Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Soft Magnetic Material Core in PMSM: A Comprehensive Review

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ABSTRACT

This systematic literature review examines the widespread utilization of Soft Magnetic Material (SMM) cores in Permanent Magnet Synchronous Motors (PMSM). The objective is to present a thorough summary of the existing research in this area, emphasizing notable progress, obstacles and potential avenues for further exploration. The rising demand for energy-efficient motors has spurred the adoption of PMSMs with SMM cores. However, a lack of consolidated understanding hampers progress. Employing the PRISMA approach, this study systematically searched academic databases like Scopus and the Institute of Electrical and Electronics Engineers (IEEE), amassing a comprehensive collection of (n=29) relevant studies, reviews and articles concerning soft magnetic composites in PMSM cores. Advanced keyword searches employing terms such as "soft magnetic material," "PMSM," and "core" revealed the crucial role played by soft magnetic composites in enhancing PMSM efficiency. The findings were categorized into key themes encompassing magnetic motor design and analysis, energy storage, electromagnetic systems and analytical modelling. The review highlights the importance of SMM cores in boosting the performance of PMSMs. This enhancement encompasses improvements in efficiency and power density and it sheds light on critical factors such as SMM materials, manufacturing methods and design considerations. Furthermore, it discusses challenges, including core losses and material expenses. In summary, this thorough review underscores the crucial role played by SMM cores in the advancement of efficient PMSMs, providing valuable insights into material choices, production techniques and design optimization. Despite advancements, challenges in minimizing core losses and reducing material costs persist, warranting future research to focus on innovative approaches for enhancing the application of SMM cores in PMSMs, contributing to sustainable energy solutions.

Keywords:
Soft magnetic material; PMSM; core design; motor efficiency; electromagnetic properties

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https://doi.org/10.37934/araset.64.2.3046

1. Introduction

Permanent Magnet Synchronous Motors (PMSMs) have evolved into a crucial technology with widespread applications in electric propulsion, renewable energy generation and industrial automation due to their superior efficiency, high power density and precise control capabilities as highlighted by Singh *et al.,* [1] and Ma *et al.,* [2]. Amidst the often-celebrated aspects of PMSMs, such as their permanent magnet strength and winding design, the SMM core remains an unsung hero that significantly influences performance, as noted by Fang *et al.,* [3]. This comprehensive review aims to illuminate the essential role played by the soft magnetic material core in PMSMs by delving into its various aspects and exploring recent developments in the field.

The choice of core materials, including iron, iron-silicon alloys, nickel-iron alloys and amorphous metals, profoundly affects the motor's efficiency and magnetic performance, as articulated by several authors [4-6]. Exploring these materials and their core properties, such as saturation magnetization, permeability and hysteresis losses, is critical, with Table 1 exemplifying common electrical machine core materials like Soft Magnetic Composite (SMC).

Table 1
Common electrical machine core materials Krings *et al.,* [4]

Material type	Material composition	Sheet thickness (mm)	Flux density at 0.8 ka/m (t)	Flux density at 2.5 ka/m (t)	Resistivity (μΩcm)	Material density (g/cm3)
CoFe	49% cobalt, 49% iron, 2% V	0.2–0.5	2.1	2.23	40	8.12
NiFe	40% nickel,60% iron	0.1–0.5	1.44	1.48	60	8.2
High-silicon-content SiFe	6.5% silicon, iron balanced	0.1–0.2	1.29	1.4	82	7.49
Thin non-oriented SiFe	3% silicon, 0.4% aluminium, iron balanced	0.1–0.3	1.15	1.63	52	7.65
Non-oriented SiFe	1-3% silicon, iron balanced	0.35–1	—	1.64	20-60	7.6-7.8
Amorphous iron	20% (silicon and boron), 80% iron	0.025	1.55	—	130	7.18
Soft magnetic composite	<1% lubrication, iron balanced	Substantial material	0.7	1.22	20000	7.57

Understanding how these properties impact motor design is essential. The shape and geometry of the soft magnetic core have far-reaching consequences, impacting magnetic flux distribution, cogging torque and core losses, as elucidated by Chai *et al.,* [7]. Different core shapes like E-core, U-core and segmented cores come with trade-offs in terms of design choices. It is vital to delve into these trade-offs and understand how they manifest in PMSM performance [8]. These innovations hold the potential to transform PMSM core design and performance significantly. Investigating these manufacturing breakthroughs and their potential impact is essential.

PMSM efficiency depends on regulating magnetic core losses like hysteresis and eddy currents, as underscored by multiple authors [9-11]. Delving into the sources of these losses and strategies to mitigate them through core material selection and design optimization is crucial. Additionally, understanding effective heat dissipation methods is vital to maintain motor performance. The utility of SMM in PMSMs extends beyond conventional applications. Emerging fields such as electric vehicles, wind energy and aerospace demand higher PMSM performance standards, as highlighted

in articles by Fang *et al.,* [3,12]. Investigating evolving trends and potential applications for SMM cores in next-generation PMSMs can provide valuable insights for researchers and engineers.

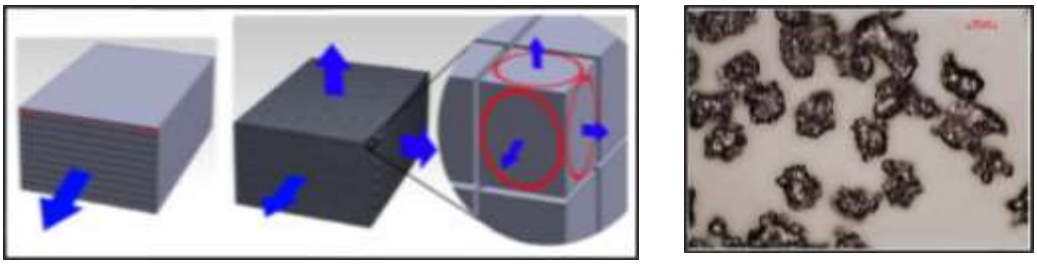
In conclusion, this comprehensive review is poised to serve as an invaluable resource within the realm of PMSMs. By exploring soft magnetic material cores in their entirety, including materials, design considerations, manufacturing innovations, loss mechanisms and future prospects, this review aims to contribute significantly to the advancement and optimization of PMSM technology. A deeper appreciation for the pivotal role of the soft magnetic material core promises more efficient and sustainable PMSM systems across a diverse range of applications.

2. Literature Review

Electrical steel magnetization depends on magnetic field direction, excitation frequency, mechanical stress and cut-edge impact. These elements affect machine design and numerical modelling. This article performs a comprehensive magnetic characterization of soft magnetic material, obtaining interpolation surfaces for a synchronous machine for an electric vehicle's traction drive. This methodology can improve electromagnetic circuit design by accurately determining local material properties and affecting global quantities like torque and losses, as detailed by Xiao *et al.*, [13]. This article emphasizes improved electromagnetic performance and presents four different slot/pole configurations tailored for traction applications spanning a wide speed range. It underscores a comparative analysis between soft magnetic composite (SMC) and laminated steel stators and the efficacy of a modified spoke-type rotor in conjunction with a segmented SMC stator core. In contrast to laminated motors, the SMC stator, as illustrated in Figure 1, offers both cost efficiency and a higher torque density per unit volume. The comprehensive design incorporates segmentation of the axial magnet, optimization of flux weakening techniques, examination of heat analysis and in-depth evaluation of rotor mechanical stress factors, as discussed by Muthusamy *et al.,* [14].

Fig. 1. SMC Stator elaborated by Muthusamy *et al.,* [14]

SMC presents an innovative approach to manufacturing magnetic components in electromechanical devices, primarily designed for small electric machines. These components are created by moulding distinct magnetic powders, effectively replacing conventional magnetic sheets. Researchers have explored the feasibility of achieving robust mechanical properties while preserving the magnetic characteristics found in commercial insulated iron powder compounds. The results of these efforts have been highly satisfactory, as indicated in Figure 2, where the basic structure and the use of ferromagnetic powder are demonstrated in the production of the suggested SMC. This suggests promising avenues for future development in this field, as demonstrated by Grande *et al.,* [15].



(a) Comparison lamination sheet 2-D and 3D structure (b) Ferromagnetic powder

Fig. 2. Basic structure (a) Ferromagnetic powder (b) was employed in the production of the suggested SMC, as detailed by Grande *et al.,* [15]

A PMSM based on an SMC architecture is described here. The Laplace equation is used to examine the model's magnetic field in the absence of a load across the air gap. The article solves the issue of unequal 3-D magnetic circuits and distortion by adding spherical-shaped pole shoes to the stator teeth. The study's theoretical framework aids in the structural optimization of the PMSM's core components using the Li *et al.,* [16]. This research thoroughly analyses the development and application of magnetic materials in electric machinery and motors. It includes a wide range of materials, from SMC and laminated steels to silicon-iron, nickel-iron and cobalt-iron amorphous and nanocrystalline magnetic materials. Also included is a discussion of the state of the art in the study of novel magnetic materials for use in electrical machines, emphasising recent advances and practical applications Krings *et al.*, [17].

This study proposes a refined 2D subdomain method for spoke-type permanent-magnet machines (STPMM). In a space that is generally Cartesian, it considers the magnetization orientation of the permanent magnet. The approach simplifies the solution of partial differential equations by using hyperbolic functions, non-homogeneous Neumann boundary conditions and interface conditions. The performance characteristics of STPMM are shown to be directly controlled by the magnetization angle of the permanent magnet (PM), as shown by comparison with a 2D finite-element analysis. This new model predicts electromagnetic performance in STPMM by including the magnetization direction and relative permeability of the soft magnetic material into a pseudo-Cartesian coordinate system, as detailed in the research by Jabbari *et al.,* [18]. This research examines the operational efficiency of an induction motor (IM), initially a 6-pole and 2-pole configuration, converted into a PMSM). While the stator remained unchanged, the rotor underwent conversion into a permanent magnet rotor. Efficiency assessment also entailed replacing the electrical steel in the stator with a different grade of material. The study unveiled a notable 14% efficiency improvement in the modified stator, as demonstrated by Hofman *et al.,* [19].

This work investigates the nonlinear magnetization behaviour of SMM as a function of frequency, which has important implications for energy loss and electrical machine performance. The study utilizes measured material properties across various frequencies and magnetic flux densities, aligning them with the operating parameters of the machine under analysis. Non-oriented electrical steel grades M330-35A and M330-50A, with varying magnetization and loss behaviour, explore nonlinear, frequency-dependent material features. The paper emphasizes the crucial importance of considering frequency dependence and saturation characteristics in ferromagnetic materials and their magnetic utilization during the simulation of electrical machines. The iron-loss model plays a pivotal role in exploring and understanding this influence, as presented by Ruf *et al.,* [20]

This paper explores how machining processes affect the material properties of electrical machines. It relies on three sources of data: information from material suppliers, traditional characterization techniques and test samples. The findings are then compared to create three variations of a high-performance aerospace electrical machine. The focus is on efficiency maps, which

are particularly responsive to manufacturing methods and the material's hysteresis in the B-H curve and core loss, as expounded by Al-Timimy *et al.*, [21]. This research presents the planning, development and analysis of a claw-pole permanent magnet motor with a moulded SMC core, which could replace the induction motor in a dishwasher pump. The analysed and designed motor uses the magnetic properties of the moulded SMC core, which were measured. Motor performance predictions are made using an improved phase variable model and key parameters are determined using finite element analysis, as outlined by Guo *et al.,* [22]. This study proposes a method for using a cell model to evaluate effective permeability and iron loss in SMC. This method accounts for eddy currents and nonlinear magnetic properties and investigates how frequency and particle size affect these characteristics numerically. Below 10 kHz, estimated iron losses agree well with observed values, demonstrating the method's theoretical validity, as detailed by Gao *et al.,* [23].

The development of new technologies and improvements in materials have led to an increase in the number of wind turbines that employ PMSM. SMC materials are increasingly used due to their cost-effectiveness and 3D flux paths. This investigation concentrates on the two-dimensional magnetic equivalent circuit (MEC) of PMSM machines and employs the finite element method for validation. The provided MEC model calculates machine performance using ideal slot/pole combinations. This type is useful for fractional slot direct drive synchronous generators, as conceived by Oner *et al.,* [24]. The paper explores the use of SMC material in electrical machines, specifically in PMSM. It compares three types of stators, focusing on magnetic properties, parameters and electromagnetic and electromechanical properties using the finite element method and is comprehensively documented by Cvetkovski *et al.,* [25] This paper examines an approach to cost reduction in variable speed drives that utilize high-efficiency permanent magnet motors, incorporating SMC and powder metallurgy technology. The emphasis is on electrical machine designs, drive techniques and material magnetic property measurement and modelling, as discussed by Zhu *et al.,* [26].

3. Material and Methods

In this systematic literature review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) technique serves as the cornerstone of the methodology for data collection. PRISMA's systematic and transparent approach ensures a rigorous and unbiased review process for comprehensively synthesizing past research studies related to the chosen topic. This section introduces the PRISMA framework, outlines the steps for study identification, selection and data collection, discusses inclusion and exclusion criteria for study robustness and touches upon data extraction and management procedures. The utilization of PRISMA, combined with stringent methodologies, facilitates a comprehensive analysis of the research topic.

3.1 Identification

The procedure of conducting a systematic review consists of three primary stages, each of which was used in order to select a number of applicable publications for this inquiry. The initial stage involves discovering keywords and exploring associated and related terms by utilizing thesauri, dictionaries, encyclopaedias and previous scholarly investigations. After carefully identifying all relevant phrases, keyword searches for the Scopus and IEEE databases were developed, as shown in Table 2. Initial results from the systematic review indicate that the current research effort is successful, with 1232 papers retrieved from both databases.

Table 2
The advanced keyword searches

Scopus	("soft magnetic material" OR "soft magnetic composite") AND (pmsm OR "permanent magnet synchronous motor") AND (LIMIT-TO (EXACTSRCTITLE, "IEEE Transactions On Magnetics") OR LIMIT-TO (EXACTSRCTITLE, "IEEE Transactions On Industrial Electronics") OR LIMIT-TO (EXACTSRCTITLE, "IEEE Transactions On Industry Applications") OR LIMIT-TO (EXACTSRCTITLE, "IEEE Transactions On Energy Conversion") OR LIMIT-TO (EXACTSRCTITLE, "IEEE Access") OR LIMIT-TO (EXACTSRCTITLE, "IEEE Transactions On Applied Superconductivity") OR LIMIT-TO (EXACTSRCTITLE, "IEEE Transactions On Transportation Electrification") OR LIMIT-TO (EXACTSRCTITLE, "IEEE Transactions On Power Electronics"))
IEEE	("soft magnetic material" OR "soft magnetic composite") AND (pmsm OR "permanent magnet synchronous motor")

3.2 Screening

During the preliminary screening process, redundant papers were eliminated. During the initial round, a total of nine articles were excluded. In the subsequent stage, 224 papers were subjected to a rigorous screening process, wherein a predefined set of inclusion and exclusion criteria were applied, as determined by the researchers. The main determinant for inclusion was research publications, as they offer the most pragmatic information. The analysis excluded many sorts of publications, including systematic reviews, reviews, meta-analyses, meta-syntheses, book series, books and chapters. Furthermore, the review specifically concentrated on scholarly articles that were authored in the English language. It is noteworthy to mention that the study encompassed a duration of seven years, spanning from 2017 to 2023. In order to adhere to the study objectives, only scholarly articles published in IEEE publications will be considered reliable sources. A total of 1008 papers were removed from the analysis per the specific criteria outlined.

3.3 Eligibility

In the third phase, referred to as the eligibility stage, a total of 215 articles have been compiled. The titles and main content of all papers were carefully examined to ensure that they met the inclusion criteria and aligned with the research objectives of the present study. Hence, a total of 186 reports were excluded from the analysis since they fell outside the parameters of the research topic under consideration. A total of 29 articles are currently accessible for examination, as indicated in Table 3.

Table 3
Choosing criteria for conducting advanced searches

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2017 – 2022	< 2017
Literature type	Journal (Article)	Letter, Note, Conference, Book, Review
Publication stage	Final	In Press
Publisher	IEEE	Beside IEEE

3.4 Data Abstraction and Analysis

An integrative analysis was employed as a means of assessment, with the aim of examining and synthesizing various research approaches, including qualitative, quantitative and mixed methods. The goal of the thorough examination was to identify relevant topics and subcategories. The first step in thematic development was data acquisition. Figure 3 depicts the authors' thorough examination

of a comprehensive collection of 29 publications, specifically focusing on statements or content pertaining to the present study's subject matter. The authors proceeded to assess the existing pertinent papers pertaining to the classification of cervical cancer cells. The investigation pertains to the methodology employed in all investigations, as well as the findings derived from the research. Subsequently, the author engaged in collaborative efforts with fellow co-authors to establish thematic frameworks derived from the empirical evidence within the specific setting of this study. A log was maintained during the data analysis process to document all analyses, perspectives, inquiries and other pertinent thoughts pertaining to the interpretation of the data. Ultimately, the writers conducted a comparative analysis of the results to identify potential discrepancies in the theme-creation process. Importantly, authors engaged in discussions among themselves in case of disparities between the notions. The generated themes were subsequently adjusted to achieve coherence. The analytical selection was conducted by two experts in the field of Electrical Engineering, namely Raja Nor Firdaus Kashfi, an expert in Applied Magnetic and Machine Design and Fairul Azhar, an expert in Electrical Machine Design. Their expertise was utilized to assess the veracity of the identified difficulties. The expert review step is responsible for assessing the clarity, significance and appropriateness of each subtheme by identifying its domain.

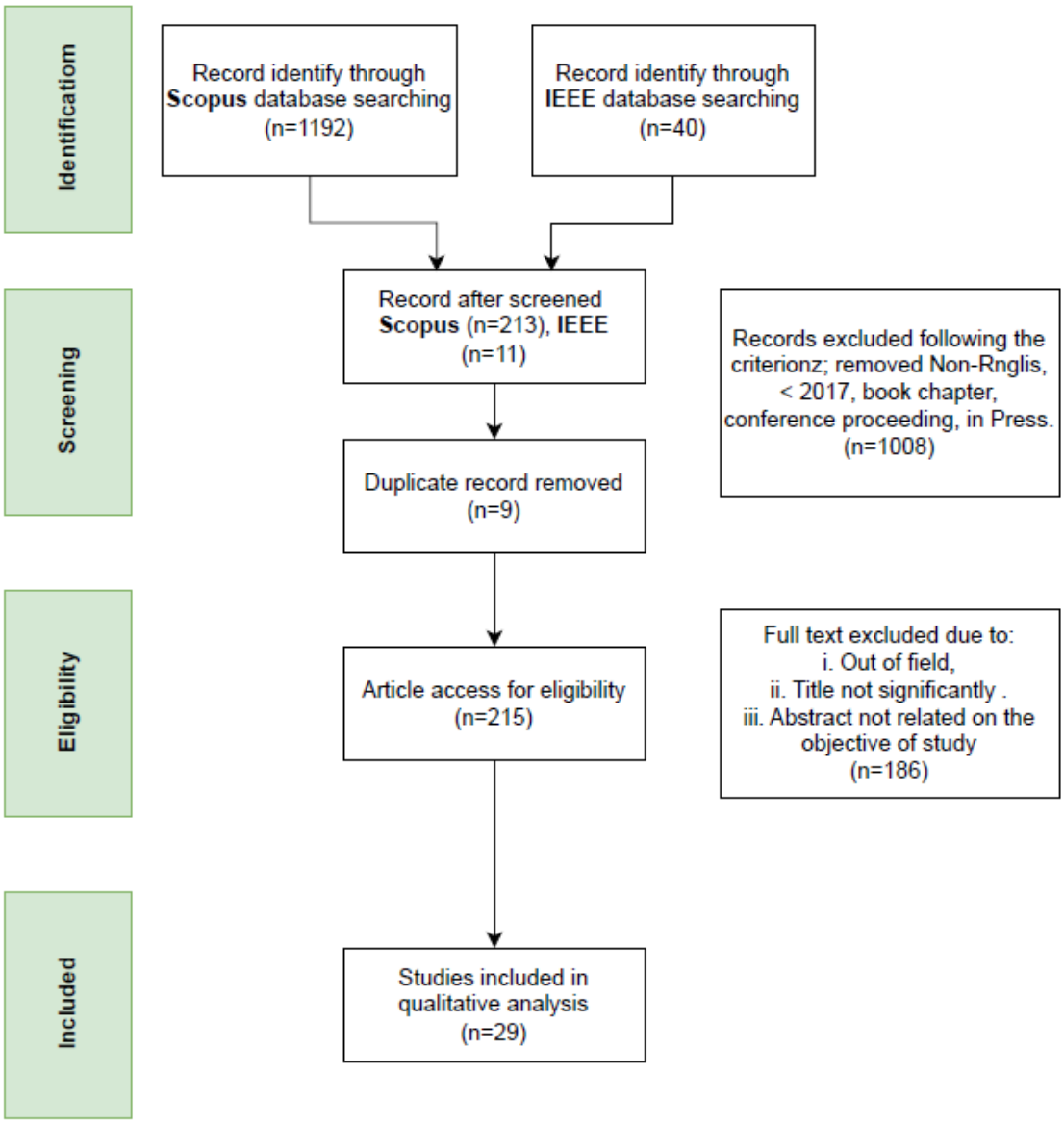


Fig. 3. Diagram illustrating the planned search study process

4. Result and Finding

By employing a meticulously crafted search strategy, a thorough investigation was carried out, involving the acquisition and examination of a total of twenty-nine (29) publications. These publications were subsequently categorized into three distinct groups, shedding light on various facets of our research endeavour. Among the topics covered within these publications are the Design and Analysis of Magnetic Motors, the exploration of Energy Storage and Electromagnetic Systems, as well as the nuanced realm of Analytical Modelling and Simulation of Magnetic Systems. These diverse areas collectively contribute to the richness and depth of our research.

4.1 Magnetic Motor Design and Analysis

This comprehensive study, centred on Magnetic Motor Design and Analysis, establishes a robust theoretical foundation for optimizing PMSM utilizing SMC cores. Table 4 provides a summary of the key findings and insights from this research on magnetic motor design and analysis. The investigation

involves a meticulous comparison between laminated steel and SMC stator structures, highlighting the trade-offs between torque and torque density, cost-efficiency and manufacturing feasibility. The research explores different facets of motor design, such as axial magnet segmentation, flux weakening, thermal analysis and rotor mechanical stress. It utilizes a computationally efficient quasi-3D analytical model that has been verified through finite element analysis (FEA). Additionally, the study emphasizes the critical impact of motor optimization, control strategies and switching frequencies on iron losses. It also explores novel stator structures, such as LWCPM and SWCPM, optimizing for torque capabilities and efficiency. The integration of SMC cores is demonstrated to significantly reduce core loss and enhance efficiency in bearingless disk motors, providing a compelling alternative to traditional solid iron cores. Furthermore, the research delves into electromagnetic circuit design, revealing the potential to improve magnetization behaviour using finite element simulations. The study also highlights the advantages of SMCs, acknowledging their drawbacks in magnetic properties compared to electrical steel. It concludes by proposing an operational range for AFPMs with electric steel cores. It introduces an innovative soft magnetic composite stator structure, validated through experiments, offering a promising avenue for enhancing axial force in magnetic motors. Overall, this study contributes valuable insights and methodologies for the design and analysis of magnetic motors, addressing key performance factors, materials and optimization techniques to advance the field.

Table 4
Summary of magnetic motor design and analysis

Reference	Research Scope	Method	Advantage and finding
[16]	Permanent Magnet Spherical Motor with SMC Core Magnetic Field Analysis	This article addresses magnetic field distortion by adding spherical pole shoes to stator teeth, increasing air-gap magnetic field distribution and developing a static torque measurement platform.	The structural optimization design of PMSM with SMC core is theoretically supported in this work.
[14]	Spoke-type PMSM with SMC Stator Core for Traction Applications	The article discusses four slot/pole configurations for traction applications, enhancing electromagnetic performance with a modified spoke rotor and segmented SMC stator core.	The study compares laminated steel and SMC stators, finding laminated motors have higher torque but lower torque density, while SMC motors are cheaper and more efficient.
[27]	Considering Magnetic Saturation, a new quasi-3D analytical model for axial flux motors	The paper presents a fast, quasi-three-dimensional (3D) analytical model for predicting magnetic fields in axial flux motors, simplifying the problem into a two-dimensional (2D) one.	The proposed quasi-3D analytical model, validated through nonlinear FEA, is computationally efficient and suitable for the preliminary design of AFMs.
[28]	Quasi-3-D Nonlinear Analytical Modelling of Axial-Flux Switched Reluctance Motor Magnetic Field	This article presents a quasi-3-D nonlinear AM method for predicting magnetic field distributions and electromagnetic performances of an AFSRM, comparing accuracy with FEM simulations and balancing accuracy and time cost.	The quasi-3-D nonlinear AM method effectively considers curvature, edge and saturation effects, making it suitable for performance predictions and parametric studies of AFSRMs.

[5]	An analysis of iron loss in axial flux permanent magnet synchronous motors with soft magnetic composite cores	This paper investigates iron losses in axial flux motors using soft magnetic composite material, proposing an analytical model, comparing optimized and non-optimized motors and analysing torque ripple and motor control schemes.	Motor optimization, control scheme and switching frequency significantly impact iron losses in a motor. Field Oriented Control and high switching frequency can vary iron losses by 14%.
[29]	New Permanent Magnet Claw Pole Machine Design and Analysis with S-Shape Winding	The article proposes a new S-shape winding CPM (SWCPM) to improve the linear winding CPM (LWCPM) performance, which has been extensively studied due to its improved magnetic and mechanical properties.	The LWCPM and SWCPM stator structures have been optimized for optimal torque capability, with SWCPM offering greater torque, power factor and efficiency, but its decreased flux weakening ability is a drawback.
[30]	Different Stator Core Materials for a Multi-Stage Axial Flux Permanent Magnet Machine	The paper presents a 3D finite element method-based analysis of a multi-stage axial flux permanent magnet machine, examining properties with various stator core materials.	FEM results indicate that three materials have a similar impact on various motor characteristics, except for core loss variations. A prototype featuring an SMC stator core is then fabricated.
[31]	Hybrid Axial-Flux Motor Design with 3D-Printed SMC Core	The paper presents a 3D-printed AFPMSM using high torque density, amorphous electrical steel sheet and a hybrid AFPMSM, comparing core loss to target RFPMSM.	The 3D-printed AFPMSM increased core loss by 48%, while the hybrid model reduced the electrical steel sheet ratio by over 25%, confirming its validity using the finite element method.
[13]	Soft Magnetic Material Magnetization Scalar Dependencies Modelling for Electrical Machine Finite-Element Simulation	This article explores the modelling and simulation of soft magnetic material, utilizing insights into magnetization amplitude, angle, mechanical stress and cut edge effect for electric vehicle traction drive.	This article presents a method for analysing local influences on the magnetization behaviour of electrical steel in a finite-element simulation, potentially enhancing electromagnetic circuit design.
[32]	Experimental study of soft magnetic composites for consequent-pole bearingless disk motor core loss reduction.	The paper explores the use of a soft magnetic composite (SMC) C-shaped stator core in reducing core loss in a consequent-pole bearingless disk motor.	The SMC core significantly reduces core loss and improves efficiency in bearingless disk motors with C-shaped stator cores, compared to solid iron's 3.8W core loss and 27% efficiency with solid iron.
[33]	Durable PM claw pole motor tolerance design optimization with soft magnetic composite cores	The paper presents a tolerance design optimization method for a permanent magnet claw pole motor, utilizing the six-sigma technique, Kriging model and 3-D thermal network model for high-dimensional electromagnetic and thermal performance optimization.	The proposed robust tolerance optimization method exhibits improved motor performance and diversity control without increasing costs, as per the analysis.
[34]	Axial Flux Permanent Magnet Synchronous Machines with Electrical Steel Core and Soft Magnetic Composite Core Comparison	The paper compares axial flux permanent magnet machines (AFPMs) with an electrical steel core and those with a soft magnetic composite (SMC) core.	The study reveals that an AFPM with an electric steel core performs well in the low-frequency range, improving with frequency increase and proposing an operation area.

[35]	An Active Axial Force Improvement Stator Structure for a One-Axis Actively Positioned Single-Drive Bearingless Motor	This paper introduces a novel stator structure in a 1-degree-of-freedom bearingless motor, regulating torque and active axial force independently with a single three-phase inverter.	A new stator structure, made of soft magnetic composites, has been designed to increase active axial force by 50%, as confirmed by experiments.

4.2 Energy Storage and Electromagnetic Systems

Within the field of Energy Storage and Electromagnetic Systems, this collection of research represents a substantial contribution by presenting a series of notable advancements. Table 5 succinctly summarizes the key findings and progress made in the realm of energy storage and electromagnetic systems as explored in this research collection. Notably, it showcases the successful fabrication and testing of a flywheel prototype, affirming the practical viability of theoretical analyses and achieving a commendable level of stability and reliability. The study also introduces the concept of an Advanced Flux Homopolar Electromagnet (AFHEM) with a comprehensive analysis highlighting its superior torque density and broader speed range, making it an appealing choice for Hybrid Electric Vehicle (HEV) drives. Furthermore, the research explores the promising potential of in-wheel motors for electric vehicles, emphasizing the need for specific design considerations to meet high-power density, low torque density and aspect ratio requirements. The incorporation of an innovative method that mitigates drawbacks related to mesh density and model complexity is particularly noteworthy. The study also highlights the accuracy of iron loss predictions across various operational scenarios, bolstering confidence in the computational toolchain's effectiveness, which combines multiple simulation approaches. The proposed equivalent circuit model for predicting core loss and motor performance under different conditions is another valuable contribution, validated through experimental measurements. This body of work pushes the boundaries of energy storage and electromagnetic system design and underscores the importance of rigorous experimental validation, ultimately advancing the field's knowledge and practical applications.

Table 5
Summary of energy storage and electromagnetic systems

Reference	Research Scope	Method	Advantage and finding
[36]	Large-Capacity Energy Storage Flywheel Electromagnetic System Research	A high-power flywheel energy storage system (FESS) is developed for wind farms, featuring efficient electromagnetic components like motor/generator, radial magnetic bearing and axial magnetic bearing, offering low power consumption.	The flywheel prototype is successfully fabricated and tested, confirming the theoretical analysis and achieving stable and reliable operation.
[37]	HEV drive axial flux hybrid excitation motor electromagnetic performance analysis	Hybrid electric vehicle drive machines utilize AFPM motors for high power density, efficiency and low iron consumption, with an extra DC excitation winding for improved constant power speed.	The AFHEM, according to a comprehensive analysis, offers a larger torque density and wider speed range, making it suitable for the use of HEV drives.
[38]	The Air-Cooled YASA Motor for in-wheel electric vehicles	A YASA topology axial field machine is devised for high aspect ratio needs. Heat-spreading components enhance heat dissipation and power density and nonplanar flux transport is accomplished using a soft magnetic composite material.	This article details the design, analysis, manufacturing and testing of in-wheel motors for electric vehicle design, focusing on high-aspect ratio, power density and low torque density.

[39]	Numerical Simulations Using Soft Magnetic Material Degradation	Using a simulation tool, the research proposes a numerical model for local degradation in soft magnetic materials during the cutting and punching processes of electric machines.	The proposed method avoids multilayer approaches' drawbacks, requiring finer mesh density and increased model complexity.
[40]	Improved Complex Flux Waveform Iron Loss Estimation with Generalized Dynamic Hysteresis Model	With the use of a flexible magnetic property measurement technique and better model considerations, this work presents a dynamic hysteresis model for estimating iron loss in complicated flux waveform	Experiments confirm that model parameters derived from symmetrical hysteresis loops provide accurate predictions of iron loss across different operational ranges.
[41]	Numerical Simulation of Electrical Machines with Advanced Soft- and Hard-Magnetic Material Models	The paper explores the Institute of Electrical Machines' modelling methods for soft and hard-magnetic materials in rotating machine simulations, utilizing a traction drive case and pyMOOSE solver for material degradation losses.	The computational toolchain combines simulation methods to get accurate findings over the operational spectrum.
[42]	An Equivalent Circuit Model for Predicting Claw-Pole Permanent Magnet Motor Core Loss with Soft Magnetic Composite Core	Using a precise finite-element method, the research predicts core loss in a claw-pole permanent magnet motor with an SMC stator core.	The suggested similar circuit model successfully predicts core loss and motor performance when loaded and unloaded.
[43]	Axial Flux Machine Iron Losses Calculation Based on Three-Dimensional FEA Results for One-Sixth Electrical Period	The paper explains how to calculate iron loss in an axial flux machine with a segmented armature structure using only a few 3-D finite element analysis findings.	The validity of the method is established by the utilization of the famous Bertotti formula for the determination of iron losses, which is applied to measure a prototype.
[44]	Application-oriented robust design optimization for batch permanent-magnet motor production	This research introduces a reliable approach for optimizing the design of permanent-magnet motors involving 18 high-dimensional multiphysics problems for domestic applications, focusing on applications, multiphysics analysis and uncertainty analysis.	Experimental and simulation results confirm the validity of the proposed models and methods.

4.3 Analytical Modelling and Simulation of Magnetic Systems

Within the domain of Analytical Modelling and Simulation of Magnetic Systems, this extensive body of research establishes a strong foundation for precisely computing electromagnetic performance across various core materials. These materials encompass grain-oriented silicon steels, non-oriented silicon steels, amorphous alloys and SMCs. Table 6 serves as a concise summary, capturing the essential insights and outcomes derived from this research into the analytical modelling and simulation of magnetic systems. The study leverages FEA techniques, demonstrating exceptional results and highlighting the adaptability of the proposed model for different core material types. Furthermore, it introduces an insightful examination of manufacturing impact sensitivity, shedding light on the relationship between design changes and manufacturing considerations. This study also delves into the interplay between torque components and model parameters, emphasizing their critical influence on torque calculation accuracy. Notably, the research extends its practical applications to the development of improved subdomain methods for predicting electromagnetic performance in Dual Rotor Magnetic Wave Machines (DRMWMs), showcasing their potential for Hybrid Electric Aircraft (HEA) applications. Validating the model with experimental data and confirming motor performance with 3-D finite-element modelling strengthens the study's

contributions. In summary, this research significantly advances the analytical modelling and simulation of magnetic systems, offering valuable insights into core material adaptability, manufacturing considerations and performance prediction, with clear implications for diverse applications in the field of electromagnetic engineering.

Table 6
Summary of analytical modelling and simulation of magnetic systems

Reference	Research Scope	Method	Advantage and finding
[45]	Dynamic Hysteresis Modelling for Magnetic Circuit Analysis and Validation for Core Materials with Skin Effect	The article introduces a new magnetic circuit model that considers skin effect and dynamic hysteresis characteristics, making it simpler and more practical for complex devices like electric motors.	Experimentally shown model's computation accuracy and adaptability for grain-oriented (GO) and non-oriented (NO) silicon steel ring cores, an amorphous alloy and a soft magnetic composite.
[46]	Exact Subdomain 2-D Semi-Analytical Magnetic Field Calculation for Flat Permanent-Magnet Linear Machines	Slotted synchronous machines with surface-mounted magnets provide a linear solution for flat linear electromagnetic devices under no-load and armature current circumstances.	The developed technique, known as finite-element analysis (FEA), has shown exceptional results.
[47]	Manufacturing Impact on Optimal Electric Machine Design and Performance	The article examines how manufacturing methods affect the design and performance of permanent magnet synchronous machines, with a focus on optimizing efficiency and reducing cogging torque.	The study evaluates manufacturing impact sensitivity in designs and explores changes in optimal design shape, suggesting future optimization for low-sensitivity performance.
[48]	Effects on Permanent Magnet Synchronous Machine Torque Calculation Accuracy	The study examines torque generation mechanisms, machine parameters, environmental conditions and two traction drive machine designs, evaluating machine torque through 2D magnetostatic Finite-Element simulations.	The study reveals the interplay between torque components and model parameters, emphasizing the impact of these parameters on torque calculation accuracy.
[49]	Double-Rotor Multiwinding Machine Analytical Modelling for Hybrid Aircraft Propulsion	The DRMWM (Double-Rotor Multiwinding Machine) is a novel electric machine specifically created for hybrid electric aircraft. It makes use of flux modulation principles and an enhanced subdomain method to optimize the distribution of magnetic fields within the machine.	The article introduces an enhanced subdomain method for DRMWMs, focusing on electromagnetic performance prediction and its applicability in diverse operational modes for Hybrid Electric Aircraft (HEA)
[50]	Modelling and Measuring Soft Magnetic Composite Material Magnetic Hysteresis under Different Magnetizations	This work describes operator density in SMC materials' response to alternating and rotational magnetic excitations using a vectorial elemental operator and distribution function.	Compare the computed magnetic hysteresis of SMC material with experimental results from a three-dimensional magnetic property measurement equipment to verify the model's validity and applicability.

[51]	Permanent Magnet Motor Multilevel Design Optimization Methods	The paper outlines a multilevel optimization strategy for electrical machines and drive systems, primarily aiming to optimise permanent magnet claw-pole motors to reduce material costs while maximizing power output.	Experimental results verify motor performance using a 3-D finite-element model, demonstrating simple implementation techniques and multilevel optimization framework, improving performance and reducing finite-element analysis sample number.

4. Conclusion

In summary, these three thematic areas of research collectively advance the field of electromagnetic engineering. The first theme, Magnetic Motor Design and Analysis, offers valuable insights into optimizing PMSMs with SMC cores, emphasizing efficiency gains, novel stator structures and the reduction of core losses. The second theme, Energy Storage and Electromagnetic Systems, demonstrates practical viability in flywheel prototypes, introduces advanced electromagnets for hybrid vehicles and underscores the importance of rigorous experimental validation for system design. The third theme, Analytical Modelling and Simulation of Magnetic Systems, provides a robust foundation for accurately computing electromagnetic performance across diverse core materials, with implications for various applications. Together, these studies contribute to the ongoing evolution of electromagnetic engineering, offering innovative solutions, theoretical foundations and practical validation methods to propel the field forward.

Acknowledgment
This research was not funded by any grant.

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