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FLYWHEEL SYSTEMS COUPLED TO BEARINGLESS MOTORS: LITERATURE REVIEW

SISTEMAS FLYWHEEL ACOPLADOS A MOTORES SEM ROLAMENTOS: REVISÃO DA LITERATURA

SISTEMAS DE VOLANTE ACOPLADOS A MOTORES SIN COJINETES: UNA REVISIÓN BIBLIOGRÁFICA

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ABSTRACT
With the growing need for more sustainable and efficient energy storage technologies, flywheel-based energy storage systems, such as Flywheel Energy Storage Systems (FESS), have become increasingly relevant in this context, especially when coupled with bearingless motors. This article presents a review of current flywheel systems coupled to bearingless motors, analyzing their topologies, control strategies, optimization, thermal performance, and emerging applications. In addition, the goal is to identify the most promising technological trends, research opportunities, and the main challenges faced. The results point to the great potential of flywheel systems with bearingless motors in critical applications, smart grids, electric vehicles, aerospace systems, and integration with other technologies in hybrid energy storage architectures.

Keywords: Bearingless Motors. Flywheeling. Energy Storage. Flywheel. Hybrid Excitation Motors.

RESUMO
Com a crescente necessidade mundial por tecnologias de armazenamento de energia mais sustentáveis e de maior eficiência, os sistemas baseados em volantes de inércia (Flywheel Energy Storage Systems – FESS) tem ganhado cada vez mais relevância neste contexto, sobretudo quando acoplados à motores sem mancais. Este artigo apresenta uma revisão do estado da arte atual dos sistemas flywheel acoplados a motores sem mancais, analisando suas topologias, estratégias de controle, otimização estrutural, desempenho térmico e aplicações emergentes. Além destes, também busca identificar as tendências tecnológicas mais promissoras, oportunidades de pesquisa e os principais desafios enfrentados. Os

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resultados apontam para um grande potencial dos sistemas flywheel com motores sem mancais em aplicações críticas, redes inteligentes, veículos elétricos, sistemas aeroespaciais e integração com outras tecnologias em arquiteturas híbridas de armazenamento de energia.

Palavras-chave: Motores sem Mancais. Flywheel. Flywheeling. Armazenamento de Energia. Volante de Inércia.

RESUMEN

Ante la creciente necesidad global de tecnologías de almacenamiento de energía más sostenibles y eficientes, los sistemas de almacenamiento de energía mediante volante de inercia (FESS) han cobrado mayor relevancia, especialmente al combinarse con motores sin cojinetes. Este artículo presenta una revisión del estado actual de los sistemas de volante de inercia con motores sin cojinetes, analizando sus topologías, estrategias de control, optimización estructural, rendimiento térmico y aplicaciones emergentes. Asimismo, busca identificar las tendencias tecnológicas más prometedoras, las oportunidades de investigación y los principales desafíos. Los resultados apuntan a un gran potencial para los sistemas de volante de inercia con motores sin cojinetes en aplicaciones críticas, redes inteligentes, vehículos eléctricos, sistemas aeroespaciales e integración con otras tecnologías en arquitecturas híbridas de almacenamiento de energía.

Palabras clave: Motores sem Mancais. Flywheel. Flywheeling. Armazenamento de Energia. Volante de Inércia.

1 INTRODUCTION

The growing demand for efficient and sustainable energy storage solutions has driven the development of new technologies. In this context, Flywheel Energy Storage Systems (FESS) have emerged as a promising alternative due to their capacity to store kinetic energy at high speeds with high efficiency, long life, and superior dynamic response to traditional electrochemical batteries (Yang et al., 2021). Flywheel technology allows the conversion of electrical energy into rotational mechanical energy, which can be quickly reconverted into electrical energy in a controllable way (Zhou et al., 2021)..

In this context, given the growing relevance of flywheel-based energy storage systems coupled to bearingless motors, it is essential to consolidate existing scientific knowledge and identify gaps for future research. Recent literature shows significant advances in the structural optimization, control strategies, and applications of these systems (Zhou et al., 2021; Yang et al., 2021). However, technical and economic challenges still limit their large-scale adoption (Xiang et al., 2022; Zhu et al., 2021a).

Thus, based on information obtained from articles published in the last decade, this systematic review seeks to answer the following key questions: What are the most promising bearingless motor topologies for flywheel applications? Which control strategies have proved most effective in stabilizing the rotor and in torque-lift decoupling in bearingless motors? What structural and material approaches have been used to reduce energy losses and optimize the efficiency of flywheel systems? What challenges still need to be overcome to implement flywheel systems with bearingless motors?

By answering these questions, this systematic review aims to provide a synthesis of the state of the art, identifying emerging trends, technical challenges, and opportunities for research and development in the field of bearingless motor flywheel systems.

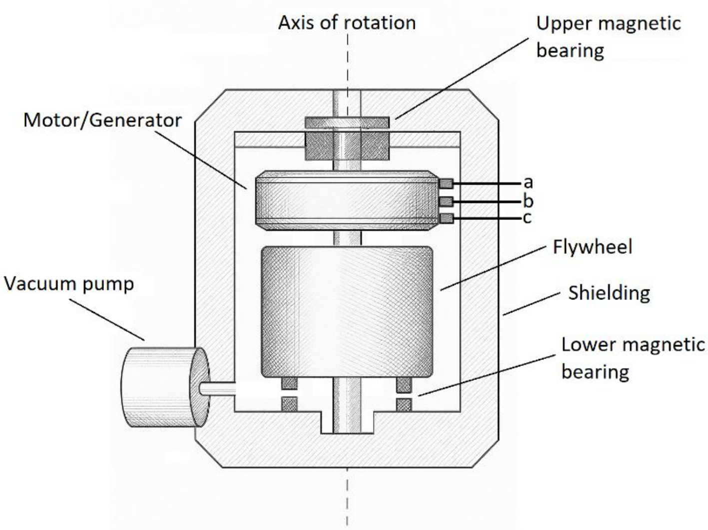
The article presents a guide to the Introduction Section 1. The theoretical background is presented in the section 2. In Section 3, the methodologies is presented. In Section 4, the results and discussions are presented.In Section 5, conclusions are drawn.

2 THEORETICAL BACKGROUND

FESS-based energy storage has been widely studied as a possible high-efficiency and reliable solution for applications variety, including power grids, renewable energy generation systems, and aerospace systems (Zhou et al., 2021; Yang et al., 2021). These systems operate on the basis of converting electrical energy into rotational kinetic energy, stored in a rotor spinning at high speed. When necessary, this energy is converted back into electricity using a reversible electric machine coupled to the flywheel shaft, which can function as a motor or as a generator, allowing for a fast and efficient dynamic response (Zhu et al., 2021b). Figure 1 shows a representation of a flywheel module.

Figure 1

Cutaway representation of a flywheel module



Source: authors.

The operation of flywheel systems is based on the principles of energy conservation and angular momentum. The stored energy (E) in a flywheel is determined by the fundamental equation (1) given by:

$$E = \frac{1}{2} J w^2 \qquad (1)$$

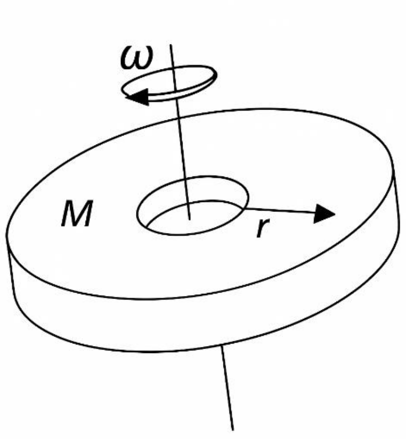
Where:

J is the moment of inertia of the rotor, which depends on the mass distribution and geometry of the flywheel; ω is the angular velocity of the rotor.

Figure 2 illustrates a generic flywheel model with typical physical variables that influence energy storage.

Figure 2

Representation of a flywheel



Source: authors.

Where:

M is the mass of the flywheel; r is the radius of the flywheel; ω is the angular speed of rotation.

The energy storage capacity is directly proportional to the mass and radius of the flywheel and increases exponentially with the angular velocity (ω^2). In this way, the system efficiency is maximized when the flywheel operates at very high rotational speeds, reaching up to 100000 rpm in some advanced models (Zhou et al., 2021).

Modern flywheels use lightweight composite materials with high mechanical strength, such as carbon fibers, to withstand the high centrifugal forces and minimize losses due to friction and structural deformation (Xiang et al., 2023). In addition, active magnetic bearings are used to eliminate mechanical contact, increase efficiency, and reduce maintenance costs (Zhu et al., 2021a).

Flywheel systems offer advantages over other energy storage technologies, such as:1)High energy efficiency: Studies show that the overall efficiency of flywheel systems can exceed 95%, depending on the magnetic control used (Zhu ; Lu, 2016). 2) Long service life and low degradation: Unlike batteries, which suffer chemical degradation over time, flywheel systems do not lose storage capacity overcharge and discharge cycles, being able to operate for decades without replacing critical components (Zhou et al., 2021).3) Fast dynamic response: The conversion between charging and discharging takes place in milliseconds, allowing applications that require instantaneous power responses, such as stabilizing electrical networks and compensating for oscillations in power generation systems (Yang et al., 2021). 4) Low environmental impact: Because they do not use heavy metals or degradable chemical processes, flywheel systems are considered more sustainable than conventional batteries, especially when used for long periods (Xiang et al., 2023). 5) High power density: The ability to supply large amounts of energy in short periods makes these systems attractive for applications in electric vehicles and regenerative braking (Yang; Tao, 2021).

Bearingless motors have established themselves as an essential solution for high-speed systems, eliminating mechanical friction and providing energy efficiency, reliability, and longer service life (Zhou et al., 2021; Yang et al., 2021). These motors combine magnetic suspension and rotational torque functions, allowing the rotor to levitate using controlled electromagnetic forces. This principle eliminates the need for conventional mechanical bearings, reducing wear and making them ideal for applications in flywheel energy storage systems (Zhu et al., 2021a).

Magnetic suspension in bearingless motors can be active, passive, or hybrid. In active systems, sensors detect the rotor positions in real time and adjust the magnetic fields to keep it suspended, while passive systems use permanent magnets to stabilize the rotor without the need for external control (Xiang et al., 2023). Hybrid systems are a combination of active and passive bearings.

Active systems require advanced dynamic control strategies (Zhang ; Zhu, 2017), such as direct torque control and predictive current control, which allow radial forces to be compensated, minimizing disturbances (Sun et al., 2018a). Bearingless motors are classified into different types according to the electromagnetic principle used, and the most studied in the literature today are: switched reluctance motors, permanent magnet synchronous motors, and hybrid magnetic excitation motors.

3 METHODOLOGIES

This systematic literature review aimed to identify, analyze, and bring together the most recent advances in the use of flywheel systems for energy storage, especially when coupled to bearingless motors. To guarantee the quality and reliability of the results, the study followed recognized guidelines for systematic reviews, based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, which is widely adopted in scientific research.

3.1 LITERATURE SEARCH

The search for scientific articles was carried out in high-impact databases, guaranteeing access to relevant publications in the field. The following databases were consulted:

- IEEE: Reference in the field of electrical and electronic engineering;
- Scopus: Multidisciplinary database that aggregates engineering articles;
- Web of Science: Consolidated platform for analyzing academic impact and emerging trends.

3.2 SEARCH STRATEGY AND ARTICLE SELECTION

The literature search was carried out using keywords that related to the most relevant articles. The combinations of terms used were:

- "Flywheel" AND "Bearingless"
- "Flywheeling" AND "Bearingless"

These terms were applied to the abstract field of the indexed articles. The search was limited to the period 2015 to 2025, in English, and open access. The articles found were subjected to a multi-stage screening process, as shown in Table 1:

Table 1

Systematic Literature Review

Research Databases	IEEExplore	Scopus	Web of Science
Filter 1	5	25	19
Filter 2	25	documents	deleted
Total	eligible articles	24	

Source: authors.

Thus, Total eligible articles 24 Documents.

Where filter 1:

1) Summary (combination of keywords); 2) Type (open access); 3) Period (2015 to 2025); 4) Language (English).

Result after Filter 1: 49 articles found.

Where filter 2: 1)Removal of duplicate articles; 2) Application of inclusion and exclusion criteria;

After this screening process, 24 articles were selected to form the basis of the systematic review, covering different research approaches.

3.3 INCLUSION AND EXCLUSION CRITERIA

To ensure the quality of the review and avoid bias in the selection of articles, the following criteria were defined:

(i) *Inclusion criteria*: 1)Papers presenting innovative contributions; 2) Articles with experimental analyses, numerical simulations or modeling; 3) Papers dealing with practical applications of flywheel systems.

(ii)Exclusion criteria: ***1)*** Publications that do not directly address flywheel systems or bearingless motors; 2) Studies that do not present experimental or computational validation; 3) Research that deals mainly with motors with conventional mechanical bearings.

The application of these criteria ensured that only articles relevant to the state of the art in question were included in the analysis, enabling greater adherence to the objective of this research.

3.4 INFORMATION ANALYSIS

The information analysis available in the database is a crucial stage in the preparation of a systematic review, as it makes it possible to organize the available scientific knowledge in a structured way. This process facilitates a more in-depth critical analysis of the advances, challenges, and gaps related to the research.

Based on a thorough analysis of each of the 24 articles selected, the information considered relevant was extracted from each one. The following information was obtained: 1) Bibliographic reference: Authors, title, journal/conference, and year of publication. 2) Objective of the study: Delimitation of the problem addressed by each author. 3) Main findings: Quantitative and qualitative results on efficiency, vibration control, thermal stability, commercial viability, among others.4) Gaps and challenges identified: Unresolved problems, such as heat dissipation at high rotation speeds, rotor eccentricity, implementation costs, among others. 5) Scope of the article: What contributions are presented or expected by the article in its respective area of scope.

Methodology used: The studies were classified according to their approach to obtaining the results: 1) Computer simulations; 2) Mathematical modeling; 3) Experimental validations on prototypes.

To ensure consistency and reproducibility of the analysis, a thematic mapping was carried out to categorize the articles based on the research axes adopted in each of them, ensuring a uniform and comparable analysis between the papers.

Axes of research: The articles were classified according to the area of research to which they related, which were as follows: 1)Topologies of bearingless motors in flywheel systems. 2) Control strategies for magnetic suspension and torque. 3) Structural optimization and energy efficiency. 4) Fault tolerance in high-power systems: Study of failures at high rotation speeds and mitigation proposals (Xiang et al., 2022).

This categorization according to the research area allowed an analysis between the different proposals contained in the reviewed articles, enabling the identification of trends, ongoing studies, and the search for challenges that are still unresolved. The classification of the 24 selected articles according to their research area is shown in Table 2.

Table 2

Classification of articles according to the research focus

Research Focus	Articles
Topologies of bearingless motors in flywheel systems	(Yang et al., 2021) (Zhou et al., 2021) (Yang et al., 2022) (Jin et al., 2018) (Zhang ; Zhu, 2017) (Xiang et al., 2023) (Xiang; Peng ; Ou, 2022) (Yuan et al., 2020) (Sun et al., 2017)
Control strategies for magnetic suspension and torque	(Sun et al., 2018a) (Ye, Sun ; Huang, 2015) (Yang; Tao, 2021) (Zhou, Jiang; Sun ; Hu, 2021)
Structural optimization and energy efficiency	(Zhu; Lu, 2016) (Zhu et al., 2021a) (Zhu et al., 2019) (Zhu et al., 2020) (Yang et al., 2023)
Thermal impact and stability at high speeds	(Liu; Zhu ; Xu, 2022) (Zhu et al., 2022) (Zhu et al., 2021b) (Circosta et al., 2018)
Emerging applications and industrial feasibility	(Zhu et al., 2023) (Sun et al., 2018b)

Source: authors.

4 RESULTS AND DISCUSSIONS

After a detailed analysis of each article, their main contributions in the field of this research were extracted. Thus, the most relevant results presented by the articles are listed below, along with an analysis of each of these topics within the general context of energy storage through flywheel systems coupled to bearingless motors.

4.1 BEARINGLESS MOTOR TOPOLOGIES

The main topologies of bearingless motors used in recent literature are listed below.

4.1.1 Bearingless Switched Reluctance Motors (BSRM)

Bearingless switched reluctance motors are based on the principle of minimizing magnetic reluctance, where the rotor is attracted to positions of lower reluctance within the magnetic field generated by the stator. The absence of permanent magnets makes these motors more economical and robust, in addition to reducing environmental impacts associated with the mining of rare earth elements (Zhu et al., 2021a).

The main advantages of these include:1) Low manufacturing cost, due to the simplicity of construction and the absence of permanent magnets. 2) Magnetic suspension and torque can be controlled independently in different sets of windings.

However, such motors still present challenges that need to be solved to ensure better efficiency in flywheel systems, such as: 1) High torque ripple, which can compromise system stability (Zhou et al., 2021). 2) Difficulty in controlling magnetic suspension, requiring sophisticated algorithms for rotodynamic stabilization (Zhu et al., 2021a; Ye et al., 2015).

4.1.2 Bearingless Permanent Magnet Synchronous Motors (BPMSM)

Bearingless permanent magnet synchronous motors utilize permanent magnets in the rotor to generate the magnetic field (poles) that will interact with the stator's magnetic field, producing electromagnetic torque. In this configuration, there is a significant reduction in losses due to the absence of current flowing through the rotor, as well as a simplification of the machine, since there is no need for external current supply to the rotor. These motors offer higher power density, making them a popular choice for high-speed flywheel systems (Yang et al., 2021).

Other advantages of these motors include:1) Lower torque ripple, ensuring more stable operation at high speeds. 2) Good dynamic response, enabling good control of magnetic suspension and torque.

However, they present some limitations, such as: 1) High cost due to the use of rare earth permanent magnets, such as neodymium-iron-boron (NdFeB). 2) Thermal sensitivity with the possibility of demagnetization of the magnets at high temperatures. 3) Limitation for high power applications.

4.1.3 Performance comparison between different motor topologies

Table 3 presents a comparison between the three most commonly used bearingless motor topologies in flywheel systems with bearingless motors, considering technical and operational criteria.

The comparative analysis shows that: 1) BSRM motors are more robust and economical, but require advanced control strategies to minimize torque ripple. 2) BPMSM motors offer the best energy efficiency and rotodynamic stability, but have high costs and thermal sensitivity. 3) Hybrid motors combine the advantages of the two previous topologies, but require greater control and construction complexity.

The choice of the best topology for flywheel systems depends on the specific application, cost requirements, energy efficiency, and the availability of specific magnetic materials.

Table 3

Comparison between motor topologies

Criterion	BSRM	BPMSM	Hybrid
Energy Efficiency	Medium	High	High
Manufacturing Cost	Low	High	Medium
Power Density	Medium	High	High
Control Complexity	High	Medium	High
Torque Ripple	High	Low	Medium
Thermal Sensitivity	Low	High	Medium

Source: authors.

4.1.4 Hybrid Excitation Motors

Hybrid excitation motors combine the characteristics of switched reluctance motors and permanent magnet synchronous motors. This approach aims to optimize power density and magnetic suspension stability, providing better control and energy efficiency (Yang et al., 2021).

Hybrid motors offer the following advantages:1) Greater flexibility in torque and magnetic suspension control, allowing dynamic adjustments to compensate for radial forces. 2) Reduction of eddy current losses, optimizing performance at high speeds. 3) Suitability for multiple applications, including energy storage and high-speed propulsion (Zhu et al., 2021b).

However, there are still challenges to overcome, such as: 1)Greater control complexity, requiring sophisticated algorithms for rotor stabilization. 2) Higher manufacturing cost, as they combine active windings and permanent magnets, increasing manufacturing complexity (Xiang et al., 2023).

4.2 CONTROL STRATEGIES FOR MAGNETIC SUSPENSION AND TORQUE

The main control methods for magnetic suspension and torque used in recent literature are listed below.

4.2.1 Direct Torque Control

Direct Torque Control is a widely used method in bearingless motors, as it allows for rapid adjustments in the dynamic response of the system, reducing torque fluctuations and optimizing the efficiency of the magnetic suspension (Zhu et al., 2021a).

This method employs a control based on the selection of discrete states of the inverter voltage, directly regulating the magnetic flux and torque without the need for pulse width modulation (PWM) (Xiang et al., 2023). Its main advantages include:

- Fast dynamic response and better control of radial force;
- Lower computational complexity compared to predictive model-based methods;
- Elimination of the need for complex transformations, such as Park and Clarke, used in traditional vector controls.

4.2.2 Predictive Current Control

Predictive Current Control has been investigated as a more advanced approach for bearingless motors, using mathematical models to predict the system's behavior over a future time horizon (Sun et al., 2018a). This method is based on optimization algorithms that adjust the inverter control voltages according to predictions of torque and radial force (Zhou et al., 2021).

Its main advantages are:1) Greater accuracy in compensating for radial forces and minimizing torque ripple. 2)Greater robustness against external disturbances and load variations. 3)Ability to operate at high speeds without compromising rotodynamic stability (Xiang et al., 2022).

4.2.3 Machine Learning

Recently, approaches based on machine learning and artificial intelligence have been explored to optimize the control of magnetic suspension and reduce the energy consumption of bearingless motors (Yang et al., 2021). Techniques such as artificial neural networks and reinforcement learning algorithms have been employed to dynamically adjust control parameters, learning optimal operating patterns in real time (Zhu et al., 2021a; Zhu et al., 2019).

The main contributions of these techniques are: 1) Ability to self-adjust and adapt to load and speed variations. 2) Reduced need for detailed modeling, allowing automatic adaptation of the control to different operating conditions. 3) Improved energy efficiency by minimizing unnecessary power consumption in compensating for radial forces (Xiang et al., 2022).

4.3 DECOUPLING METHODS BETWEEN LEVITATION FORCE AND TORQUE

In bearingless motors, electromagnetic torque and levitation force are often coupled, which can generate instabilities in the control and reduce the efficiency of the magnetic suspension (Zhou et al., 2021). Therefore, decoupling strategies between radial force and torque can ensure better system performance (Zhu et al., 2020).

4.3.1 Use of separate windings for torque and radial force control

Allowing greater precision in the control of magnetic levitation without interfering with the torque (Zhu et al., 2021a);

4.3.2 Magnetic flux modulation

Techniques that use Halbach arrays of permanent magnets to redirect the magnetic flux in order to minimize interference between torque and magnetic suspension force (Xiang et al., 2023);

4.3.3 Vector control with dynamic decoupling

Algorithms that dynamically adjust the magnetic flux vectors to automatically compensate for radial disturbances without affecting the torque (Yang et al., 2021);

4.4 MATHEMATICAL MODELS AND COMPUTATIONAL SIMULATIONS

The analysis of control strategies for bearingless motors is performed through computational simulations based, for example, on the Finite Element Method (Liu et al., 2022; Yuan et al., 2020) and Equivalent Magnetic Networks (Zhu et al., 2021b; Yang et al., 2022). These models perform functions such as: 1) Analyzing the behavior of the magnetic flux in the rotor and stator. 2) Analyzing the distribution of radial magnetic levitation forces and electromagnetic rotation torque. 3) Identifying possible instabilities for optimizing control parameters (Xiang et al., 2022).

4.4.1 Finite Element Method

The Finite Element Method is one of the most widely used techniques, allowing for a detailed analysis of the magnetic field distribution and losses in bearingless motors (Zhou et al., 2021; Yang et al., 2023). This method enables: 1) Simulation of different motor topologies and obtaining their dynamic responses (Sun et al., 2017). 2) Prediction of thermal effects and eddy current losses.3) Optimization of rotor and stator geometry to maximize efficiency (Yang et al., 2021).

4.4.2 Equivalent Magnetic Networks

Modeling using Equivalent Magnetic Networks allows for a more simplified approach to the analysis of magnetic suspension, being useful for optimizing the control of the radial levitation force in real time (Zhu et al., 2021a).

4.5 ENERGY EFFICIENCY AND STRUCTURAL OPTIMIZATION

The pursuit of greater energy efficiency combined with greater structural robustness in energy storage systems with flywheels coupled to bearingless motors has become one of the main directions of current research.

To obtain optimized performance of these systems, with minimal losses and high stability, advances in magnetic optimization techniques, reduction of electromagnetic losses, and the development of more sophisticated structural models are necessary (Zhu et al., 2021b; Xiang et al., 2022).

Among the most promising approaches in this context are the use of Halbach arrays for magnetic flux optimization, strategies for mitigating eddy current and hysteresis losses, and the application of structural optimization methods based on Finite Element Simulations.

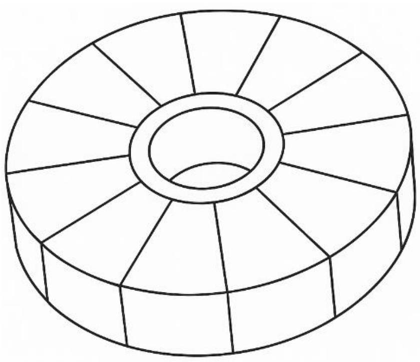
4.5.1 Use of Halbach Arrays for Magnetic Flux Optimization

The Halbach array of permanent magnets is a magnetically optimized configuration that allows the projection of magnetic flux in a single direction, minimizing losses and increasing the useful flux density in the air gap (Zhu & Lu, 2016). For the application in question, Halbach arrays provide significant benefits, such as: 1) Increased magnetic efficiency, reducing magnetic flux dispersion and increasing magnetic suspension force and rotational torque. 2) Reduction in rotor weight and volume, allowing the use of more compact structures without compromising performance. 3) Reduction of eddy current losses, since the external magnetic field is minimized, reducing induced currents in nearby metallic components;

In addition, the application of Halbach arrays contributes to improving thermal stability by minimizing heat concentration points caused by dispersive fluxes, which is interesting in high-speed systems (Xiang et al., 2023). Figure 3 shows an illustrative example of a stator of a six-pole machine in a Halbach array. Figure 4 shows the respective magnetic field orientations of each magnet in this machine.

Figure 3

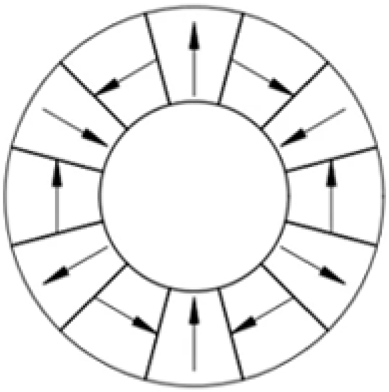
Representation of a stator of a six-pole machine in a Halbach arrangement



Source: authors.

Figure 4

Orientation of the magnetic field in each stator magnet of a six-pole machine



Source: authors.

4.5.2 Strategies for Mitigating Eddy Current and Hysteresis Losses

Eddy current and magnetic hysteresis losses are significant sources of energy dissipation, directly affecting the overall efficiency of the system (Zhou et al., 2021).

These losses occur mainly: 1) In the ferromagnetic cores of the stator and rotor, due to the temporal variation of the magnetic field. 2) By induction of electric currents in metallic parts close to the dispersed magnetic flux.

To mitigate such losses, several strategies have been implemented, including: 1) Use of materials with high electrical resistivity and low magnetic losses in the construction of the motors, such as iron-silicon alloys and grain-oriented steels, which reduce eddy currents (Zhu et al., 2021a). 2) Optimization of the operating frequency, reducing the temporal variation of the flux and, consequently, the intensity of hysteresis losses (Sun et al., 2018b).

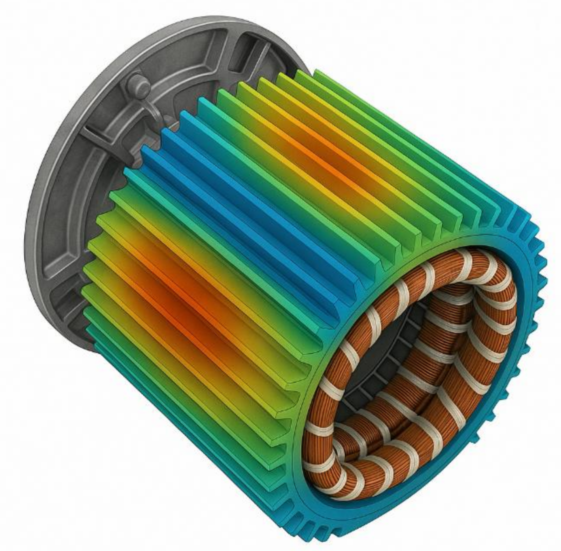
4.5.3 Structural Optimization Techniques via Finite Element Simulations (FEM)

The Finite Element Method is one of the main simulation tools used in the electromagnetic, thermal, and structural modeling of bearingless motors (Zhu et al., 2021b; Zhu et al., 2023). This technique allows: 1) Analyzing the magnetic field distribution, identifying regions of saturation or low magnetic efficiency. 2) Evaluating the structural impact of centrifugal forces at high rotation speeds, in order to analyze the mechanical integrity of the rotor and stator during continuous operation. 3) Predicting the thermal behavior of the components, allowing for the adequate sizing of heat dissipation systems. 4) Optimizing the geometry of the windings, the magnetic core, and the cooling channels, aiming to maximize power density and minimize losses.

Figure 5 shows an illustration of the application of FEM to the casing of an electric machine.

Figure 5

Application of the FEM method to the casing of an electric machine.



Source: authors.

FEM models are also used to test different combinations of materials, magnetic arrangements, and geometries in different motor topologies, without the need for constructing physical prototypes (Xiang et al., 2022).

Furthermore, the integration of FEM with numerical optimization algorithms and artificial intelligence has enabled the development of more efficient designs, allowing simulations that simultaneously consider energy efficiency, thermal stability, and structural resistance (Zhu et al., 2021b).

4.6 IMPACT OF ECCENTRICITY, VIBRATION, AND THERMAL PERFORMANCE

High-speed rotation regimes pose significant challenges to stability and reliability, especially with regard to rotor eccentricity, electromagnetic vibrations, and thermal dissipation. These factors, when not properly controlled, can compromise system performance, induce premature failures, or reduce energy efficiency (Zhu et al., 2021a; Xiang et al., 2022; Zhu et al., 2022). A deeper understanding of the causes and effects of these variables is therefore essential for the development of more robust and reliable solutions.

4.6.1 Effects of Rotor Eccentricity on Stability

Rotor eccentricity occurs when there is a displacement between the center of mass and the geometric center of the rotor, generating unbalanced radial forces during rotation. This condition is particularly critical in flywheel systems, where the rotor operates at very high speeds, increasing the risk of rotodynamic instabilities (Xiang et al., 2022).

There are two main types of eccentricity: 1) Static eccentricity, characterized by a fixed displacement of the rotor axis. 2) Dynamic eccentricity, in which the rotor axis describes an orbital movement around the stator.

The effects of eccentricity include: 1) Increased vibration. 2) Reduction of the effective levitation force, compromising the magnetic suspension of the rotor. 3) Possible collisions between rotor and stator, leading to operational failures or possible structural damage (Zhu et al., 2021b).

To reduce such effects, the literature proposes the use of high-resolution position sensors, predictive control algorithms, and active feedback systems capable of compensating for variations in rotor positioning in real time (Yang et al., 2021).

4.6.2 Thermal Analysis Methods and Heat Dissipation Strategies

The thermal performance of bearingless motors is a critical factor in flywheel applications, as continuous high-speed operation generates heat in the stator windings, permanent magnets, and power electronic components (Zhou et al., 2021). Heat accumulation, if not adequately dissipated, can: 1) Demagnetize permanent magnets. 2) Reduce the dielectric strength of the winding insulation.

Several thermal analysis methods have been used in the literature, including: 1) Computational models via the Finite Element Method, which allow mapping the temperature distribution in critical components (Zhu et al., 2021b). 2) Simplified models using Equivalent Thermal Networks, which represent the system as a thermal resistance circuit for rapid heat exchange simulations (Xiang et al., 2022).

The most effective thermal dissipation strategies cited in the literature are: 1)Insertion of forced ventilation channels or the use of liquid cooling systems. 2) Use of materials with high thermal conductivity, such as aluminum and graphene-based composites. 3) Use of thermal coatings and insulating barriers that prevent heat conduction to sensitive components;

4.6.3 Influence of Electromagnetic Vibration on System Reliability

Electromagnetic vibration in bearingless motors is caused by the forces of attraction and repulsion between the magnetic fields of the stator and rotor, especially in the presence of asymmetries or variations in the air gap.

The impacts of these vibrations are significant because they: 1) Cause acoustic noise and increased energy consumption, reducing overall efficiency. 2) Negatively affect the performance of the active magnetic suspension, requiring constant compensations from the control system (Xiang et al., 2023). To mitigate these vibrations, the literature proposes: 1) Implementation of decoupled vector control, which independently regulates the rotational torque and the radial levitation force. 2) Application of real-time adaptive strategies, based on machine learning, to adjust operating parameters in response to detected vibrations (Yang ; Tao, 2021).

This phenomenon can also be amplified by: 1) Torque ripple in switched reluctance motors. 2) Mechanical eccentricity and dynamic unbalance. 3) Interference between the torque and magnetic levitation vectors.

4.7 APPLICATIONS AND FUTURE PERSPECTIVES

The design of flywheel energy storage systems coupled with bearingless motors significantly expands the potential for applying this technology in strategic sectors that require high power density, operational robustness, and rapid dynamic response. Recent literature highlights the technical feasibility and operational benefits of these systems applied in electrical systems, electric vehicles, and aerospace applications, as well as promising future applications related to their integration with new storage technologies (Zhou et al., 2021; Yang ; Tao, 2021).

4.7.1 Applications in Electrical Systems

In electrical power distribution systems, flywheel systems are being used for frequency stabilization and reactive power compensation in smart grids, offering support in situations of abrupt load variations.

Due to their high charge and discharge capacity, with response times of less than milliseconds, they are also suitable for short-term energy storage applications in distribution systems.

Furthermore, their integration into hybrid electricity generation systems from intermittent renewable sources, such as solar and wind power, significantly contributes to balancing supply and demand, promoting greater stability in the generation system (Yang ; Tao, 2021).

4.7.2 Applications in Electric Vehicles

In the automotive sector, especially in electric and hybrid vehicles, flywheels are being applied as a means of recovering and redistributing kinetic energy during regenerative braking. This application reduces the demand on chemical batteries, improves the energy efficiency of the vehicle, and contributes to increasing the lifespan of the traction systems (Zhou et al., 2021; Zhou, et al., 2021).

4.7.3 Applications in Aerospace Systems

In the aerospace industry, flywheel systems with bearingless motors have been studied for energy storage and altitude control in satellites and spacecraft. The absence of mechanical friction allows for prolonged operation in microgravity environments with minimal maintenance requirements. Furthermore, the ability to generate torque by varying the rotational speed of the flywheel allows for precise control of the spacecraft's orientation without the need for thrusters, resulting in savings in mass and fuel (Circosta et al., 2018).

4.7.4 Fault Tolerance and Robustness in Extreme Environment

Application in harsh operating environments, such as space, marine environments, or high-vibration industrial zones, requires high tolerance to disturbances, failures, and thermal and mechanical robustness. In this context, bearingless motors offer superior advantages compared to conventional motors, since they:

1) Operate reliably in vacuum, radiation, or thermal extremes;
2) Possess active self-correction capabilities for position, via vector control and sensor feedback, which guarantees stability even in the event of partial failures (Xiang et al., 2022).

4.7.5 Future Perspectives

The future of flywheel systems points to a possible integration with other emerging energy storage technologies, forming possible hybrid architectures that combine the strengths of each technology. Among the possibilities for integration, the following stand out:

1) Combination with lithium-ion batteries or supercapacitors, where the flywheel system acts as a power buffer, relieving peak loads and extending the life of the electrochemical systems;
2) Integration with hydrogen and fuel cell systems, where the flywheel system provides immediate power during start-up or operational transition periods (Zhou et al., 2021);
3) Application in data centers and critical infrastructure, such as UPS (Uninterruptible Power Supply), providing instant power during voltage drops until the main generators are activated;

In addition, the literature points to the development of intelligent energy management systems, capable of coordinating flows between multiple sources and storage systems in real-time, based on machine learning algorithms and predictive optimization (Yang et al., 2021).

4.8 DISCUSSIONS

The main findings of this review include:

1) In Bearingless Switched Reluctance Motors (BSRM): the literature indicates that advanced control strategies, such as Predictive Current Control and Pulse Width Modulation (PWM) technique can reduce torque ripple and improve dynamic.
2) In Bearingless Permanent Magnet Synchronous Motors (BPMSM)*:* Recent research has explored structural optimization techniques, such as Halbach arrays of permanent magnets to improve magnetic flux distribution and reduce thermal losses in these motors.
3) The evolution of bearingless motor topologies, with emphasis on switched reluctance motors, permanent magnet synchronous motors, and hybrid magnetic excitation

motors, each presenting compromises between energy efficiency, structural robustness, and control complexity (Zhou et al., 2021; Yang et al., 2021);

4) The incorporation of advanced control strategies, such as direct torque control, predictive current control, and the use of artificial intelligence, has promoted greater rotodynamic stability, precision in magnetic suspension, and a reduction in torque ripple losses (Sun et al., 2018a; Zhu et al., 2021a);
5) The use of Halbach arrangements, high electrical resistivity materials, and computer simulations have contributed significantly to the mitigation of eddy current losses, hysteresis, and thermal effects, resulting in significant efficiency gains (Zhu ; Lu, 2016; Xiang et al., 2022);
6) Flywheel systems with bearingless motors show concrete potential for application in smart grids, electric vehicles, and aerospace missions, due to their high power density, low maintenance, and fast dynamic response (Yang & Tao, 2021; Circosta et al., 2018).

Although the results obtained show technical progress on several fronts, the consolidation of these systems as widespread energy solutions still requires progress in several aspects. We therefore recommend: 1) Investing in robust experimental validations, especially in real operating environments, to corroborate the results obtained by simulations and computer models; 2) Improve control strategies so that operating parameters can be adjusted dynamically in response to variations in load, vibration, and temperature;3)Explore hybrid storage architectures, to complement different technologies; 4) Expanding studies into the reliability of long-term use; 5) Carry out detailed economic analyses of financial viability, maintenance costs, and return on investment, which are fundamental aspects for greater reliability in industrial adoption. These gaps represent opportunities for future research aimed at contributing to the technological and commercial maturity of flywheel systems with bearingless motors.

5 CONCLUSIONS

This article examines energy storage based on flywheels (FESS), which has been widely studied as a possible high-efficiency, reliable solution for various applications, including power grids, renewable energy generation systems, and aerospace systems. These systems operate by converting electrical energy into rotational kinetic energy, which is stored in a rotor that rotates at high speed. When needed, this energy is converted back into electricity using a reversible electric machine coupled to the flywheel shaft, which can operate as a motor or a generator, enabling a fast and efficient dynamic response. The search for scientific articles was conducted across high-impact databases, ensuring access to relevant publications in the field. The following databases were consulted: 1)IEEE: A reference in the field of electrical and electronic engineering; 2) Scopus: A multidisciplinary database that aggregates engineering articles; 3) Web of Science: A consolidated platform for analyzing academic impact and emerging trends. The main control methods for magnetic suspension and torque, and their advantages and disadvantages, were studied. On the other hand, the study of Direct Torque Control was widely used in bearingless motors, as it allows rapid adjustments to the system's dynamic response, reducing torque fluctuations and optimizing the efficiency of magnetic suspension; respective comparisons were made. Analysis of control strategies for bearingless motors was performed through computer simulations. To achieve optimized performance of these systems with minimal losses and high stability, advances in magnetic optimization techniques, reductions in electromagnetic losses, and the development of more sophisticated structural models were necessary. Rotor eccentricity occurs when the center of mass and the geometric center of the rotor are displaced, generating unbalanced radial forces during rotation. This condition is particularly critical in flywheel systems, where the rotor operates at very high speeds, increasing the risk of rotodynamic instabilities. The thermal performance of bearingless motors has been a critical factor in flywheel applications, as continuous high-speed operation generates heat in the stator windings, permanent magnets, and power electronic components. A systematic review was conducted, presenting a critical analysis of current energy storage systems that utilize flywheels coupled to bearingless motors, focusing on machine configurations, control methods, structural refinement, energy performance, mechanical integrity, thermal effects, and new applications. This study synthesized the main technological advances of the last decade and highlighted unresolved issues that offer opportunities for future research to improve and expand the global adoption of this technology. The results reveal significant progress in the development of these systems, demonstrating that, when designed with optimized structures and appropriate control strategies, flywheels associated with bearingless motors show great potential as an energy storage solution. The review study is very promising and points to the potential integration with other emerging energy storage technologies, forming hybrid architectures that combine the strengths of each technology.

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