Design of an Axial Flux-Modulated Magnetic Coupler for Efficient Energy Conversion

Aneesh Sattiraju

Abstract

Conventional configurations of electric machines involve mechanical parts to transmit torque that often suffer from damages from friction, heat, and overload. In contrast, magnetic couplers retain the ability to transmit torque and convert energy without any physical contact. The absence of contact allows magnetic couplers to silently operate with an inherent overload protection. While radial magnetic couplers are known to have lower efficiencies than mechanical parts at high speeds, less research has been conducted on axial topologies. This project aimed to design an axial magnetic coupler with high power efficiency and torque density by converting energy through a magnetic interface. The design included two parallel disks with concentrically arranged magnets in specific configurations on each disk. A flux modulator was placed between the two disks, balancing the magnetic flux to achieve a four-to-one gear ratio, allowing for the two disks to rotate at differential speeds. Disk A was powered by a motor on one end and was coupled to Disk B, which experienced load by turning a high torque generator on the other end. Utilizing flux modulation as the input power to the motor increased the rpm of Disk A, the rpm of Disk B was accelerated by a factor of four, enabling the generation of electricity. The system was able to maintain an overall 94% power efficiency while effectively transmitting torque. The data obtained suggests that axial magnetic couplers may be viable replacements to mechanical parts with fewer repairs, safer conditions for workers, and applications in renewable energies.

***Keywords*: Flux-Modulation, Magnetic Coupling, Mechanical Gears, Energy Conversion.**

Introduction

The modern technological landscape has featured groundbreaking advancements in electromagnetic machines, amid concerns about climate change and energy conversion. Mechanical gearboxes, essential for high torque and speed applications, face issues like wear, short lifespan, environmental vulnerability, and high maintenance due to frictional heat. While the short-term efficiency of gears is unmatched, a single damaged gear can compromise the entire gearbox (Ruiz-Ponce, 2023). In contrast, magnetic couplers present a promising alternative. Developments in permanent magnet technology have yielded magnetic couplers which transmit torque synchronously without physical contact. These couplers use magnetic attraction between two separated magnets to provide tangential force, reducing friction and wear, and offering inherent overload protection. The radial topology, the most common design, involves a large cylindrical rotor surrounding a smaller one. Effective but challenging, it requires precise alignment and faces challenges like flux leakage and size constraints (Wang, 2021). However, an axial topology was designed in this study. The engineering goal was to design an axial system with an efficiency greater than 85%. Axial couplers, though underexplored in literature, offer theoretical advantages such as scalable disks, easier fabrication, and reduced sensitivity to misalignments. ("Implementation Considerations for Synchronous Magnetic Torque Couplers," 2022). Flux modulation, a novel approach in this context, involves regulating magnetic flux between the disks to achieve differential speeds and "gear ratios" without contact. This innovation broadens the potential applications of magnetic couplers beyond synchronous coupling. Despite the many factors affecting their efficiency, magnetic couplers possess a lower torque capacity than mechanical gears. This study aimed to further optimize the geometry and torque density of magnetic couplers to create innovative machinery built towards achieving maximum efficiency, sustainability, and safety in next generation technology.

Methodology

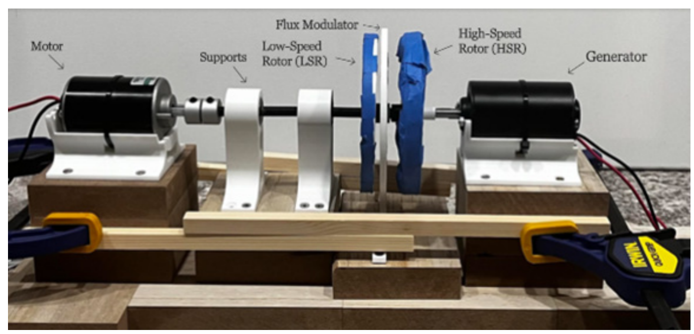


Fig. 1. Full assembled configuration

To measure the efficiency of the magnetic coupler, an isolated system was set up as follows: The motor (left) and generator (right) were mounted on three 25.4 mm tall wooden blocks to ensure a level alignment. The 3D-printed supports and flux modulator were placed on identical blocks. The left disk was connected to the flux modulator with a slight air gap, while the right disk was connected to the generator, which measured the output voltage, current, and torque.

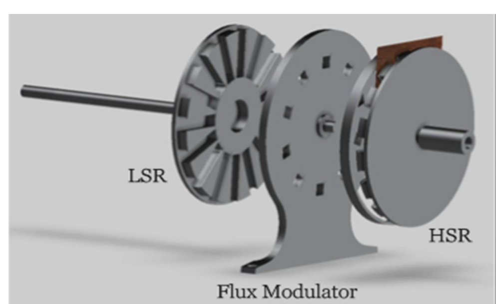
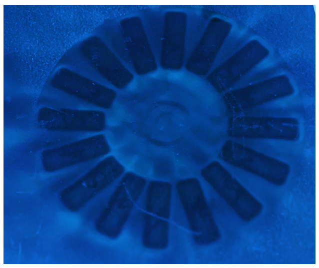


Fig. 2. CAD rendering of the 3 disks

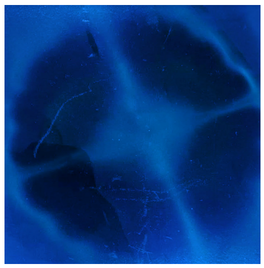
The disks were designed in Fusion 360 and 3D printed using PLA filament.

The low-speed rotor (LSR): Shown on the left (Fig 2), it is a 3D-printed disk with 16 evenly spaced (22.5° apart) slots for N52 Neodymium bar magnets (30 mm x 10 mm x 5 mm) arranged in alternating polarity (8 pole pairs). The LSR, mounted on a long axle, connects to a 24V DC motor via supports and is linked to the flux modulator through a central frictionless bearing.

High-Speed Rotor (HSR): The other end of the modulator featured a 9 mm tall ridge supporting the high-speed rotor (HSR) on the right (Fig 2.). The HSR, with a shorter D-slotted axle, directly connects to the generator. It used the same type of magnets but oriented differently to achieve a 4:1 gear ratio, with 16 magnets configured in a pattern of 4 adjacent north poles and south poles.

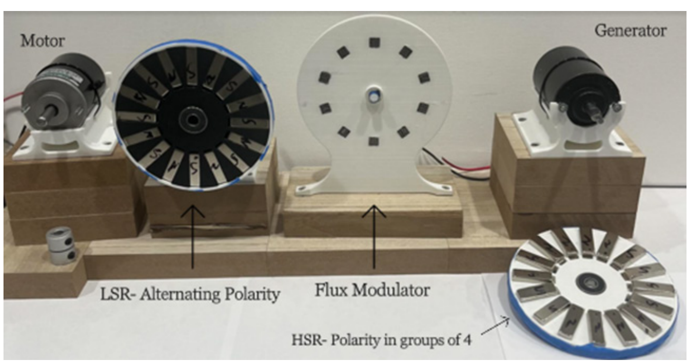


(LSR magnetic fields, alternating individual polarity)



HSR magnetic fields, alternating polarity in groups of 4

The flux modulator: As shown in the middle (Fig 2.), it is a 3D-printed disk with 10 equally spaced (36 degrees apart) 8mm x 5mm squares packed tightly with a unique transformer core metal (silicon steel sheet EI core-86-4hole Z11/0.35) which has a very high magnetic permeability. By focusing magnetic field lines from each small field (LSR) onto each big field (HSR) with the flux modulator, the LSR rotates 22.5 degrees while the HSR rotates 90 degrees in the opposite direction, creating a gearing effect. This setup generates a 4x RPM increase in the HSR, driving the generator. The total airgap between the disks was 13mm.



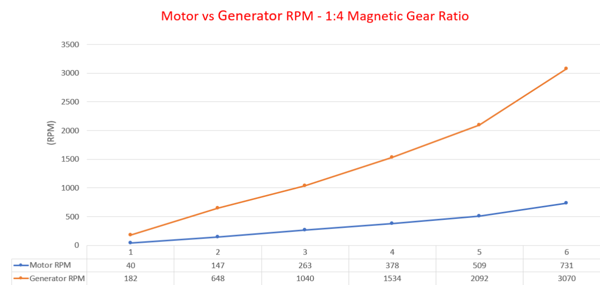
Analysis

Data was collected by comparing the input power from the motor to the output power generated in the generator, across 6 different initial input power settings. Additionally, temperature, RPM ratio, and output torque were measured.

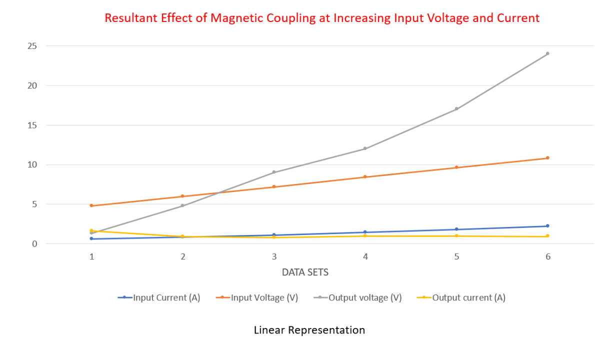
Data set	Regulated Input voltage (% of 24V)	Input Voltage (V)	Input Current (A)	Input Power (W) or (V·A)	Motor RPM	Output voltage (V)	Output current (A)	Output power (W) or (V·A)	Generator RPM	Overall Power efficiency (W)
1	20%	4.8	0.58	2.784	40	1.3	1.6	2.08	182	74.71%
2	25%	6	0.83	4.98	147	4.8	0.92	4.42	648	88.76%
3	30%	7.2	1.09	7.848	263	9	0.8	7.2	1040	91.74%
4	35%	8.4	1.47	12.348	378	12	0.95	11.4	1534	92.32%
5	40%	9.6	1.83	17.568	509	17	0.96	16.32	2092	92.89%
6	45%	10.8	2.22	23.976	731	24	0.937	22.488	3070	93.80%

Table 1.

Highlighted in the blue, the motor (LSR) RPM was accelerated by a factor of 4 due to flux modulation and measured through the generator (HSR) rpm. The ratio was sustainably around 4:1 across all input powers and speeds as shown in Graph 1.

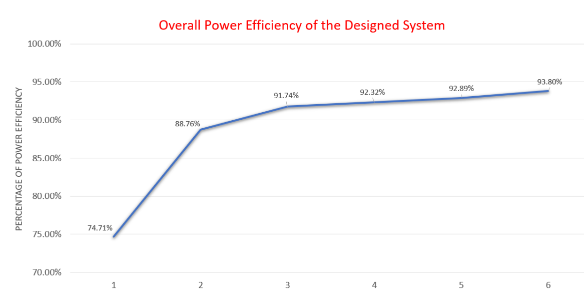


Graph 1: Motor (LSR) vs Generator (HSR) consistent 4:1 ratio



Graph 2: Output voltage vs Input voltage, and Output current vs Input current, across 6 input power sets.

As input power increased, the (LSR) speed increased. Measured through the multimeter, the output voltage (gray) exceeded the input voltage (orange) as shown in Graph 2, with an increasing trend after reaching a critical speed due to the magnetic coupler's acceleration from the flux modulator.



Graph 3

Additionally, the overall power efficiency of the magnetic coupler increases as speed increases, maximizing at the fastest testing input speed with 93.8% efficiency at a ratio of 731: 3070 rpm, seen in Graph 3.

Finally, there was no temperature increase across all trials, as there was no friction in the system. The design had a maximum torque density calculated by turning a load before slipping (decoupling), and had a final torque density of 2.3 $N·m/m^3$, considerably high for 3D printed disks at this small scale. When excessive torque was placed on the system, the couplers slipped with no damage.

Discussion

The data suggests that the constructed coupler topology would be sufficient in various high speed, high torque applications. Its unique axial topology combined with flux modulation could potentially replace conventional mechanical gears where fit. Contactless torque transfer enhances durability, reduces maintenance, and prevents heat damage, offering advantages for wind turbines, electric vehicles, and chemical facilities, where rotational motion is necessary but physical contact is not preferable. While past studies investigate the efficiencies of synchronous axial and radial coupling, the stable gear ratio achieved through flux modulation indicates the potential application of this design in technologies that employ variable mechanical gear ratios.

The magnetic coupler also has tremendous potential for further innovation when combined with mechanical gears and used with automation/customizable ratios and modulators to achieve dynamic rotational systems adaptable to a variety of environments.

Conclusion

This investigation aimed to design and analyze the performance of an axial-flux modulated coupler in driving a load and generating electricity, fulfilling the goals of current gears but with sustainability. The engineering goal was surpassed with a power efficiency of 93.8% as input voltages and speeds increased. Effective flux modulation and disk configuration increased the torque density, allowing stable coupling throughout all tested RPMs while powering the generator. Under excessive torque, the couplers slipped without physical contact, preventing damage and heat buildup and demonstrating an effective overload mechanism. The data warrants further investigation into properties of axial magnetic couplers in high-speed, high-torque applications. Constraints included the scale, 3D printed disks, modulator, supports, and the magnets available. Further experimentation may include a design with iron/steel backplates, a stronger motor, and stacking magnets onto rotors, so the design could be subject to various torques and thousands of RPMs. Essentially, flux-modulated magnetic couplers may help create safer machinery with high durability, efficiency, and safer conditions for workers who must repair the machinery, creating sustainable systems that don't suffer the wear, friction, and damage of current mechanical gears.

References

Guide to magnetic linear couplers. (2020). *DuraMag*. https://www.duramag.com/techtalk/magnetic-couplers/guide-to-magnetic-linear-couplers/

Implementation considerations for synchronous magnetic torque couplers. (2022). *DuraMag*. https://www.duramag.com/techtalk/magnetic-couplers/implementation-considerations-for-synchronous-magnetic-torque-couplers-geometric-misalignment/

Ruiz-Ponce, G., Arjona, M. A., Hernandez, C., & Escarela-Pere, R. (2023). A review of magnetic gear technologies used in mechanical power transmissions. *Energies* 2023. 16 (4) 1721; https://www.mdpi.com/1996-1073/16/4/1721

Villalobos, A. (2019). *Transferring power through a magnetic couple*. Linfield University. https://digitalcommons.linfield.edu/cgi/viewcontent.cgi?article=1042&context=physstud_theses

Wang, Q., Zhao, X., & Niu, S. Flux-Modulated Permanent Magnet Machines. World Electr. Veh. J. 2021 12 (1), 13;