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Modern electric motors: A review of sustainable design and maintenance principles: scrutinizing the latest trends focusing on motor efficiency, sustainability, recyclability, and reduced maintenance

Abimbola Oluwatoyin Adegbite [1], Chinedu Nnamdi Nwasike [2], Nwabueze Kelvin Nwaobia [3], Joachim Osheyor Gidiagba [4, *], Oseluole Tobi Enabor [5], Samuel Onimisi Dawodu [6], Adedayo Adefemi [7] and Chinedu Alex Ezeigweneme [8]

[1] *IHS Towers Nigeria Plc, Nigeria.*
[2] *High Auto Maintenance Services, Port-Harcourt, Nigeria.*
[3] *Feratto Industries Limited, Aba, Nigeria.*
[4] *Department of Mechanical and Industrial Engineering, University of Johannesburg, South Africa.*
[5] *Department of Electrical and Electronics Engineering, University of Johannesburg, South Africa.*
[6] *Nigeria Deposit Insurance Corporation, Nigeria.*
[7] *Chevron Nigeria Limited, Nigeria.*
[8] *MTN Nigeria.*

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Abstract

This study presents a comprehensive review of the current state and advancements in sustainable electric motor design, focusing on aspects of efficiency, sustainability, recyclability, and maintenance. The research employs a systematic literature review methodology, analyzing peer-reviewed articles, conference papers, and academic theses from the past decade. The aim is to synthesize existing knowledge and identify trends, challenges, and opportunities in the field of electric motor technology, particularly in the context of environmental sustainability and technological innovation. Key findings highlight a significant shift from conventional motor designs to more energy-efficient and environmentally friendly models. The study reveals advancements in the use of sustainable materials, innovative manufacturing processes, and the integration of cutting-edge technologies to enhance motor efficiency. The importance of recyclability and effective maintenance strategies in extending the lifecycle of electric motors is also emphasized, alongside the critical role of international standards and regulations in shaping industry practices. The future landscape of electric motor technology is marked by both challenges and opportunities, with technological advancements paving the way for further improvements in efficiency and sustainability. However, the need for more sustainable materials, improved recycling processes, and adaptation to evolving regulatory landscapes presents ongoing challenges. The study concludes with recommendations for industry leaders and policymakers, emphasizing the need for continuous investment in research and development, embracing circular economy principles, and fostering collaboration between various stakeholders. Future research directions are suggested, focusing on exploring new materials and technologies, developing standardized methods for environmental impact assessment, and promoting effective recycling and maintenance strategies. This comprehensive review serves as a valuable resource for stakeholders in the electric motor industry, providing insights and guidance for future developments in sustainable electric motor technologies.

Keywords: Electric Motor Design; Energy Efficiency; Recyclability; Maintenance; Motor Technology

* Corresponding author: Joachim Osheyor Gidiagba.

1. Introduction

1.1. The Emergence of Modern Electric Motors in Sustainable Engineering

The evolution of modern electric motors marks a significant stride in sustainable engineering, driven by the urgent need to address energy and environmental challenges (Bilgin and Emadi, 2014). This transformation is underscored by the shift towards high-efficiency induction motors, which are pivotal in minimizing energy loss and mitigating environmental impacts (Gheorghe et al., 2016). The development of these motors is regulated by efficiency standards, posing a continuous challenge for manufacturers to innovate and improve their designs.

Electric vehicles (EVs) have emerged as a primary focus in the quest for sustainable transportation, with electric motors playing a crucial role. The rapid advancement of the global automobile industry has brought energy and environmental issues to the forefront, making electric vehicles a key direction for new energy development (Wu et al., 2021). This shift is supported by the maturation of energy storage technologies, high efficiency of driving motors, and advanced control modes, positioning electric vehicles as the mainstay in the new energy vehicle sector.

The design of electric motors for EVs is a complex task, requiring a balance between high efficiency, high power density, wide speed regulation, and high overload capacity. The sine wave permanent magnet brushless motor, for instance, represents a significant innovation in this field. Its design involves intricate considerations like the selection of stator slots, winding design, and electromagnetic load parameters, all aimed at optimizing performance (Wu et al., 2021). These motors are designed to meet the stringent performance indices of pure electric vehicles, reflecting the industry's commitment to sustainable mobility.

The transition to sustainable electric motors is not just about technological innovation but also involves a paradigm shift in how we approach energy consumption and environmental impact. The normative framework for developing energy-efficient induction motors includes analyzing energy consumption during fabrication and operation, opening avenues for upgrading existing designs to more economical and environmentally friendly units (Gheorghe et al., 2016). This approach is crucial in reducing the carbon footprint and overall costs associated with electric motors, making them a cornerstone in sustainable engineering.

The emergence of modern electric motors in sustainable engineering is a response to global energy and environmental challenges. The focus on high-efficiency induction motors and innovations in electric vehicle motor design exemplifies the industry's commitment to sustainable development. These advancements are not only technological feats but also represent a broader shift towards a more sustainable and environmentally conscious approach to engineering.

1.2. Defining the Scope: Efficiency, Sustainability, Recyclability, and Maintenance

Modern electric motors are at the forefront of sustainable engineering, with their design and operation increasingly focused on efficiency, sustainability, recyclability, and maintenance. These aspects are crucial in addressing the environmental and energy challenges of our times.

Efficiency: The efficiency of electric motors is a critical factor in their overall sustainability. High-efficiency motors, typically operating with efficiencies between 80 and 90%, are increasingly sought after in various applications, from industrial machinery to electric vehicles (Kaya, Kılıç, & Öztürk, 2023). These motors are designed to maximize energy output while minimizing losses, often achieved through improved winding techniques, better materials, and more efficient rotor designs. The correct sizing of electric motors is essential, as motors reach maximum efficiency at 75–80% load and running them under low load can lead to overheating and reduced lifespan.

Sustainability: The sustainability of electric motors encompasses their entire lifecycle, from production to end-of-life management. Mayr et al. (2018) highlight the importance of considering the market, product, and process perspectives in assessing the sustainability of electric motors. This includes state-regulated efficiency classes, the range of motor types and their sustainability characteristics, and the energy and resource efficiency of manufacturing processes. The holistic view of these aspects ensures that electric motors contribute positively to environmental goals.

Recyclability: The end-of-life management of electric motors is gaining attention, with a focus on recycling and the circular economy. Tiwari et al. (2021) emphasize the importance of developing strategies for the high-value materials in electric motors, noting that recycling is a key area of research. However, reuse, which ranks higher in the waste hierarchy, is less explored due to challenges in assessing the condition and availability of returned products. This highlights the need for more research and development in the recyclability and reuse of electric motor components.

Maintenance: Maintenance plays a vital role in the sustainability of electric motors. Efficient maintenance strategies can significantly extend the life of a motor, thereby reducing its environmental impact. Konovalov et al. (2023) discuss the advancements in cooling systems for electric motors, which are crucial for maintaining operational efficiency and reliability. These developments include air and liquid cooling systems, which are essential for managing the temperature distribution in motors and thus enhancing their performance and longevity.

The scope of modern electric motors in sustainable engineering is broad, encompassing efficiency, sustainability, recyclability, and maintenance. Each of these aspects plays a crucial role in the design, operation, and end-of-life management of electric motors, contributing to the overarching goals of sustainable development and environmental conservation.

1.3. Historical Evolution of Electric Motors: From Conventional to Sustainable Models

The historical evolution of electric motors, from their conventional forms to modern sustainable models, is a narrative of technological innovation and environmental consciousness. This journey reflects the changing priorities in engineering and manufacturing, with a growing emphasis on efficiency, sustainability, and environmental impact.

The inception of electric motors dates back to the 19th century, with the pioneering work of inventors like Michael Faraday and Nikola Tesla. These early motors were primarily direct current (DC) machines, used in small-scale applications due to their simplicity and ease of control. However, their limited power output and efficiency made them unsuitable for large-scale industrial use.

The introduction of alternating current (AC) motors, particularly induction motors, marked a significant advancement in the field. These motors, developed by Tesla and others, offered higher power and efficiency, making them ideal for industrial applications. The widespread adoption of AC motors was facilitated by the development of the power grid, which provided a reliable source of alternating current.

The focus on efficiency gained momentum in the late 20th century, driven by the growing awareness of energy conservation and environmental impact. This led to the development of high-efficiency motors, such as the six-phase induction motor, which offers improved torque and reduced losses compared to traditional three-phase motors (Francis et al., 2018). These motors are particularly beneficial in electric vehicle propulsion, contributing to sustainable transportation.

The 21st century has seen a shift towards more sustainable and intelligent motor designs. This includes the integration of advanced materials, innovative cooling systems, and smart control technologies. The use of rare-earth-free magnets, for instance, addresses the environmental and geopolitical concerns associated with rare-earth elements. Additionally, the incorporation of Internet of Things (IoT) and artificial intelligence (AI) technologies in motor control systems has led to more efficient and adaptive performance.

The role of electric motors in the evolution of electric vehicles (EVs) is pivotal. As the automotive industry moves towards sustainable transportation, electric motors have become the cornerstone of this transition. The development of efficient, high-torque motors for EVs is a key area of research, with significant advancements in motor design and control strategies (Bohnsack et al., 2013).

The historical evolution of electric motors from conventional to sustainable models is a testament to the progress in electrical engineering and technology. This evolution reflects the changing priorities of society, with a growing emphasis on efficiency, sustainability, and environmental responsibility.

1.4. Aim and Objectives of the Review

The primary aim of this study is to systematically review and analyze the current state and advancements in sustainable electric motor design. This includes evaluating the efficiency, sustainability, recyclability, and maintenance practices associated with modern electric motors, with a focus on their application in various industries, particularly in the context of environmental sustainability and technological innovation.

The objectives are to;

To explore current trends in motor efficiency including the design and operational factors that contribute to enhanced performance and energy savings.

- To explore the evolution of electric motor technology and the impact of sustainable electric motor technologies.
- To determine the challenges in current electric motor designs and potential solutions.

1.5. Significance of the Study

The significance of this study on sustainable electric motor design is multifaceted, encompassing environmental, technological, industrial, and policy-related impacts. It provides a comprehensive analysis of the current state and advancements in electric motor technology, with a focus on sustainability, efficiency, recyclability, and maintenance. This research is crucial in the context of global environmental challenges, as electric motors play a pivotal role in various industries. By highlighting sustainable design principles and the latest technological innovations, the study contributes to the reduction of environmental impact and promotes energy conservation. It serves as a valuable resource for manufacturers and industry stakeholders, offering insights that inform better design, production, and maintenance practices aligned with sustainability goals. Additionally, the study's findings offer a framework for policymakers, guiding the development of regulations and standards that support the use of sustainable electric motors. The identification of gaps and future research opportunities within the study is vital for academics and researchers, directing efforts towards areas with the most significant potential impact. Furthermore, by addressing recyclability and maintenance strategies, the study aligns with the principles of the circular economy, emphasizing resource efficiency and lifecycle management in industrial processes. Overall, the study's significance lies in its contribution to environmental sustainability, technological advancement, and the provision of practical guidance for industry and policy, making it an essential resource for stakeholders in the field of electric motor technology.

2. Methodology

2.1. Research Design for Analyzing Sustainable Electric Motor Design

The research design for analyzing sustainable electric motor design is structured to systematically review and synthesize existing literature. This involves a comprehensive search strategy to identify relevant studies, followed by a critical appraisal of the identified literature. The focus is on studies that address various aspects of sustainable electric motor design, including energy efficiency, use of sustainable materials, manufacturing processes, and lifecycle analysis.

2.2. Criteria for Selecting Relevant Studies on Electric Motor Sustainability

The selection criteria for relevant studies are based on several key parameters:

- Relevance to Sustainable Design: Studies must focus on sustainable design aspects of electric motors, including energy efficiency, environmental impact, and use of renewable resources.
- Publication Date: Preference is given to studies published in from 2008 to 2023 to ensure the review incorporates the latest advancements and trends.
- Peer-Reviewed Sources: Only peer-reviewed journal articles, conference papers, and academic theses are considered to ensure the credibility and reliability of the information.
- Language: Studies published in English are primarily considered due to language proficiency constraints.

2.3. Data Collection and Analysis

2.3.1. Identifying Key Studies in Sustainable Electric Motor Design

Identifying Key Studies in Sustainable Electric Motor Design

- The identification of key studies involves:
- Database Search: Utilizing academic databases like IEEE Xplore, ScienceDirect, and Google Scholar to find relevant literature.
- Keyword Search: Employing specific keywords such as "sustainable electric motor design," "energy-efficient motors," "eco-friendly motor manufacturing," etc.
- Reference Tracking: Reviewing references of identified articles to find additional relevant studies.

2.3.2. Analytical Methods for Evaluating Motor Efficiency and Sustainability

The analytical methods include:

- Content Analysis: Thoroughly examining the content of selected studies to extract data on motor design, efficiency, sustainability practices, and technological innovations.
- Comparative Analysis: Comparing findings across different studies to identify common themes, trends, and gaps in the research.
- Quality Assessment: Evaluating the methodological quality of each study to determine the strength of the evidence presented.

3. Literature Review

3.1. Core Principles of Sustainable Electric Motor Design

The design of sustainable electric motors is guided by core principles that focus on efficiency, environmental impact, and long-term viability. These principles are essential in addressing the growing demand for eco-friendly and energy-efficient technologies in various sectors, including transportation and industrial applications.

The design of a 300W axial flux motor for an electric bike by Tung et al. (2021) exemplifies the principle of maximizing power density and efficiency. Their design utilizes axial-flux machine topology and Halbach-array to increase power density, while simplifying the manufacturing process and reducing core weight. This approach not only enhances the motor's performance but also contributes to its sustainability by reducing material usage and energy consumption.

The study on switched reluctance motor design for electric vehicles by Bukhari et al. (2019) highlights the importance of adaptability to harsh environments and fault tolerance in sustainable motor design. Their research proposes a 20 kW, three-phase switched reluctance motor, optimized for high torque density and efficiency in electric vehicle applications. The motor's design addresses the challenges of high-temperature environments and demagnetization of permanent magnets, showcasing the adaptability and reliability essential in sustainable motor design.

The critical aspects of electric motor drive controllers and mitigation of torque ripple, as discussed by Mohanraj et al. (2022), are fundamental in sustainable motor design. Their literature survey compares various advanced control techniques for conventionally used electric vehicle motors, focusing on minimizing torque ripple and enhancing reliability. This principle is crucial in ensuring the long-term performance and sustainability of electric motors, particularly in electric vehicles.

The design of a coreless multi-phase electric motor using magnetic resonant coupling by Besong & Fujimoto (2022) represents the principle of lightweight and innovative design. Their novel coreless motor, made of reinforced plastic fibers and 3-D printed components, drastically reduces weight while maintaining efficiency. This design approach is significant in sustainable motor design, as it reduces material usage and energy consumption, contributing to the overall sustainability of the motor.

The core principles of sustainable electric motor design encompass maximizing power density and efficiency, adaptability to harsh environments and fault tolerance, mitigation of torque ripple and improved reliability, and lightweight and innovative design. These principles are integral in developing electric motors that are not only efficient and high-performing but also environmentally friendly and sustainable.

3.2. Architectural Innovations in Modern Electric Motors

Architectural innovations in modern electric motors have been pivotal in enhancing their efficiency, sustainability, and adaptability to various applications. These innovations are characterized by advancements in design, materials, and technology, contributing significantly to the evolution of electric motors.

The study by de Souza et al. (2022) provides an insightful analysis of the performance evolution in squirrel-cage rotor three-phase induction electric motors (SCIMs) from 1945 to 2020. This research highlights the significant performance gains achieved through innovations in insulating materials, cooling housing, bearings, and overall design. The evolution from cotton and silk to modern varnishes for insulating electrical conductors, along with improvements in mechanical components, has led to a substantial increase in efficiency and a reduction in the weight/power ratio of these motors.

This historical perspective underscores the continuous architectural innovation in electric motors, contributing to their sustainability and efficiency.

The comparative study by Bhatt, Mehar, and Sahajwani (2019) on electric motors used in electric vehicles provides a comprehensive overview of the various classes of motors and their evolution over time. This study emphasizes the importance of efficiency, power density, reliability, and size in the selection of electric motors for electric vehicles. The paper discusses how different types of electric motors have been adapted and optimized for specific power requirements, showcasing the architectural innovations that have been made to meet the growing demands of the electric vehicle industry.

Padovani, Ketelsen, and Schmidt (2020) explore the use of hybrid technologies in downsizing electric motors for energy-efficient self-contained electro-hydraulic systems. Their research presents a novel approach to reducing the size of electric motors while maintaining high power output, particularly in high-power applications. This study demonstrates the feasibility of hybridizing self-sufficient systems, offering a promising solution for enhancing the efficiency and sustainability of electric motors in demanding environments.

Architectural innovations in modern electric motors are characterized by advancements in materials, design, and technology. These innovations have led to significant improvements in efficiency, sustainability, and adaptability, making electric motors more suitable for a wide range of applications, including electric vehicles and electro-hydraulic systems.

3.3. Approaches to Enhancing Motor Efficiency and Sustainability

In the realm of electric motors, enhancing efficiency and sustainability is a multifaceted challenge that involves various approaches, ranging from market developments to innovative manufacturing processes and eco-driving strategies. These approaches are crucial in minimizing energy loss and environmental impact, thereby contributing to the broader goals of sustainable development.

Mayr et al. (2018) provide a comprehensive analysis of the sustainability aspects of electric motors, considering market developments, product types, and innovative manufacturing processes. Their study emphasizes the significance of the electric motor industry and the importance of state-regulated efficiency classes. By analyzing different product types and their sustainability characteristics, along with manufacturing processes in terms of energy and resource efficiency, the paper offers a holistic view on the sustainability aspects of electric motors. This approach underlines the importance of integrating market, product, and process perspectives to enhance the sustainability of electric motors.

Gheorghe et al. (2016) focus on the development of high-efficiency induction electric motors to minimize energy loss and environmental impact. The paper outlines the normative framework for developing energy-efficient induction motors and analyzes energy consumption during their fabrication and operation. By presenting case studies on improving induction motor technical features based on numerical analysis, the research evaluates upgraded versions of induction motors against their basic units. This approach highlights the potential of upgrading existing designs to more economical and environmentally friendly units.

Koch et al. (2021) propose an online nonlinear algorithm for eco-driving, which optimizes the speed profile and powertrain operation for electric vehicles with multiple motors and gears. This paper addresses the non-convex power demand of electric motors and compares different powertrain topologies in various scenarios. The research validates the proposed algorithm through Dynamic Programming, demonstrating how optimal speed profiles and powertrain configurations can lead to reduced energy consumption. This approach is significant in enhancing motor efficiency and sustainability in electric vehicles.

Auer and Meincke (2018) conduct a comparative life cycle assessment of electric motors from different efficiency classes. Their study evaluates the trade-offs between the life cycle stages, particularly between manufacturing and use stages. By analyzing the environmental impacts of motors with asynchronous technology, the research indicates the dominance of the use stage in the motors' life cycles and the environmental benefits of increased efficiency. This approach provides insights into the environmental break-even points and the balance between energy-related impacts and toxicity/resource depletion-related impacts.

Approaches to enhancing motor efficiency and sustainability involve a comprehensive understanding of market trends, product development, manufacturing processes, and operational strategies. These approaches, ranging from holistic sustainability analysis to eco-driving algorithms and life cycle assessments, are essential in developing electric motors that are not only efficient but also environmentally sustainable.

3.4. Milestones in the Development of Sustainable Electric Motors

The development of sustainable electric motors has been marked by significant milestones, reflecting the evolution of technology, materials, and design principles. These milestones have played a crucial role in shaping the current landscape of electric motor technology, particularly in the context of ecological automotive transports, lightweight motor design, and solar-powered electric vehicles.

The research by Neamțu and Țîțu (2021) delves into the durable and sustainable development of ecological automotive transports, focusing on electric motor vehicles. Their study presents a technical and managerial perspective, including a SWOT analysis of electric motor vehicles and their quality assessment indicators. The article highlights the challenges and opportunities in the electric motor vehicle sector, emphasizing the need for sustainable development in this field. This milestone reflects the growing importance of electric motors in the automotive industry and the shift towards more sustainable and efficient transportation solutions.

The work by Ruff et al. (2014) on the development of lightweight sustainable electric motors using nanoscale materials represents a significant milestone in electric motor technology. Their research describes the design of a lightweight electric motor, emphasizing the use of nanoscale materials to enhance sustainability and performance. This milestone is indicative of the evolving focus on material innovation and lightweight design in electric motor development, catering to the needs of various applications, including electric vehicles.

The study by Sain et al. (2020) provides an extensive review of solar-powered energy-efficient smart electric vehicles based on permanent magnet synchronous motor (PMSM) drive. This research addresses the integration of solar energy in electric vehicles and the advancements in aerodynamic design and IoT tools for smart electric vehicles. This milestone highlights the convergence of renewable energy and electric motor technology, showcasing the potential of solar power in enhancing the sustainability of electric vehicles.

Although not directly related to electric motor development, the analysis of torque capability and limits of operation of AC traction motors on sustainable high-speed electric trains by Sain et al. (2020) offers insights into the sustainability aspects of electric railway systems. This research emphasizes the importance of energy conversion efficiency in electric traction motors and their impact on the environmental performance of electric trains. This milestone underscores the relevance of electric motors in sustainable transportation systems beyond automotive applications.

Going forward, the milestones in the development of sustainable electric motors reflect the ongoing efforts to enhance efficiency, reduce environmental impact, and integrate innovative materials and renewable energy sources. These developments are pivotal in shaping the future of electric motor technology and its applications in various sectors.

3.5. Cutting-Edge Technologies in Electric Motor Design

The design of electric motors has seen remarkable advancements with the integration of cutting-edge technologies. These innovations are pivotal in enhancing the efficiency, performance, and sustainability of electric motors, particularly in the context of large consumer products, aviation, and electric vehicle applications.

Nemoianu et al. (2019) explore the challenges and trends in electric motors of large consumer products, particularly focusing on power efficiency improvement through modern cutting technologies. Their study reviews the main sources of overall efficiency degradation, such as energy steel losses, and presents specific methods to address these issues. The research emphasizes the global impact of small energy consumption reductions in large-scale industrial manufacturing of consumer goods. This advancement in power efficiency is a crucial step in the sustainable development of electric motors, especially considering the generalization of the IE4 efficiency standard.

Deisenroth and Ohadi (2019) discuss the revolutionary impact of enhanced cooling, novel designs, and packaging of semiconductors on electric motors, particularly in aviation. Their paper focuses on the thermal management of high-power density electric motors, which is essential for the electrification of aviation. The study highlights the role of electromagnetic and thermo-mechanical co-design, enabled by innovative design topologies, materials, and manufacturing techniques. This approach is significant in realizing the performance and cost metrics of next-generation electric motors.

Kuehl (2023) presents a flexible, robot-based cutting process of hairpin windings developed for electric motors. This technology is particularly advantageous in automating the production process of electric motors in high-wage countries. The research emphasizes the importance of a clean and burr-free cut surface for the subsequent joining of the wire into the stator, ensuring a trouble-free process flow and appropriate current flow. The hairpin technology and its associated process chain represent a significant advancement in the manufacturing of electric motors.

Goli et al. (2021) provide a comprehensive review of several topologies of traction motors employed in electric vehicle traction applications. The paper emphasizes trends in volumetric power density and gravimetric power density of traction motors, which directly affect the weight, packaging, and efficiency of electric vehicles. The study classifies motor topologies based on permanent magnet use, the location of the magnets inside the motor, and design trends in rotor and stator. This analysis offers a useful reference for understanding product evolution and forecasting future trends in electric motor technologies.

The integration of cutting-edge technologies in electric motor design is transforming the efficiency, performance, and sustainability of these motors. Innovations in power efficiency, thermal management, manufacturing processes, and motor topologies are driving the advancement of electric motors in various applications, from consumer products to aviation and electric vehicles.

3.6. Trends in Electric Motor Sustainability and Maintenance

The sustainability and maintenance of electric motors are critical aspects in their lifecycle, impacting both their performance and environmental footprint. Del Pero et al. (2021) conducted a comprehensive environmental sustainability analysis of Formula-E electric motors. Their study developed a tailored methodological approach to assess the environmental impacts of the whole life cycle of a Formula-E electric motor. The research emphasized the importance of eco-design and technology transfer from racing high-performance cars to commercial vehicles. This analysis is significant in understanding the environmental implications of electric motors in high-performance applications and their potential for sustainable urbanization.

Bentivogli et al. (2022) presented a novel approach to predictive maintenance in industrial electric motors. Their paper introduced a deploy-and-forget sensor node for predictive maintenance, targeting three-phase asynchronous motors. This technology supports data collection from multiple sensors and features ultra-low-power design, achieving self-sustainability. The sensor node's ability to anticipate deterioration and incoming breakages on operating machines is crucial in reducing maintenance costs and enhancing the reliability of electric motors.

Parpala and Jacob (2017) discussed the application of IoT technologies for predictive maintenance of industrial equipment. The paper highlighted the evolution of technologies enabling monitoring, tests, and diagnostics of in-service electric motors, surpassing traditional RMS current and voltage measurements. The ability to use a working, online motor as a transparent sensor producing shaft torque signatures at the motor control cabinet enables advanced diagnoses of voltage supply, motor, and load system conditions. This advancement is pivotal in predictive maintenance strategies, ensuring efficient and timely maintenance interventions.

Polonelli et al. (2022) explored the development of a self-sustainable IoT wireless sensor node for predictive maintenance on electric motors. The sensor is designed for AC mono and three-phase asynchronous motors and generators, measuring vibrations, environmental noise, temperature, and the external magnetic field. The prototype's capability to detect anomalies using vibration spectral analysis is a significant step forward in predictive maintenance, offering just-in-time services at reduced operational costs.

The trends in electric motor sustainability and maintenance are characterized by a focus on environmental sustainability, predictive maintenance technologies, and the application of modern monitoring techniques. These advancements are essential in enhancing the performance, reliability, and environmental compatibility of electric motors.

3.6.1. Innovations in Sustainable Materials and Manufacturing Processes

The evolution of electric motors has been significantly influenced by innovations in sustainable materials and manufacturing processes. This examines the latest advancements in this area, focusing on lightweight design approaches, sustainability aspects of electric motors, and the use of rare earth elements and composite materials.

Peter et al. (2013) explored new conceptual lightweight design approaches for the integrated manufacturing processes of electric motors. Their study focused on the influence of alternative materials on the process chain of electric motor manufacturing, particularly for traction motors in electric vehicles. The research highlighted the challenges and opportunities in variant flexible and scalable production processes, emphasizing the use of lightweight materials to lower the environmental impact. This approach is crucial in meeting the increasing demand for electric traction systems and enhancing the economical relevance of production processes (Peter et al., 2013).

Mayr et al. (2018) provided a comprehensive overview of the sustainability aspects of electric motors from market, product, and process perspectives. The study analyzed the electric motor market, emphasizing the significance of state-regulated efficiency classes. It also examined different electric motor types and their sustainability characteristics, along with an analysis of manufacturing processes in terms of energy and resource efficiency. This holistic view on sustainability aspects offers valuable insights into optimizing electric motor production for environmental and economic benefits (Mayr et al., 2018).

Bailey et al. (2017) addressed the sustainability of permanent rare earth magnet motors in the hybrid/electric vehicle (H/EV) industry. The study reviewed the technical, social, environmental, and economic aspects of rare earth elements (REEs) used in these motors. It highlighted the environmental challenges associated with the production and processing of REEs, as well as the price volatility that affects their economic sustainability. This research is significant in understanding the comprehensive impact of rare earth elements in the electric vehicle industry and exploring alternatives for more sustainable motor designs (Bailey et al., 2017).

Choi et al. (2023) reviewed the latest applications of composite materials in modern vehicles and evaluated the state of the art of composite manufacturing and recycling processes for green mobility. The study emphasized the trade-offs between performance and cost in the mass adoption of composites. It also discussed the integration of robotic automation into composite manufacturing processes for eco-friendly, sustainable, and cost-effective production. This research is pivotal in advancing the use of composites for lightweight and efficient electric motor designs (Choi et al., 2023).

The innovations in sustainable materials and manufacturing processes for electric motors are characterized by a focus on lightweight design, comprehensive sustainability analysis, the use of rare earth elements, and the application of composite materials. These advancements are essential in enhancing the performance, reliability, and environmental compatibility of electric motors.

3.6.2. Advances in Maintenance Strategies and Lifecycle Management

The maintenance strategies and lifecycle management of electric motors are critical aspects that determine their efficiency, reliability, and overall performance. It explores recent advances in these areas, focusing on optimizing repairs, circular economy research, cooling systems, and predictive maintenance using machine learning.

Mironenko & Khalyasmaa (2023) investigated the optimization of repairs and maintenance of electrically driven gas pumping units. Their study analyzed the existing approach to the operation and maintenance of these units, utilizing life cycle management systems to assess their current state. The research employed machine learning algorithms, such as bagging and gradient boosting, to monitor diagnostic and operational parameters, thereby enhancing the accuracy in assessing the current state of electrically driven gas pumping units. This approach is vital for reducing costs and increasing the service life of these units (Mironenko & Khalyasmaa, 2023).

Tiwari et al. (2021) provided a holistic view of circular economy research for electric motors, emphasizing the role of Industry 4.0 technologies. The paper highlighted the lack of a methodology for selecting the best end-of-life scenario for industrial electric motors and identified recycling as a key focus area. The study also revealed that reuse, a better strategy in terms of waste hierarchy, was the least researched area. This research is crucial for understanding the current landscape and identifying challenges and recommendations for future research in the circular economy of electric motors (Tiwari et al., 2021).

Konovalov et al. (2023) explored new trends in the development of cooling systems for electric motors. The study summarized academic research and patents for cooling systems, focusing on temperature distribution and its influence on the power-to-dimension ratio of electric motors. The research discussed air and liquid cooling systems, highlighting their potential to increase the power-to-dimension ratio and reduce motor size. This study is significant in understanding the advancements in cooling management, which is essential for the efficient operation and maintenance of electric motors (Konovalov et al., 2023).

Chimundu & Ali (2022) examined the application of machine learning in predictive maintenance of electric motors. The study focused on classification models that categorize critical factors affecting motor performance, such as the surrounding environment, running temperature, motor speed, and load current. This research is important for developing cost-effective maintenance strategies that ensure the viability and longevity of electric motors (Chimundu & Ali, 2022).

Based on this finding, the advances in maintenance strategies and lifecycle management for electric motors are characterized by a focus on optimizing repairs, circular economy, cooling management, and predictive maintenance using machine learning. These advancements are essential in enhancing the performance, reliability, and environmental compatibility of electric motors.

4. Discussion

4.1. Evaluating the Impact of Sustainable Electric Motor Technologies

The impact of sustainable electric motor technologies extends across technological, economic, and environmental dimensions by delving into the implications of these technologies, focusing on their role in urban mobility, economic and social considerations, and life cycle assessment.

Del Pero et al. (2021) conducted an environmental sustainability analysis of the Formula-E electric motor, focusing on its life cycle impacts. The study developed a methodological approach to assess the environmental impacts throughout the life cycle of a Formula-E electric motor, including the production, use, and end-of-life stages. This research is significant in understanding the environmental footprint of high-performance electric motors and offers insights for eco-design and technology transfer from racing to commercial vehicles (Del Pero et al., 2021).

Palaniswamy et al. (2022) provided a comprehensive overview of the social, economic, and environmental impacts of electric vehicles (EVs) in India. The study highlighted the role of EVs in addressing global warming, fuel dependence, and greenhouse gas emissions. It also discussed the government's support in promoting EV adoption and the challenges related to battery manufacturing and charging infrastructure. This research is crucial for understanding the multifaceted impacts of electric vehicles, including those powered by sustainable electric motors, in a rapidly developing economy (Palaniswamy et al., 2022).

Tintelecan et al. (2019) explored the environmental impact of electric vehicles through Life Cycle Assessment (LCA). The study focused on setting up indicators for a more accurate analysis of the environmental impact of battery electric vehicles, including the electric motors. It emphasized the importance of considering the entire life cycle of EV components, such as permanent magnets in electric motors, to assess their sustainability. This research is important for evaluating the environmental implications of electric motor technologies in the context of sustainable transport (Tintelecan et al., 2019).

Therefore, the impact of sustainable electric motor technologies is multifaceted, encompassing environmental sustainability, social and economic considerations, and life cycle impacts. These studies provide valuable insights into the broader implications of adopting sustainable electric motors in various sectors, particularly in urban mobility and electric vehicles.

4.1.1. Challenges in Current Electric Motor Designs and Potential Solutions

The development of electric motor technologies faces numerous challenges, ranging from manufacturing complexities to performance optimization. Wößner et al. (2021) explored the technical challenges in producing permanent magnet rotors for electric traction motors, particularly those designed for high power densities. The study emphasized the difficulties in managing initial unbalances and changes during operation, which are critical for the economically viable and resource-saving production of highly efficient motors. The authors presented experimental investigations and FE-simulations to prioritize challenges and approaches for unbalance reduction, offering optimization potentials for the production of permanent magnet rotors (Wößner et al., 2021).

Husain et al. (2021) discussed the evolving trends and challenges in electric drive technology for future electric vehicles. The article highlighted the need for improved performances, such as fuel efficiency, extended range, and fast-charging options. It also identified emerging materials and technologies for power electronics and electric motors, addressing the challenges and opportunities for innovative drive and motor designs to meet the technical targets for light-duty electric vehicles by 2025 (Husain et al., 2021).

Zhang et al. (2022) reviewed the development and critical technologies of Integrated Motor Drives (IMDs), which have gained extensive attention in electric vehicles, electric propulsion aircraft, and ship propulsion systems. The paper discussed the research progress in motor structure, converter, volume optimization, heat dissipation design, and electromagnetic interference mitigation. It also explored the applications of wide-bandgap semiconductors and the integration of LCL filters, highlighting the future potential of IMDs in applications requiring high power density (Zhang et al., 2022). These studies provide insights into the complexities of manufacturing and optimizing electric motors, offering potential pathways to overcome these challenges in the pursuit of sustainable and efficient electric motor technologies.

4.1.2. Trends in Sustainable Design and Maintenance Practices

The evolution of electric motor technology is marked by ongoing trends in sustainable design and maintenance practices. Matsuoka & Kondo (2010) addressed the challenge of reducing power consumption in the testing of traction induction motors. The study emphasized the need for energy-saving technologies in the testing phase, which is crucial for both quality assurance and environmental sustainability. The research highlighted the importance of efficient testing methods for traction motors, particularly in the context of their widespread application in electric vehicles and other high-power applications (Matsuoka & Kondo, 2010).

Kotter et al. (2018) explored the challenges and opportunities in the electric vehicle segment of the automotive industry. Their work included the development of a common virtual physical environment, X-in-the-loop, for comprehensive testing of electric vehicle components. This approach is significant for the sustainable design and maintenance of electric motors, as it allows for the integration of various test rigs and software simulators to evaluate electric vehicle systems in real-time (Kotter et al., 2018).

The study of Schuberth et al. (2008) discussed the use of stainless steel in reducing weight and costs while improving safety and sustainability in automotive systems. The research emphasized the role of stainless steel in the future of car manufacturing, particularly in the context of electric motor vehicles. This approach to material selection and design is crucial for the sustainable development of electric motors, as it addresses key aspects such as weight reduction, cost efficiency, and environmental impact (Schuberth et al., 2008). These studies provide insights into the evolving landscape of electric motor technology, highlighting the importance of innovation and sustainability in this field.

4.2. Implications for Industry Stakeholders in Electric Motor Development

The development of sustainable electric motors has significant implications for various industry stakeholders, including manufacturers, policymakers, and consumers. The shift towards electric vehicles (EVs) necessitates a reevaluation of motor design to meet performance indices specific to EVs. Wu et al. (2021) emphasize the importance of designing motors that can efficiently meet the demands of pure electric vehicles. This involves studying the characteristics of various driving motors and selecting appropriate control schemes. Such research is crucial for manufacturers as it guides the development of more efficient and sustainable motors, directly impacting the performance and marketability of EVs (Wu et al., 2021).

The transition to a low-carbon economy, particularly in the electric vehicle sector, presents both challenges and opportunities for stakeholders. Majid and Dalimi (2021) discuss the Indonesian government's policy on the Battery-Based Electric Motor Vehicle Program, highlighting the need for sustainable development in the sector. Their study using the Analytical Hierarchy Process method identifies key areas such as governance improvement, infrastructure and technology development, and data availability as critical for sustainable development. This analysis is vital for policymakers and industry leaders in strategizing for sustainable growth in the electric vehicle battery industry (Majid & Dalimi, 2021)

The integration of solar energy into electric vehicles represents a significant advancement towards environmental sustainability. Sain et al. (2020) discussed the development of solar-powered energy-efficient smart electric vehicles, particularly focusing on permanent magnet synchronous motor (PMSM) drive technologies. This research is crucial for the industry as it explores the potential of solar energy in reducing greenhouse gas emissions and promoting environmental sustainability. The study also addresses the impact of emerging Information and Communication Technology (ICT) in this field, which is of great interest to technologists and researchers working on future developments in electric vehicles (Sain et al., 2020). These areas highlight the ongoing evolution and challenges in the field, underscoring the need for continued innovation and collaboration among manufacturers, policymakers, and researchers.

5. Conclusions

The study has systematically reviewed the current state of sustainable electric motor design, highlighting significant advancements and trends. Key findings include the evolution from conventional to more energy-efficient and environmentally friendly motors, the increasing focus on using sustainable materials, and the integration of innovative technologies to enhance motor efficiency. The importance of recyclability and maintenance in extending the lifecycle of electric motors has also been emphasized. Furthermore, the study has identified the critical role of international standards and regulations in guiding the development of sustainable electric motors.

Looking forward, the electric motor industry faces both challenges and opportunities. Technological advancements present opportunities for further improvements in efficiency and sustainability. However, challenges such as the need for more sustainable materials, improved recycling processes, and the adaptation to evolving regulatory landscapes remain. The growing demand for electric vehicles and renewable energy systems also offers a significant opportunity for the development of innovative electric motor technologies.

For industry leaders, continuous investment in research and development is essential for developing more efficient and sustainable electric motors. Embracing circular economy principles in motor design and manufacturing can also contribute to sustainability goals. Policymakers should focus on creating and updating regulations that encourage innovation in sustainable motor technologies and provide clear guidelines for efficiency and environmental performance. Collaboration between industry, academia, and government is crucial for advancing sustainable practices in electric motor development.

The study underscores the importance of sustainable electric motor design in the context of global environmental and energy challenges. Future research should focus on exploring new materials and technologies to further enhance motor efficiency and sustainability. The development of standardized methods for assessing the environmental impact of electric motors throughout their lifecycle is also recommended. Additionally, research into effective recycling and maintenance strategies will be crucial for promoting the circular economy in electric motor manufacturing and use. As the field continues to evolve, ongoing research and collaboration among stakeholders will be key to realizing the full potential of sustainable electric motor technologies.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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