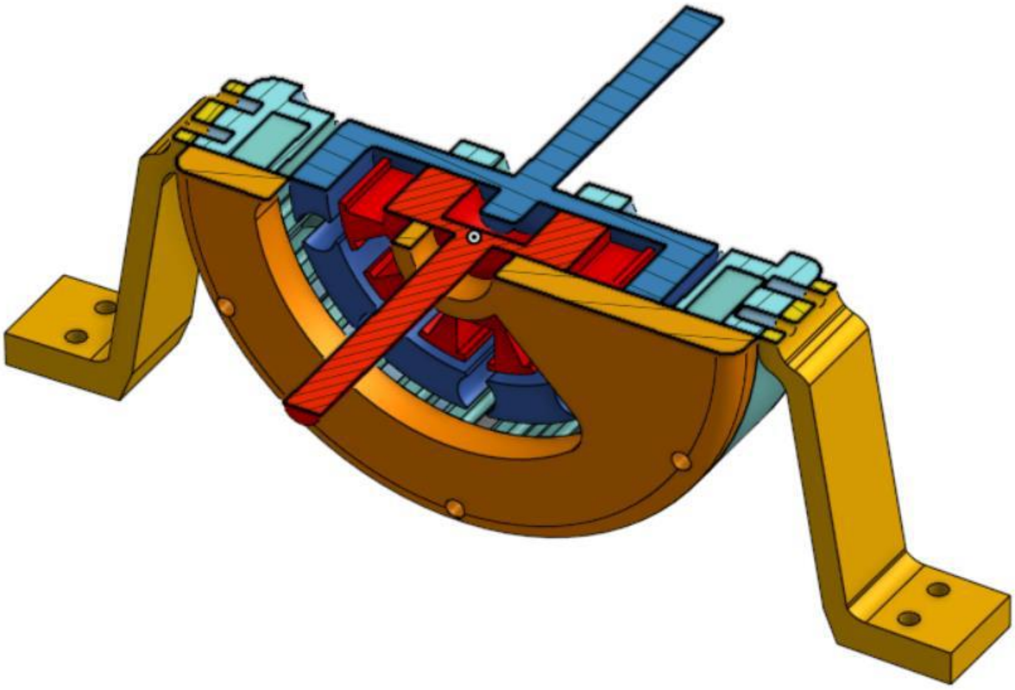
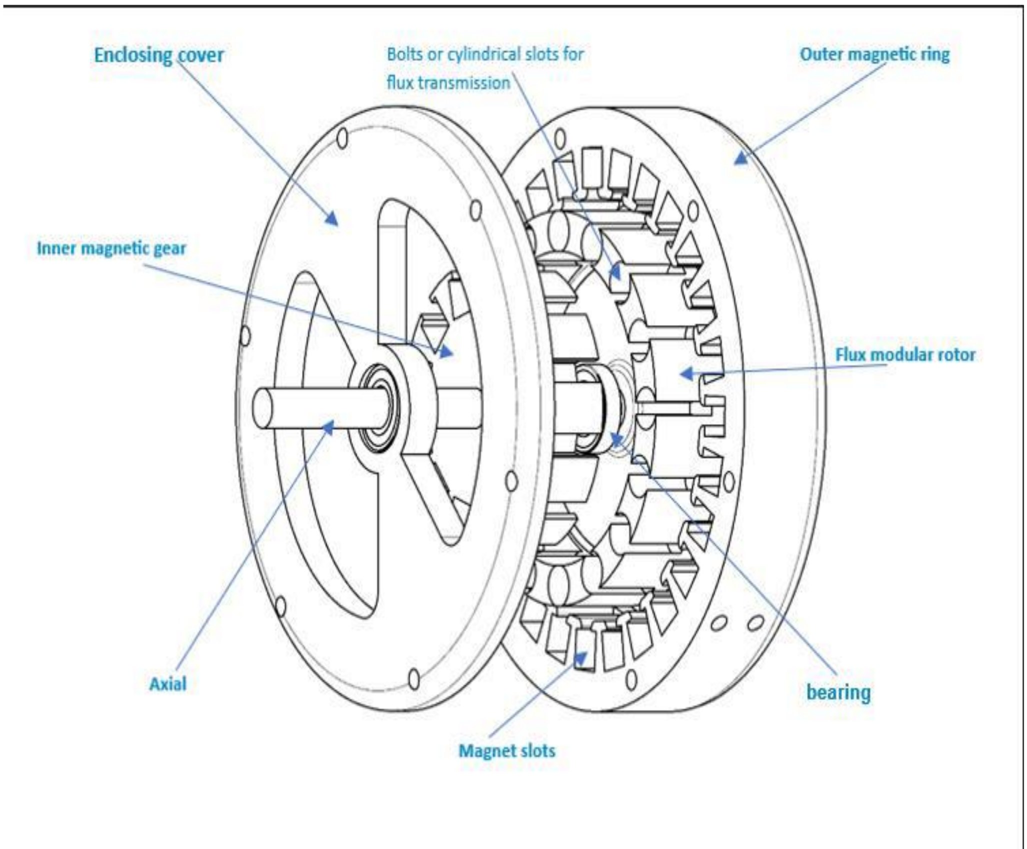


Figure 8-Martin coaxial design showing the flux modulations pieces between the inner and outer rotor magnets(Thomas, 1968)

METHODOLOGY



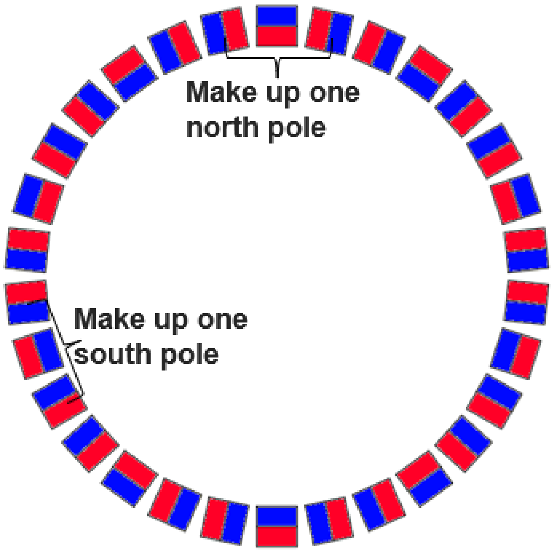
Keeping the basics mechanism of the radial flux magnetic gear, following is the fully assembled magneticgearbox.

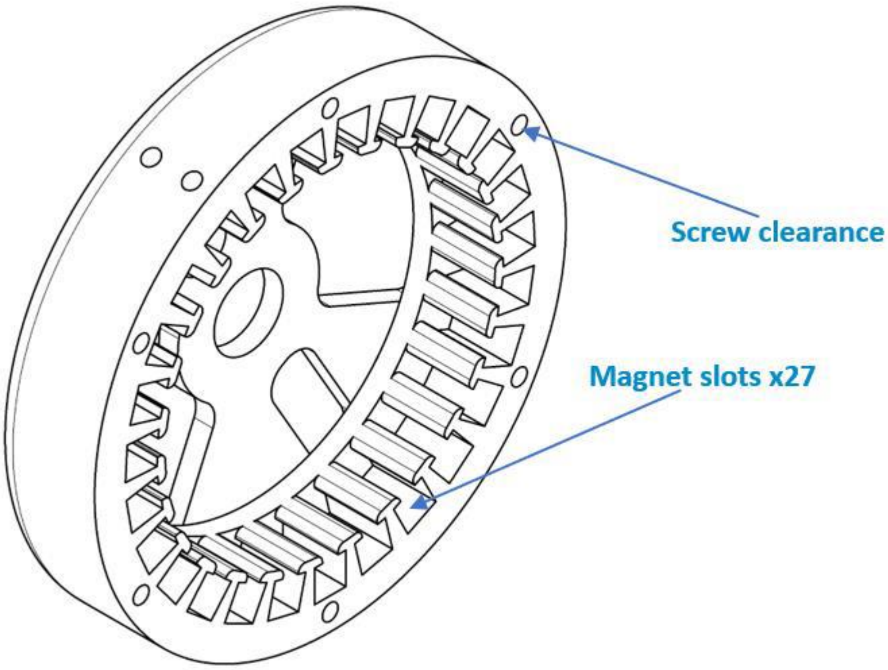


Breakdown of Mechanism of Each Part

The outer magnetic ring:

- this ring or case consists of 27 rectangular slots of 20mmx10mmx10mm, in which alternating magnetic poles of **neodymium N35 magnets** which has a strength of 12,200 Gauss are fixed. This outer ring can be held stationary or can be given a rotation, if it is rotated in and clockwise direction, holding the modular ring stationary we observed that the inner magnetic gear rotates with a speed of 4.33 times the input rotation on the outer magnetic ring. thus, making a ratio of **4.33:1**.
- The magnetic pole pattern made in the outer ring directly impacts the slipping torque of the Magnetic gear box. Knowing the history of the magnetic most of them had an alternating magnetic poles pattern. which is ideal but the drawback in such pattern is that due to the to alternating poles the magnetic field are make their way outside the gear box, making it a big block of magnet due to which the magnetic field lines are not efficiently used reducing the sleeping torque (sleeping torque is defined as the torque provide to the magnetic gear causing it to sleep and readjust itself).
- Therefore, to overcome this problem we have made a magnetic pole pattern which will efficiently make use of the magnetic flied line increasing the sleeping torque and leaving no magnetic field lines outside the gear box. Below figure shows the pole configuration





- This pole pattern on the outer magnetic ring, where a single pole is made using two magnets such that one full side and two half side of a pole contribute in making one single pole.
- Applying this pattern leaves no magnetic field line outside the gear box which increases the efficiency of the magnetic gear as the maximum magnetic flux is now interreacting with the inner rotor

The flux modulator ring:

- A **flux modulator** is a key component in a **radial magnetic gearbox** (RMG). It serves to mediate the magnetic interactions between the input and output rotors, enabling torque transfer without physical contact. Here's a detailed explanation of its mechanism and role:

4.2.2.1) Flux Path Modification:

Permanent magnets on the outer ring are at stationary thus the magnetic flux linking with the permeable material in the modular ring and when an input rotation is given to the modular it creates a rotating magnetic field.And to match these rotating magnetic field lines the inner magnetic ring rotates with a speed ratio, The number of permeable materials to be fixed in a modular are determined by,

Let

N = be the number of permeable materials,

P1 = be the pole pair in outer magnetic gear

(pole pair i.e., one north pole and one south pole make a one pole pair)

P2 = pole pair on inner magnetic gear

(these pole pair can also be represented as a single teeth in reference to classical mechanical gears)

Thus,

N = (P1 + P2)

Which is the summation of total pole pairs on outer and inner magnetic ring

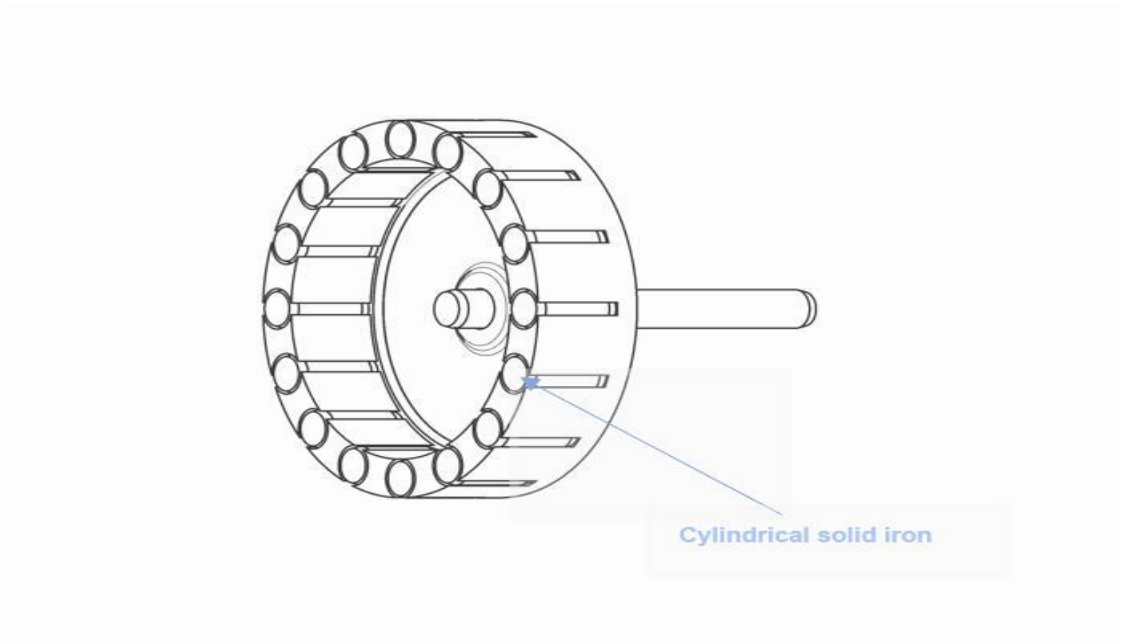
Material Selection:

The flux modulator is usually made of low-loss ferromagnetic material to minimize eddy current and hysteresis losses.

Example, the permeability of pure iron is 6.3 x 10^-3 henry/meter.

Shape:

The shape should be free of any sharp edges in general cases, but one can use any shape as per the design keeping in mind the material should have high permeability to minimize the loss of magnetic flux.



Inner Magnetic Ring:

the inner magnetic smaller in diameter and consist of permanent magnets, usually in the inner rotor the magnetic pole is made using two consecutive magnets of same pole or in some case even three.

Working Mechanism:

Magnetic Field Generation:

The inner rotor's permanent magnets create a magnetic field that rotates with the rotor's motion.

Flux Modulation:

As the magnetic field from the inner rotor passes through the flux modulator, the ferromagnetic teeth create periodic spatial variations in the field. This generates harmonics in the flux distribution.

Magnetic Coupling:

Among the harmonics produced, specific harmonics match the magnetic configuration of the outer rotor. This harmonic matching enables torque transfer from the inner rotor to the outer rotor.

Gear Ratio Determination:

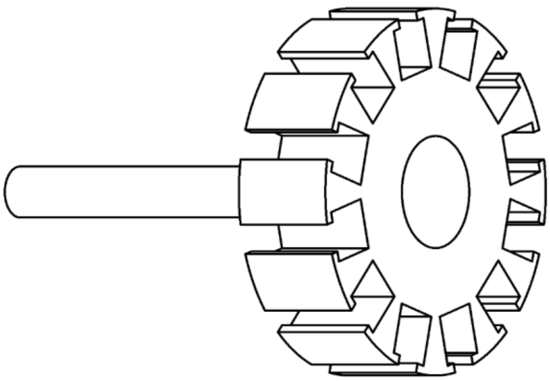
The gear ratio is determined by the number of poles in the inner and outer rotors and the number of teeth in the flux modulator.

For example: ***Gear Ratio=Number of Poles on Outer Rotor/Number of Poles on Inner*** Rotor

The flux modulator plays a key role in ensuring the required harmonic relationship between the two rotors.

Torque and Speed Conversion:

The magnetic interaction ensures torque is transferred efficiently while converting rotational speeds as per the gear ratio.



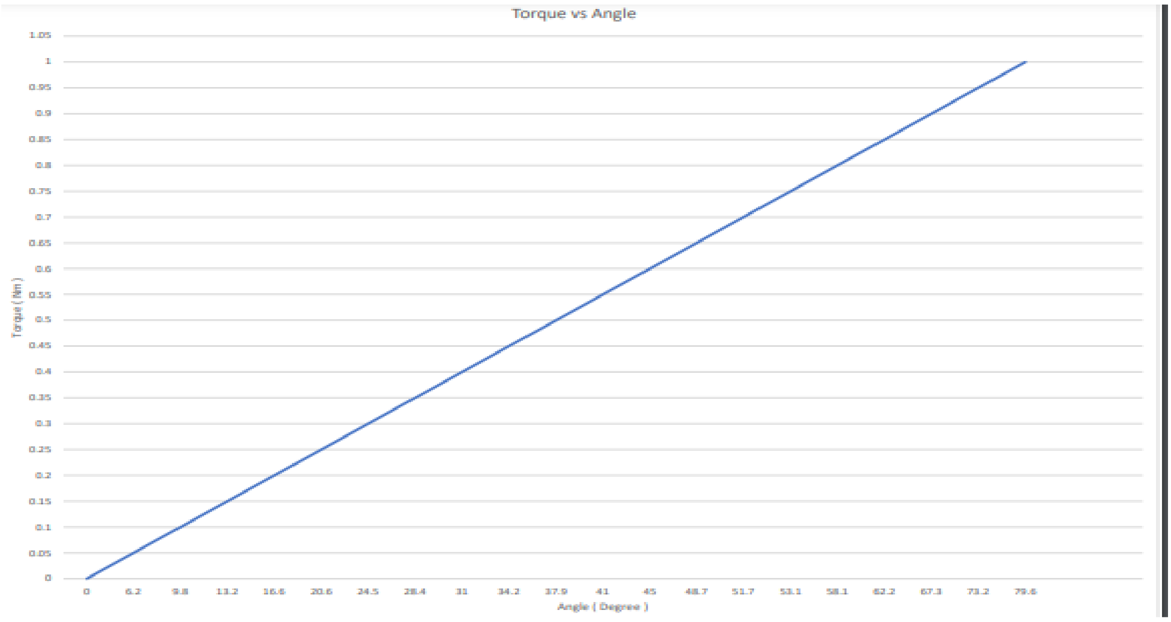
Test and Result Analysis:

Determination of Slipping Torque:

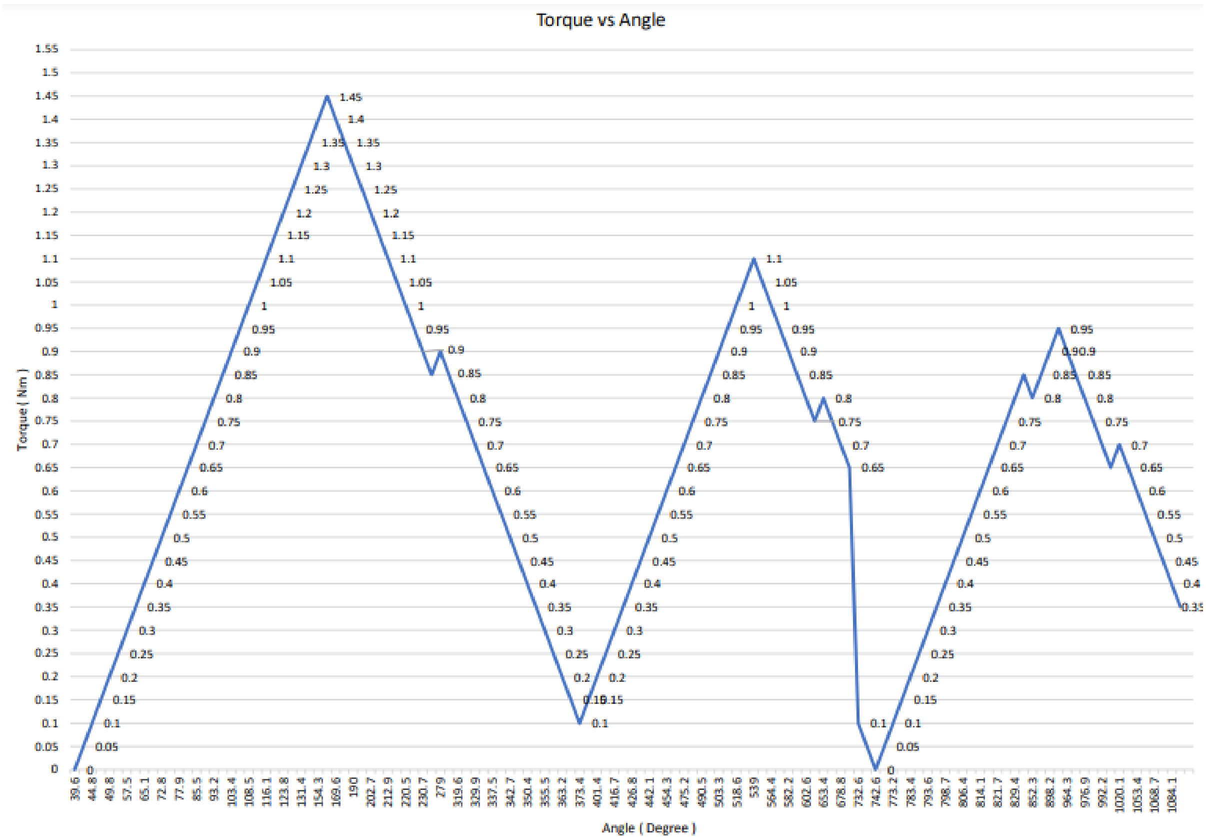
- With the help of torsional testing machine where we had fixed the axial of modular to the stationary jaws while the axial of inner rotor was fixed to the rotating jaws.
- With this arrangement we did three tests:
- Test 1: when the inner rotor was given a rotation very slowly manually. Following is the torque vs angle rotated graph.
- The peak torque achieved before the gear slipped and re-adjusted was 1 Nm.

Let,

T1 = 1 Nm



Test 2: when the inner rotor was given a motorized rotation. Following is the torque vs angle rotated graph.



In the motorized test we had three different peak torque

Let,

T2 = 1.45 Nm

T3 = 1.1 Nm

T4 = 0.95 Nm

Therefore, the average torque Tavg = T2 + T3 + T4 / 3

Tavg = 1.167 Nm

Result Analysis:

Torque vs angle:

The torques vs angle graph show a uniform increase where the torque peaks and then slips uniformly decreasing to 0 Nm and then again re-adjust itself and the process continues.

Applications:

- Automotive Industry: Hybrid and electric vehicle drivetrains.
- Wind Energy: Efficient torque transmission in wind turbines
- Industrial Machinery: Low-maintenance, high-efficiency systems for

heavy-duty applications.

Gear Ratios:

- The gear ratio of a magnetic gear depends on the pole pairs of the outer and inner rings. Here's how we calculate the gear ratio and create the chart:
- Formula for Gear Ratio:

The **magnetic gear ratio (G)** is calculated using the pole pairs of the outer ring (Po) and the inner ring (Pi):

G=Po/Pi

Where:

- Po=13 (outer ring pole pairs)
- Pi=3P (inner ring pole pairs)

G=13/3=4.33 (approx.)

Chart representation:

Inner Ring Speed (RPM)	Outer Ring Speed (RPM)	Gear Ratio
30	130	4.33
60	260	4.33
90	390	4.33
120	520	4.33
150	650	4.33

Challenges:

Magnet Alignment:

Precise alignment is crucial for optimal performance. Making sure the distance between the inner rotor and outer stator should designed very precisely as to fit the middle modular effectively optimizing the space between the inner rotor and outer stator as a permeable medium in order to have optimum magnetic field line interaction.

Material Cost:

High-strength magnets can be expensive. The parts of the magnetic gear should be made using non-ferromagnetic materials to reduce the disturbance of magnetic field lines within the gearbox.

Thermal Stability:
Managing heat in high-torque applications. Because the generated can decrease the pole strength of the magnetic which results in the decrease in the slipping torque of the magnetic gear. Therefore, managing the formation of eddy currents in the permeable material is important these eddies are generated to the constant change in the flux pattern within the permeable material.

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