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DESIGN OF A PLANETARY MAGNETIC DRIVE WHEEL USING THE AXIOMATIC DESIGN METHODOLOGY

BY

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Abstract. Magnetic gears are devices that transmit torque between two rotating shafts without physical contact, using magnetic forces instead of traditional mechanical teeth. Torque is transmitted purely through magnetic attraction and repulsion. If excessive torque is applied, magnetic gears slip instead of breaking. The objective of the research is to develop a magnetically geared motor wheel, used in an application where slips under overload are not allowed. For this, a research of documentary sources was done to identify existing solutions/ideas, and these ideas/solutions were organized in matrices/diagrams of solutions/ideas. This approach allowed the contrastive analysis of the solutions and the identification of a solution where slips under overload are not allowed. The solution was designed using the axiomatic design methodology.

Keywords: magnetic gears, converted topology, field modulated topology, axiomatic design, contrastive analysis.

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1. Introduction

Magnetic gears are devices that transmit torque between two rotating shafts without physical contact, using magnetic forces instead of traditional mechanical teeth. Unlike conventional gears that rely on meshing teeth to transfer motion, magnetic gears operate through the interaction of magnetic fields, providing efficient, silent, and maintenance-free torque transmission.

The gears function based on the principles of magnetic field modulation, enabling gear ratio conversion while eliminating direct friction, wear, and lubrication requirements. Torque is transmitted purely through magnetic attraction and repulsion. If overload torque is applied, magnetic gears slip instead of breaking.

2. Description of the research problem

The objective of the research is to develop a magnetically geared motor wheel, used in an application where slips under overload are not allowed.

3. Research method

The research method aimed at establishing a library of journal articles/conference papers/books/patents/company catalogs and based on them to develop an organized structure of ideas/solutions regarding magnetic gears. The form of organization of solutions/ideas regarding magnetic gears is the matrix/diagram of ideas. Contrastive analyses were carried out between different magnetic gear solutions, presented in tables and intended to highlight the strengths or weaknesses of the solutions. In the investigation of the evolution of ideas/solutions regarding magnetic gears, similar ideas/solutions were found in different sources. A unitary interpretation of ideas/solutions from different sources of investigation was attempted. The fact that an idea/solution is found in several sources, referencing an idea/solution each time would have complicated the presentation. For this reason, it was considered appropriate to present the investigation sources used in a unified manner, and the method of organization/interpretation to be considered specific to this research. Therefore, the documentation sources used are presented below, with a brief presentation.

The first source with reference to magnetic gears was identified in a patent (Armstrong Charles, 1901) and which states that the object of invention is to provide a device whereby power may be transmitted from one shaft to another by a means employing magnetic lines of force, and as a result the operation of the said device is noiseless, efficient, and easily controlled.

Another patent (Neuland, 1916) refers to method and apparatus for transmitting power between two rotatable elements or shafts which are adapted to rotate at the same or different speeds and in the same or different directions.

In the patent (Faus and Mass, 1940), the invention relates to magnetic gearing by which rotational motion between shafts can be transmitted without friction or mechanical contact and at any desired speed ratio by using magnetic gears in which the teeth are permanent magnets and the driving forces are transmitted by repelling the magnetic forces produced by such magnets.

Over time, patenting activities for various magnetic gear solutions have intensified and increasingly complex solutions have emerged (Atallah and Rens, 2017; Leas, 2016; Mita, 2015; Morris *et al.*, 2021; Nakatsugawa *et al.*, 2016; Powell and CaKerley, 2018; Rabien, 2022; Voghel, 2022).

Another source of documentation was the master's or doctoral theses. A comparative study between axial and radial flux-focusing magnetic gear topologies and mechanical gearboxes was developed at The University of North Carolina at Charlotte (Calvin, 2015). In the doctoral thesis Magnetically Geared Electrical Drives (Cooke, 2018), developed at The University of Sheffield, solutions for flux-modulated axial magnetic gears are proposed, manufactured, studied and tested. The thesis (Frandsen, 2016), Aalborg University, Denmark, treats the subject, design and prototyping of a permanent magnet gear combined with an electrical machine. A design optimization methodology for magnetically geared machines has been proposed in the thesis (Gerber, 2017). Structural analysis of the magnetic gears components is focused in the thesis (Modaresahmadi, 2020). The principal objective of this thesis (Montagne, 2011) is to determine the issues that arise, and potential solutions, to control a drive train that incorporates a non-contact magnetic gear box.

Of great importance for our approach were the studies of literature reviews (Bharani and Sivaprakasam, 2020; McGilton *et al.*, 2018; Miladinovic *et al.*, 2017; Ruiz-Ponce *et al.*, 2023; Shoaie and Wang, 2023; Tlali *et al.*, 2014; Tröger, 2022; Yan *et al.*, 2024; Yawei *et al.*, 2019; Zhu, 2018).

Numerous of papers concerning magnetic gears have been published where various topologies have been proposed, and many prototypes have been made and design details have been investigated (Atallah and Howe, 2001; Gardner *et al.*, 2018; Kohei *et al.*, 2018; Li *et al.*, 2013; Shen *et al.*, 2017; Zhang *et al.*, 2014; Zhu *et al.*, 2018).

No significant commercial magnetic gears have emerged, but there are also reported manufacturer catalogs (ccmagnetics, 2025; Tröger, 2022).

4. Results following the investigation of the field of magnetic gears

The analysis of the documentation in the library established according to the specification in the previous chapter reveals a great diversity of use of concepts, methods and approaches regarding magnetic gears. Pursuing the objective of organizing the ideas/solutions from the investigated documentation in matrices/idea diagrams, a first approach is to classify magnetic gears by topology into two classes: *converted topology and field-modulated topology*.

Converted topologies magnetic gears are presented below.

In mechanical engineering, various gear types (spur, helical, planetary, harmonic, bevel, etc.) have been developed to meet specific torque, speed, and spatial constraints. Each mechanical gear topology has unique advantages based on its structure and operating principles. *The concept of converted topologies in magnetic gears is inspired by the conversion of mechanical gear topologies.*

Magnetic gears are often conceptualized as the magnetic analogs of mechanical gears. This process of "conversion" is not just a direct replication but also involves leveraging the unique advantages of magnetic fields (like contactless operation, low maintenance, and inherent overload protection).

Converted topologies take well-known mechanical gear designs and adapt their operating principles into magnetic form, using components like permanent magnets instead of teeth and shafts. The converted topologies concept in magnetic gears can be seen as stemming from the conversion of mechanical gear designs into magnetic field-based systems, offering new possibilities while retaining the core mechanical logic of gear operation.

Table 1 presents, in matrix form, solutions of the magnetic gears and the mechanical gear from which they are considered to have been obtained by conversion. The solutions/ideas are easy to interpret, based on what was stated above, so it was considered that no explanations were necessary for each figure.

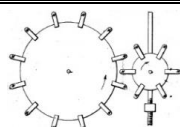
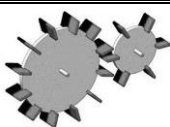
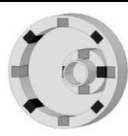
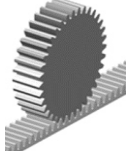
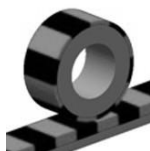
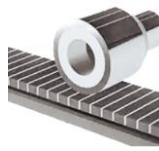
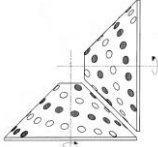
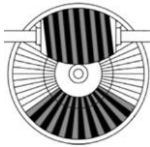
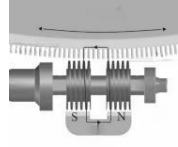
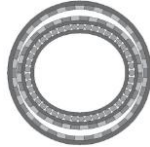
Magnetic gears with field-modulated topology operate based on magnetic field modulation, providing torque transmission through magnetic forces. The basic structure of magnetic gears with field-modulated topology consists: Inner Rotor which contains permanent magnets arranged in alternating polarity; Outer Rotor also contains permanent magnets arranged similarly and a stationary ring with ferromagnetic segments that modulate the magnetic field between the two rotors. The inner rotor generates a rotating magnetic field due to its permanent magnets. The ferromagnetic modulation ring interacts with this rotating magnetic field, creating a spatial harmonic field. This spatial harmonic field couples with the outer rotor's magnetic field, resulting in torque transmission.

In Fig. 1 the structure of magnetic gears with field modulation topology is presented. The figure includes labeled components such as the inner rotor, outer rotor, modulation ring, permanent magnets. This design significantly enhances the torque density and efficiency compared to simpler magnetic gear configurations.

Table 2 presents the matrix/diagram of solutions/ideas for magnetic gears with field modulated topology. It can be seen that the solutions are classified into two categories: radial flux modulated topology and axial field modulated topology.

Table 1

*Magnetic gears: Mechanical and Converted topologies
(adapted/modified/reorganized according to the bibliography cited in the chapter 3)*

Type	Mechanical	Magnetic gears – Converted topologies			
External spur gear	 1.1	 1.2	 1.3	 1.4	
Internal spur gear	 2.1	 2.2	 2.3	 2.4	
Rack pinion gear	 3.1	 3.2	 3.3	 3.4	
Bevel gear	 4.1	 4.2	 4.3	 4.4	
Worm gear	 5.1	 5.2	 5.3	 5.4	
Planetary gear	 6.1	 6.2	 6.3	 6.4	
Harmonic gear	 7.1	 7.2	 7.3	 7.4	

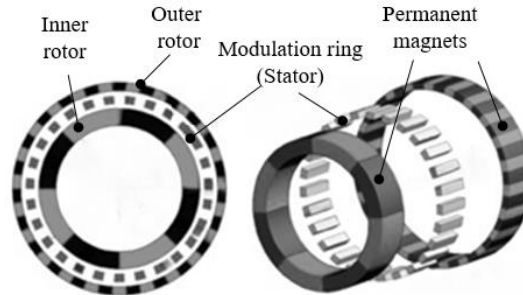


Fig. 1 – Magnetic gears with field-modulated topology (adapted/processed from (Ruiz-Ponce *et al.*, 2023)).

Field-modulated magnetic gears represent a broad class of non-contact torque transmission systems, each with distinct design variations. An overview of different field-modulated magnetic gears solutions contextualizes the rationale behind various topologies. For this reason, for all the solutions in Table 2, a brief description will be introduced from the perspective of the structural components (inner rotor, modulation ring, outer rotor) and the working principle.

Radial Flux Field-Modulation Magnetic Gear (RF-FMMG) utilizes a *radial flux path*, meaning the magnetic field lines flow radially between the inner and outer components.

Key Components and Working Principle of RF-FMMG with Spoke-Type Inner Rotor:

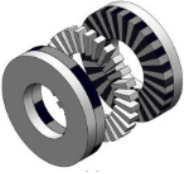
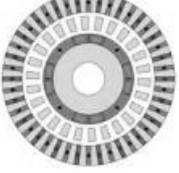
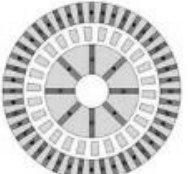
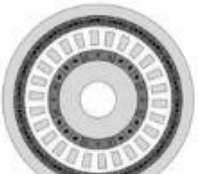
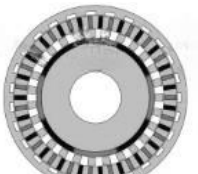
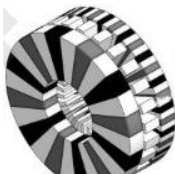
Inner Rotor (Spoke-Type Design) contains permanent magnets placed between radial "spokes" of ferromagnetic material. The spokes guide and concentrate the magnetic flux radially outward. This design enhances the magnetic flux density and torque output, making it highly efficient for high-torque applications.

Modulation Ring (Stationary Ring) made of ferromagnetic segments that modulate the magnetic field produced by the inner rotor. Acts as the intermediary that creates spatial harmonics necessary for torque transmission between the inner and outer rotors.

Outer Rotor, equipped with permanent magnets arranged in alternating polarities. Captures the modulated magnetic flux from the modulation ring, enabling torque transmission.

Working Principle of RF-FMMG with Spoke-Type Inner Rotor: The inner rotor generates a radial magnetic field through its spoke-type arrangement, increasing magnetic flux concentration. The modulation ring modulates this magnetic field, creating harmonic fields that interact with the outer rotor's magnetic field. Torque is transmitted from the inner rotor to the outer rotor via the modulated magnetic field, providing a high gear ratio without physical contact.

Table 2*Magnetic gears with field-modulated topology**(adapted/modified/reorganized according to the bibliography cited in the chapter 3)*

Radial-flux field modulated magnetic gear (RF-FMMG)	Axial-flux field modulated magnetic gear (AF-FMMG)
 Spoke-type in inner rotor	 Surface-Mounted PMs
 Spoke-type in outer rotor	 Spoke-Type PMs
 Spoke-type in both rotors	 Double-Sided FMMG
 Holbach array	 Radial Modulators on Both Sides
 Dual-Modulator FMMG	 L-Type Pole Pieces

Outer Rotor, equipped with permanent magnets arranged in alternating polarities. Captures the modulated magnetic flux from the modulation ring, enabling torque transmission.

Working Principle of RF-FMMG with Spoke-Type Inner Rotor: The inner rotor generates a radial magnetic field through its spoke-type arrangement, increasing magnetic flux concentration. The modulation ring modulates this magnetic field, creating harmonic fields that interact with the outer rotor's magnetic field. Torque is transmitted from the inner rotor to the outer rotor via the modulated magnetic field, providing a high gear ratio without physical contact.

Key Components and Working Principle of RF-FMMG with Spoke-Type Outer Rotor:

Inner Rotor contains permanent magnets or windings arranged in a radial pattern and produces a radial magnetic field directed outward towards the modulation ring.

Modulation Ring (Stationary Ferromagnetic Segments) placed between the inner and outer rotors modulates the magnetic flux generated by the inner rotor, creating harmonic fields necessary for torque transmission.

Outer Rotor (Spoke-Type Design) made up of permanent magnets mounted between ferromagnetic spokes arranged radially. The spokes guide and concentrate the magnetic flux inward, enhancing the magnetic field interaction with the modulation ring.

Working Principle of RF-FMMG with Spoke-Type Outer Rotor: The inner rotor generates a rotating magnetic field that is modulated by the stationary modulation ring. The modulated field interacts with the outer rotor's spoke-type magnetic structure, producing a high torque output. The radial flux path ensures efficient magnetic field flow from the inner rotor to the outer rotor through the modulation ring.

Key Components Working Principle of RF-FMMG with Spoke-Type in Both Rotors:

Inner Rotor (Spoke-Type Design): Permanent magnets are mounted between radial ferromagnetic spokes. The spokes guide magnetic flux radially outward towards the modulation ring, concentrating the magnetic field for efficient torque transmission.

Modulation Ring (Stationary Ferromagnetic Segments) positioned between the inner and outer rotors and modulates the magnetic flux from the inner rotor, generating spatial harmonics necessary for magnetic coupling.

Outer Rotor (Spoke-Type Design) permanent magnets are mounted between ferromagnetic spokes arranged radially. The spokes guide magnetic flux radially inward from the outer rotor, enhancing the magnetic flux interaction with the modulation ring and the inner rotor.

Working Principle: The inner rotor's radial flux is directed outward through its spokes, interacting with the modulation ring. The modulation ring

creates magnetic field harmonics, which couple with the outer rotor's radial flux, directed inward through its spokes. The result is a high-torque, contactless torque transfer, with magnetic fields efficiently interacting between the inner and outer rotors through the modulation ring.

Key Components and Working Principle of RF-FMMG with Halbach Array:

Note: A Halbach array is a specific arrangement of permanent magnets where the magnetization direction is rotated sequentially. This creates a strong magnetic field on one side and a near-zero field on the opposite side (due to magnetic field cancellation).

Inner Rotor contains a Halbach array of permanent magnets arranged radially. The Halbach array enhances the magnetic field on the active side while minimizing leakage on the opposite side.

Modulation Ring (Stationary Ferromagnetic Segments) positioned between the inner and outer rotors, modulates the magnetic field produced by the inner rotor to generate spatial harmonics for torque transmission.

Outer Rotor also employs a Halbach array of permanent magnets, captures and interacts with the modulated magnetic field from the inner rotor, ensuring efficient torque transfer.

Working Principle: The Halbach arrays in both rotors produce a strong, focused radial magnetic field on one side, enhancing flux density. The modulation ring interacts with this strong magnetic flux, creating a series of spatial harmonics. The modulated field couples with the outer rotor's Halbach array, enabling high-efficiency torque transmission without mechanical contact.

Key Components and working Principle of RF-FMMG with Consequent Pole Design:

Note: A consequent pole refers to a magnetic pole formed without a direct magnet, typically created by the magnetic flux return path. In a consequent pole magnetic gear, magnets are arranged so that some poles are formed by the flux flowing through ferromagnetic materials rather than using individual magnets for each pole. This arrangement effectively reduces the number of permanent magnets needed while maintaining or enhancing the magnetic field strength.

Inner Rotor contains permanent magnets placed in alternating polarity, with ferromagnetic segments creating consequent poles. This reduces the number of magnets needed and enhances magnetic flux concentration.

Modulation Ring (Stationary Ferromagnetic Segments) positioned between the inner and outer rotors and modulates the magnetic field from the inner rotor, creating harmonic magnetic fields for torque transmission.

Outer Rotor utilizes consequent poles formed by alternating permanent magnets and ferromagnetic materials and interacts with the modulated magnetic field from the inner rotor, allowing efficient torque transfer.

Working Principle: The inner rotor generates a radial magnetic field with both direct magnetic poles and consequent poles formed by ferromagnetic segments. The modulation ring modulates this field, creating spatial harmonics essential for magnetic coupling. The outer rotor with consequent poles interacts with these modulated fields, resulting in high-efficiency torque transmission.

In the following, a brief description of the constructive solutions for Axial-Flux Field-Modulated Magnetic Gear (AF-FMMG) will be given. Unlike radial-flux gears, where the magnetic flux flows radially, axial-flux magnetic gears have flux flowing along the axis of rotation, making them suitable for compact, high-torque applications. The description of the components of the Axial-Flux Field-Modulated Magnetic Gear (AF-FMMG) solutions also uses the concepts of inner rotor and outer rotor. This could create confusion, and to avoid this, some clarifications are introduced. The use of the terms inner rotor and outer rotor in both Radial-Flux Field-Modulation Magnetic Gear (RF-FMMG) and Axial-Flux Field-Modulated Magnetic Gear (AF-FMMG) can be understood by considering the relative positioning of components within each topology, rather than their absolute spatial orientation. The terminology is based on the functional role of the rotors rather than their absolute spatial orientation. The inner rotor always refers to the high-speed rotor, regardless of whether it is positioned radially or axially. The outer rotor always refers to the low-speed rotor, positioned further from the system's center of flux interaction. This consistent naming helps unify understanding across different magnetic gear topologies. A contrastive analysis regarding the meaning of the use of the concepts of inner rotor and outer rotor is presented in Table 3.

Table 3
Meaning of the concepts of inner rotor outer rotor

Type	Flux Direction	Inner Rotor (High-Speed Rotor)	Outer Rotor (Low-Speed Rotor)	Modulation Ring
Radial-Flux FMMG (RF- FMMG)	Radial (inward or outward)	Located inside, rotates faster	Located around the inner rotor, rotates slower	Positioned between inner and outer rotors
Axial-Flux FMMG (AF- FMMG)	Axial (along the rotation axis)	Located on one side, rotates faster	Located on the opposite side, rotates slower	Positioned between the two rotors

Key Components and Working Principle of Axial-Flux FMMG with Surface-Mounted PMs:

Inner Rotor (Surface-Mounted PMs) has permanent magnets mounted on the surface of the rotor. The magnets are arranged axially with alternating polarity, creating a strong axial magnetic field.

Modulation Ring (Stationary Ferromagnetic Segments) is a stationary ring placed between the inner and outer rotors and modulates the axial magnetic field from the inner rotor, generating the required harmonics for torque transmission.

Outer Rotor (Surface-Mounted PMs) Permanent magnets are also surface-mounted on the outer rotor and captures and interacts with the modulated magnetic field to transmit torque effectively.

Working Principle: The inner rotor's permanent magnets produce an axial magnetic field. The modulation ring modulates this field, creating spatial harmonic components. These harmonics interact with the outer rotor's surface-mounted PMs, enabling contactless torque transmission. The axial arrangement ensures high torque density while maintaining a compact design, suitable for limited axial spaces.

Key Components and of Working Principle Axial-Flux AF-FMMG with Spoke-Type PMs:

Inner Rotor (Spoke-Type PMs), permanent magnets are placed between ferromagnetic spokes arranged radially. The spoke-type design guides and concentrates the axial magnetic flux effectively, enhancing the magnetic interaction.

Modulation Ring (Stationary Ferromagnetic Segments), positioned between the inner and outer rotors. Modulates the axial magnetic field from the inner rotor, creating the necessary harmonic components for torque transmission.

Outer Rotor (Spoke-Type PMs), permanent magnets are also mounted between radial spokes on the outer rotor. These spokes guide the magnetic flux inward, providing a highly efficient magnetic coupling with the modulated field from the inner rotor.

Working Principle: The inner rotor's spoke-type PMs produce a concentrated axial magnetic field. The modulation ring interacts with this field, generating harmonics that allow for torque transfer. The outer rotor's spoke-type PMs pick up the modulated flux, enabling high-torque transmission without physical contact.

Key Components and Working Principle of Double-Sided Axial-Flux AF-FMMG:

Central Rotor (Surface-Mounted or Spoke-Type PMs), positioned in the middle, with permanent magnets mounted on both sides.

Produces a strong axial magnetic field extending to both sides of the rotor.

Two Modulation Rings (Stationary Ferromagnetic Segments), located on either side of the central rotor. Modulates the magnetic field from the central rotor, generating harmonic fields on both sides.

Two Outer Rotors (Surface-Mounted or Spoke-Type PMs), Positioned on both sides of the modulation rings. Capture the modulated magnetic field from each side of the central rotor, enabling torque transmission.

Working Principle: The central rotor generates an axial magnetic field extending to both sides. The modulation rings on each side modulate this field, creating harmonic components. The outer rotors on both sides interact with these modulated fields, resulting in balanced, high-torque transmission without mechanical contact. The double-sided design increases the magnetic interaction surface, enhancing torque density and efficiency.

Key Components and Working Principle of Axial-Flux Field-Modulated Magnetic Gear (AF-FMMG) with Modulators Located at Both Sides:

High-Speed Rotor (Radially Distributed PMs), Permanent magnets are distributed radially along the rotor surface. Operates at high speed, generating a strong axial magnetic field.

Low-Speed Rotor (Radially Distributed PMs), radially distributed permanent magnets are placed on the low-speed rotor. Rotates at a slower speed, capturing and transmitting torque from the high-speed rotor through magnetic interaction.

Modulation Rings (Located on Both Sides), two modulation rings are positioned on both sides of the rotors. Made of ferromagnetic segments that modulate the magnetic field generated by the high-speed rotor.

Working Principle: The high-speed rotor's permanent magnets produce an axial magnetic field distributed radially. The modulation rings on both sides modulate this field, creating harmonic components necessary for magnetic coupling. The low-speed rotor's magnets interact with the modulated field, enabling contactless torque transmission. The dual-sided modulators increase the surface area for magnetic interaction, enhancing torque density and efficiency.

Key Components and Working Principle of Axial-Flux FMMG with L-Type Pole Pieces:

High-Speed Rotor (Permanent Magnets), permanent magnets are arranged axially on the high-speed rotor. Generates an axial magnetic field that interacts with the modulation components.

L-Type Pole Pieces (Modulators), ferromagnetic pieces shaped like the letter L. Positioned between the high-speed and low-speed rotors. The vertical part of the L aligns axially with the magnetic field, while the horizontal part extends radially. Modulates the magnetic flux from the high-speed rotor, creating harmonic components essential for torque transmission.

Low-Speed Rotor (Permanent Magnets), arranged axially with alternating polarity. Captures the modulated magnetic field, enabling contactless torque transfer at a lower speed.

Working Principle: The high-speed rotor's permanent magnets produce an axial magnetic flux. The L-type pole pieces modulate this magnetic flux by creating distinct magnetic paths, enhancing the spatial harmonics necessary for torque transmission. The low-speed rotor interacts with the modulated field, transmitting torque without direct contact. The L-shape design increases the surface area for magnetic interaction while maintaining a compact axial profile.

After organizing, the solutions/ideas regarding magnetic gears it can be concluded that magnetic gears can be broadly classified into Converted Topologies and Flux-Modulated Topologies based on how they transfer torque.

Converted Topology Magnetic Gears *directly* replace mechanical gears with magnetic analogs, *mimicking* traditional gear kinematics.

Flux-Modulated Magnetic Gears (FMMG) use a ferromagnetic modulation ring to redirect and enhance magnetic field interaction, creating harmonic coupling for torque transmission.

A comparative analysis between Converted Topologies and Flux Modulated Topologies is presented in Table 4.

Table 4

Comparative analysis between Converted Topologies and Flux Modulated Topologies

Feature	Converted Topologies	Flux-Modulated Topologies (FMMG)
Torque Transmission Method	Direct magnetic coupling (pole interactions)	Magnetic flux modulation (harmonic interaction)
Magnetic Coupling Efficiency	Lower than FMMG (direct field interactions)	Higher due to flux concentration
Mechanical Complexity	Simpler (no modulation ring)	More complex (requires precise modulation)
Torque Density	Lower	Higher (flux modulation amplifies torque)
Gear Ratio Flexibility	More adjustable (direct control over pole interactions)	Fixed by the modulation ring design
Manufacturing Simplicity	Easier to build (no modulation components)	Requires precision manufacturing (modulation ring, multiple pole pairs)

Magnetic gears are studied across multiple fields, including electrical engineering, mechanical engineering, and materials science. A comparative analysis simplifies complex concepts, making the concepts accessible to researchers from different backgrounds. Including a comparative analysis between Converted Topologies and Flux-Modulated Topologies is essential for structuring the research field, clarifying engineering trade-offs, justifying design choices, supporting standardization, and enhancing interdisciplinary understanding.

Engineers designing new systems with magnetic gears must decide which topology is most efficient for their use case. An application suitability analysis, see Table 5, helps engineers and researchers match the right topology to the right application, improving efficiency and effectiveness.

Table 5
Application Suitability

Application	Best Choice
Electric Vehicles (EVs)	Converted Topology
Robotics (High Precision)	Converted Topology
Aerospace (Lightweight Design)	Converted Topology
Wind Turbines	Flux-Modulated Topology
Industrial Heavy Machinery	Flux-Modulated Topology
Marine Propulsion	Flux-Modulated Topology

Including an Application Suitability Analysis for Converted and Flux-Modulated Topologies serves as decision-making framework.

5. Applying Axiomatic Design approach

Axiomatic Design (AD) is a systematic design methodology that helps designers develop robust, efficient, and optimized systems by structuring the design process around a set of fundamental principles (Suh, 1990, 2005). Axiomatic Design provides a structured approach to transforming customer needs into functional requirements and design parameters while ensuring clarity, efficiency, and minimal complexity.

Axiomatic Design uses four domains, as shown in Fig. 2, to break down the design process:

Customer Domain (What is needed?), captures Customer Attributes (CAs), which define user needs and expectations.

Functional Domain (What should it do?), defines Functional Requirements (FRs) that must be met to satisfy the customer.

Physical Domain (How will it be achieved?), specifies Design Parameters (DPs) that meet the functional requirements.

Process Domain (How will it be produced?), defines Process Variables (PVs) to manufacture and implement the design.

Axiomatic Design is built on two fundamental axioms:

Axiom 1: The Independence Axiom (Maintain the independence of functional requirements FRs). Functional requirements (FRs) must remain independent of each other, should be satisfied without affecting the others and avoid coupled designs, where one change affects multiple FRs, leading to complexity.

Axiom 2: The Information Axiom (Minimize the information content of the design). The best design requires the least amount of information to function properly. Simpler designs with less uncertainty, fewer tolerances, and lower variability are preferred.

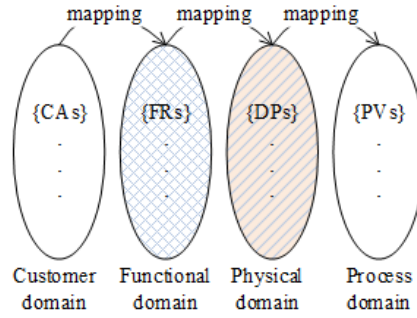


Fig. 2 – Domain mapping (Suh, 1990).

Independence axiom may be mathematical expressed by the design equation (1):

$$[FR] = [A] [DP] \quad (1)$$

Where:

$[FR]$ is the functional requirements vector;

$[DP]$ is the design parameter vector;

$[A]$ is the design matrix

In particular case equation (1) can be written in the form shown in equation (2)

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} * \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (2)$$

If all of the elements of the design matrix are nonzero axiom 1 cannot be respected and the design is called coupled design.

In the case when only the diagonal elements from design matrix are different from zero (see equation 3) the design satisfies the Axiom 1 and is defined as an uncoupled design.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} * \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (3)$$

A coupled design can be decoupled. A case is presented by equation (4) where the design matrix is a triangular matrix. The independence of FRs can be assured by adjusting the design parameters in a particular order (DP1 first, DP2 second and third DP3).

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} * \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (4)$$

This system is called decoupled design.

The objective of the present research is to develop a magnetically geared motor wheel, used in an application where slips under overload are not allowed.

Applying the recommendations in Table 5, application suitability, for the present problem, regarding develop a magnetically geared motor wheel, used in an application where slips under overload are not allowed, a converted topology of magnetic gears is suitable. Considering the high torque density parameter and analyzing the solution matrix in Table 1, a magnetic planetary gear solution seems suitable (one of the solutions 6.2, 6.3, 6.4 in Table 1).

Identifying the Four Domains of Axiomatic Design for Planetary magnetic gear (PMG) is presented in Table 6. Using the four-domain mapping of AD, is defined systematically how the design evolves from customer needs to manufacturing decisions.

Applying the Independence Axiom means that each Functional Requirement (FR) must be independent of others. It is being checked whether each FR can be satisfied without interfering with other functions. Applying the Independence Axiom ensures that changing one functional requirement does not negatively impact others (see Table 7).

Result from Table 7: The design is uncoupled, meaning each function is independently addressed, avoiding complexity.

Applying the Information Axiom means Minimize Information Content:

- Use Halbach arrays to reduce unnecessary flux paths.
- Simplify rotor structure to avoid redundant support material.
- Use optimized magnetization angles to ensure field concentration.

This results in a Low-Information Content design, meaning fewer variables must be controlled, leading to easier manufacturing and higher reliability.

Optimized Planetary Magnetic Gear Design Based on Axiomatic Design with Components and Design Decision is presented in Table 8.

The data in Table 8 ensures a robust, optimized, and efficient Planetary magnetic Gear (PMG) system.

Table 6
Identifying the Four Domains of Axiomatic Design for PMG

Domain	Description for Planetary Magnetic Gear
Customer Domain (CNs)	Develop a magnetically geared motor wheel, used in an application where slips under overload are not allowed. The magnetically geared motor wheel should deliver high torque density, efficient power transfer, and minimal magnetic leakage.
Functional Domain (FRs)	FR1: Ensure effective torque. FR2: Ensure effective torque transmission. FR3: Minimize magnetic leakage for higher efficiency. FR4: Ensure not slips under overload. FR5: Maintain a lightweight and compact structure.
Physical Domain (DPs)	DP1: Use a controlled electric motor. DP2: Use of teeth with high-performance permanent magnets for direct torque transfer. DP3: Utilize non-magnetic structural materials to reduce leakage. DP4: Mechanical takeover of the torque transmission - permitted by the shape and positioning of the teeth. DP5: Use of a planetary magnetic crown mounted on the axis of the magnetic sun wheel.
Process Domain (PVs)	PV1: Ensuring a standardized controlled electric motor. PV2: Precision alignment of planetary and sun rotors. PV3: "Optimized magnetization process for stable field interaction." PV4: "Advanced CAD and FEA simulations for structural and magnetic optimization." PV5: Polycarbonate is a high-performance material for 3D printing,

Table 7
Applying the Independence Axiom

FR-DP Relationship	Coupled or Independent?
FR1 → DP1 (Use a controlled electric motor)	Independent
FR2 → DP2 (Use of teeth with high-performance permanent magnets for direct torque transfer.)	Independent
FR3 → DP3 (Utilize non-magnetic structural materials to reduce leakage.)	Independent
FR4 → DP4 (Mechanical takeover of the torque transmission - permitted by the shape and positioning of the teeth.)	Independent
FR5 → DP5 (Use of a planetary magnetic crown mounted on the axis of the magnetic sun wheel.)	Independent

Table 8*Optimized Planetary Magnetic Gear Design Based on Axiomatic Design*

Component	Optimized Design Decision (Using AD)
Magnet Arrangement	Use Halbach arrays to focus magnetic flux efficiently.
Rotor Configuration	Sun rotor and planetary rotors designed with minimal interference.
Material Selection	Use lightweight, non-magnetic housing to reduce unnecessary weight.

Benefits of Axiomatic Design for Planetary Magnetic Gears are summarized in Table 9.

Table 9*Benefits of Axiomatic Design for Planetary Magnetic Gears*

Challenge in PMG Design	How Axiomatic Design Solves It
Magnetic coupling interference	AD ensures functional independence with optimized magnet placement.
Complexity in optimizing gear ratios	AD separates torque transmission from efficiency concerns, simplifying the system.
Magnetic leakage & losses	AD ensures flux paths are focused using Halbach arrays.
Manufacturing alignment challenges	AD reduces information complexity, making precision alignment easier.

By applying Axiomatic Design (AD) to a Converted Topology Planetary Magnetic Gear, is realized: uncoupled, optimized system design lower complexity and easier manufacturability; improved efficiency and reduced energy losses.

6. Solution design

For this purpose, it was designed and manufactured a planetary magnetic gear, as can be seen in Fig. 3, consisting of a body 1, on which a sun gear wheel 2 is mounted that drives three other gears (planet gears) 3, the movement being transmitted to a ring gear 4, the entire assembly being able to be driven by an electric motor 5 controlled through an electronic interface that allows different dynamic experiments (speed variation, accelerations, etc.).

The constructive elements of the assembly were developed by the 3D printing technological method, and the magnetic tooth 6, by sintering from Nd₂Fe₁₄B magnetic material. The teeth 6 are mounted on the wheels in type *a* slots. The geometric shape and the magnetization mode of the magnetic tooth 6 are presented in Fig. 3. The originality of the proposed magnetic gear lies in the fact that the arrangement of the gears and the geometric shape of the teeth allow, at the limit, mechanical engagement.

More explicitly: if the torque capable of being transmitted magnetically is exceeded, i.e. the teeth come into contact, the transmission of motion continues through contact engagement.

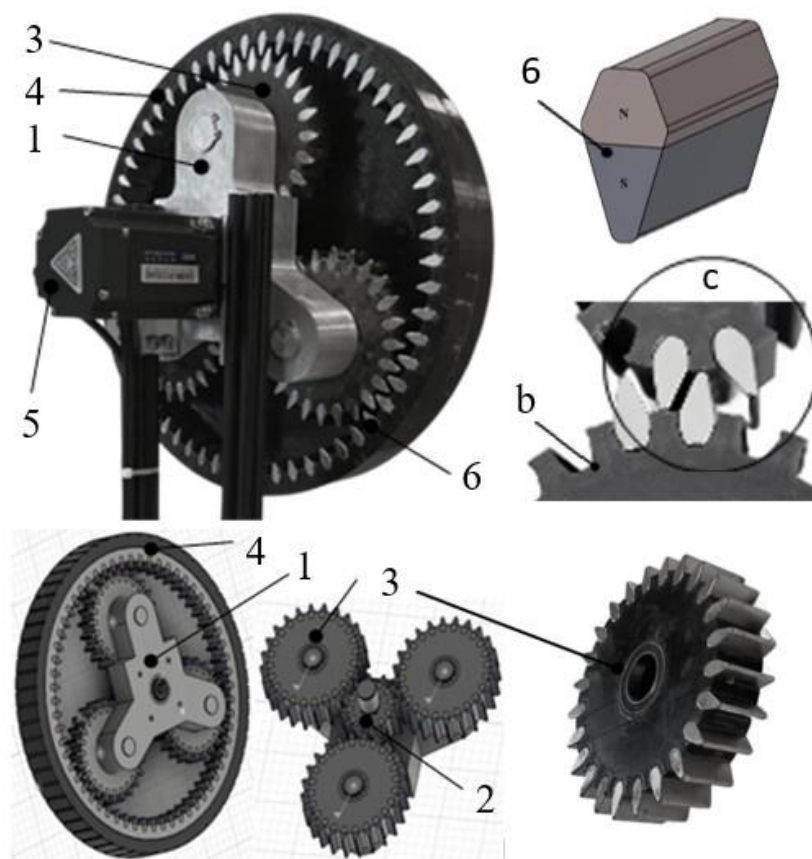


Fig. 3 – Planetary magnetic drive wheel; Solution design.

The possibility of contact between the teeth results from the positioning of the wheels, and therefore of the teeth, as can be seen in detail *c* in Fig. 3. The focus on ensuring mechanical engagement under overload conditions is a significant strength of the proposed solution. It addresses a critical challenge in the functionality of magnetic gears, thereby enhancing reliability and operational safety in practical applications.

7. Conclusions

The paper presents an investigation into magnetic gears, which transmit torque between two rotating shafts without physical contact, relying on

magnetic forces rather than traditional mechanical teeth. The primary objective of the research is to develop a magnetically geared motor wheel intended for applications that cannot tolerate slipping under overload conditions.

The research methodology involved compiling a comprehensive library of literature, including journal articles, conference papers, patents, and textbooks, focused on magnetic gears. A structured analysis was conducted to organize existing ideas and solutions regarding magnetic gears into matrices and diagrams. This facilitated contrastive analyses of various magnetic gear solutions, identifying their strengths and weaknesses.

The research categorizes magnetic gears into two primary topologies: converted topology and field-modulated topology. This classification aids in understanding the different operational principles of magnetic gears compared to traditional mechanical systems.

The research employs the axiomatic design methodology (AD) to systematically develop an optimized design for a planetary magnetic gear system. A functional prototype of a planetary magnetic gear was designed and manufactured. The unique arrangement of gears allows for mechanical engagement in cases where magnetic transmission surpasses the torque limit, ensuring continuous operation under overload conditions.

The study underscores the versatility and potential of magnetic gears, highlighting various topologies and their implications for advanced mechanical designs. The application of axiomatic design principles has led to a robust and efficient system, promising enhancements in manufacturability and performance. Future research directions include exploring new materials, optimizing magnetic configurations, and investigating various magnetization strategies for tooth designs.

This work contributes valuable insights into the design and optimization of magnetic gears, with significant implications for future developments in non-contact mechanical systems and energy-efficient applications.

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PROIECTAREA UNEI ROȚI MOTOARE CU ANGREN AJ MAGNETIC PLANETAR FOLOSIND METODOLOGIA AXIOMATIC DESIGN

(Rezumat)

Angrenajele magnetice sunt dispozitive care transmit cuplul între doi arbori rotativi fără contact fizic, folosind forțe magnetice în locul dinților mecanici tradiționali. Cuplul este transmis exclusiv prin atracție și repulsie magnetică. Dacă se aplică un cuplu excesiv, angrenajele magnetice alunecă în loc să se rupă. Obiectivul cercetării este de a dezvolta o roată motoare cu angrenaj magnetic, utilizată într-o aplicație în care nu sunt permise alunecări sub sarcină excesivă. Pentru aceasta s-a făcut o cercetare a surselor documentare pentru identificarea soluțiilor/ideilor existente, iar aceste idei/soluții au fost organizate în matrice/diagrame de soluții/idei. Această abordare a permis analiza contrastantă a soluțiilor și identificarea unei soluții în care nu sunt permise alunecări sub sarcină excesivă. Soluția a fost proiectată folosind metodologia de proiectare axiomatică.