



# Comprehensive Overview of Permanent Magnet Synchronous Motors (PMSMs)

<sup>1</sup>Atal Bihari Shringi, <sup>2</sup>Rahul Sharma

<sup>1</sup>M.Tech Scholar, <sup>2</sup>Assistant Professor

<sup>1</sup>Shekhawati Institute Of Engineering & Technology, Sikar

**Abstract:** The pursuit of enhanced energy efficiency and sustainability has spurred significant progress in electric motor technologies. Permanent Magnet Synchronous Motors (PMSMs) have emerged as a promising solution, distinguished by their high efficiency, compact design, and precise control capabilities. This conceptual review delves into key aspects of PMSMs, offering a thorough examination of their principles, design considerations, and applications. Commencing with an elucidation of fundamental principles governing PMSM operation, the review underscores the role of permanent magnets in generating a magnetic field synchronized with the stator's rotating magnetic field. A detailed exploration of the motor's construction and crucial components, including the rotor, stator, and power electronics, ensues. Special emphasis is placed on permanent magnet selection and characteristics, considering their impact on motor performance and efficiency. Moreover, the paper delves into various control strategies optimizing PMSM performance, encompassing field-oriented control, direct torque control, and sensorless control methods. It provides insights into challenges associated with control algorithms, such as parameter variations and sensitivity to operating conditions. Recent advancements in control techniques are critically evaluated, highlighting their contributions to enhancing PMSM efficiency and robustness. The review extensively examines applications, showcasing the versatility of PMSMs in industries like electric vehicles, robotics, and renewable energy systems. It explores how PMSMs contribute to higher energy efficiency standards in these applications, fostering the transition towards a more sustainable and eco-friendly future. Additionally, the paper addresses emerging trends and future prospects for PMSMs, including advancements in materials, innovative design approaches, and integration with smart grid technologies. It discusses the potential impact of PMSMs on the broader electric motor technology landscape and their role in shaping the future of sustainable energy systems. In conclusion, this conceptual review serves as a valuable resource for researchers, engineers, and practitioners seeking a deeper understanding of Permanent Magnet Synchronous Motors. By synthesizing the latest developments and addressing challenges, the paper aims to contribute to the ongoing discourse surrounding PMSMs and their pivotal role in the evolution of energy-efficient technologies.

**Index Terms – Permanent Magnet Synchronous Motors (PMSMs), Electric Motor Technologies, Motor Control Strategies, Energy Efficiency.**

## I. INTRODUCTION

In the current dynamic landscape of technological innovation and sustainable energy solutions, the pursuit of efficient electric motor technologies has become crucial. A technology that has garnered substantial attention in this context is the Permanent Magnet Synchronous Motor (PMSM). This introduction section aims to establish a comprehensive foundation for understanding the significance of studying PMSMs, highlighting their pivotal role in advancing energy-efficient electric motor technologies [1].

### 1.1 Background and Motivation for Investigating PMSMs:

Electric motors power various applications in our daily lives, from industrial machinery to household appliances. The study of Permanent Magnet Synchronous Motors (PMSMs) arises from the acknowledgment that they represent a transformative leap in motor efficiency and performance. The integration of permanent magnets in PMSMs has revolutionized conventional motor design, offering enhanced power density, compactness, and precise control. The motivation to delve into the intricacies of PMSMs is driven by the quest for sustainable energy solutions and the imperative to reduce global energy consumption. Researchers and engineers, by understanding and optimizing PMSM operations, can significantly contribute to ongoing efforts for a more energy-efficient future. Electric motors play a pivotal role in modern society, serving as the workhorses behind a multitude of applications, from powering industrial machinery to propelling electric vehicles. The motivation to study Permanent Magnet Synchronous Motors (PMSMs) is deeply rooted in the pursuit of enhancing the efficiency and sustainability of electric motor technologies [1].

- ❖ **Evolution of Motor Technologies:** The study of PMSMs is situated within the broader context of the evolution of electric motor technologies. Traditionally, motors relied on various designs, including induction motors, to convert electrical energy into mechanical motion. However, the advent of PMSMs marked a paradigm shift by incorporating permanent magnets into the rotor

structure. This innovation drastically altered the dynamics of motor efficiency, offering a more direct and efficient conversion of electrical energy into mechanical work [1].

- ❖ **Efficiency and Power Density:** PMSMs are renowned for their high efficiency, a characteristic that sets them apart in the realm of electric motor technologies. The integration of permanent magnets ensures a more efficient conversion of electrical energy to mechanical energy, resulting in reduced energy losses and improved overall system efficiency. This heightened efficiency is particularly crucial in applications where energy conservation is paramount, such as in electric vehicles and renewable energy systems [2].
- ❖ **Compact Design and Power Density:** The use of permanent magnets in PMSMs contributes to a more compact and lightweight motor design. This attribute is especially vital in applications where space and weight considerations are critical, such as in aerospace, robotics, and electric vehicles. PMSMs offer a higher power density, meaning they can deliver more power per unit of weight or volume, making them well-suited for modern, space-constrained applications [2].
- ❖ **Precision and Control Capabilities:** PMSMs provide precise control over motor operation, allowing for fine-tuned adjustments in speed and torque. This level of control is essential in applications that demand accurate and responsive motor performance, such as in robotics, industrial automation, and electric propulsion systems. The study of PMSMs involves understanding the intricacies of the control strategies that harness this precision for optimal motor operation.
- ❖ **Sustainability and Global Energy Challenges:** Against the backdrop of global concerns about climate change and the finite nature of traditional energy resources, the study of PMSMs aligns with the imperative to develop sustainable and eco-friendly technologies. The inherent efficiency of PMSMs contributes to reducing energy consumption, making them instrumental in the broader goal of creating a more sustainable energy landscape [2].

In essence, the background and motivation for studying PMSMs lie in the recognition of their transformative potential to address contemporary challenges, from the need for energy efficiency and sustainability to the demand for compact and high-performance electric motor technologies. As society continues to prioritize greener and more efficient solutions, the study of PMSMs emerges as a key pathway toward achieving these objectives.

## 1.2 Significance of Energy-Efficient Electric Motor Technologies:

The significance of energy-efficient electric motor technologies cannot be overstated in the context of contemporary global challenges such as climate change and depleting energy resources. Electric motors account for a substantial portion of the world's energy consumption, and any improvement in their efficiency directly translates into significant energy savings. PMSMs, with their inherent high efficiency and precise control capabilities, represent a key player in this paradigm shift towards sustainability. As industries and transportation increasingly transition towards electric power, the role of PMSMs becomes even more critical in ensuring a greener and more energy-efficient future. The significance of energy-efficient electric motor technologies encompasses a broad spectrum of economic, environmental, and societal benefits. As electric motors are omnipresent in various industries and applications, improving their efficiency holds substantial implications for resource conservation, emissions reduction, and overall sustainability [3].

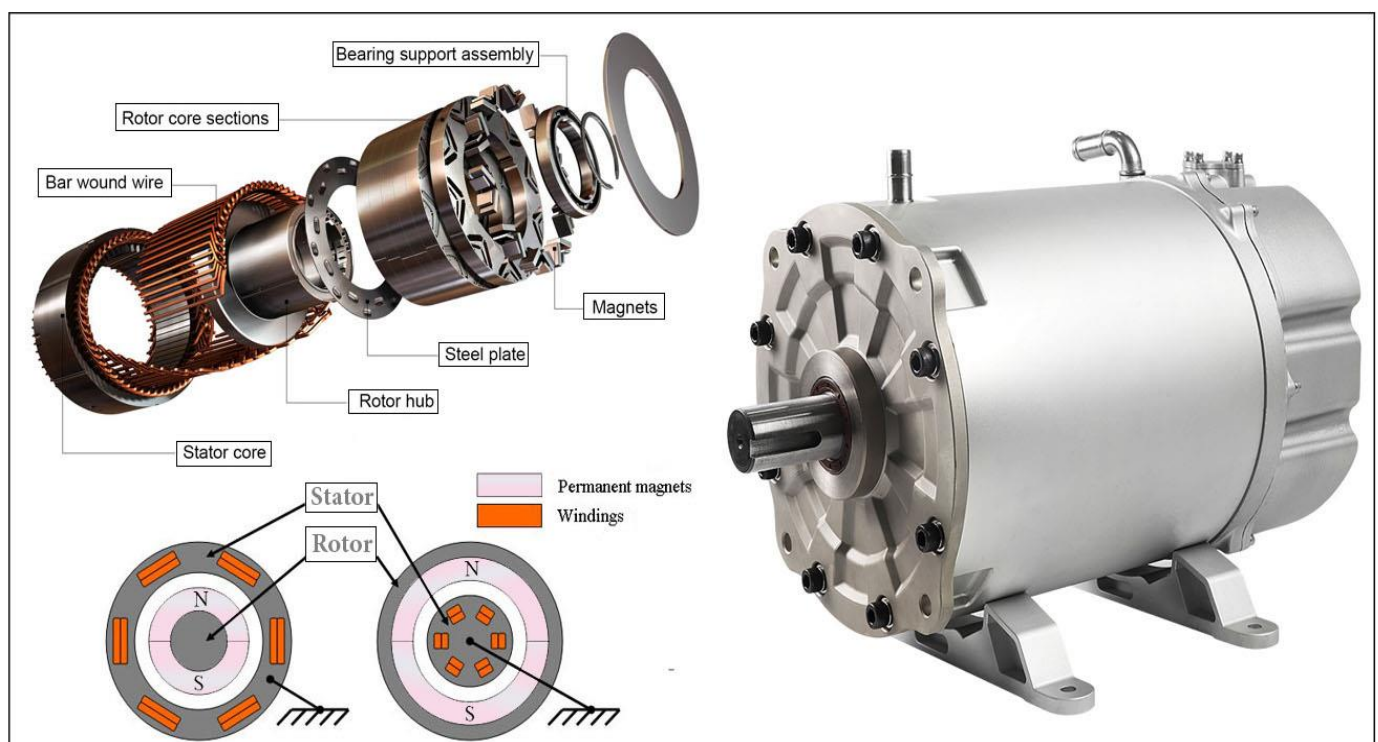
- **Global Energy Consumption:** Electric motors account for a significant portion of global energy consumption. In industrial settings, HVAC systems, transportation, and residential applications, the demand for electric power is pervasive. Enhancing the efficiency of electric motors directly translates to substantial energy savings on a global scale. This is especially critical in a world facing the challenges of increasing energy demand, resource depletion, and environmental concerns [3].
- **Energy Conservation and Cost Reduction:** Energy-efficient electric motor technologies contribute to the conservation of resources by minimizing energy losses during the conversion of electrical energy into mechanical work. Reduced energy consumption not only aligns with sustainability goals but also results in cost savings for industries and end-users. Businesses benefit from lower operational costs, and consumers experience reduced energy bills, fostering economic efficiency.
- **Environmental Impact and Emissions Reduction:** The environmental significance of energy-efficient electric motors lies in their potential to mitigate greenhouse gas emissions. By consuming less energy, these motors contribute to a reduction in the overall carbon footprint associated with electricity generation. This is particularly crucial in the context of climate change mitigation and efforts to transition to cleaner, renewable energy sources [4].

- **Compliance with Energy Standards and Regulations:** The global push for energy efficiency is reflected in the establishment of energy standards and regulations. Governments and international bodies set efficiency standards for various appliances, including electric motors, to promote the adoption of energy-efficient technologies. The significance of energy-efficient electric motor technologies is underscored by their role in ensuring compliance with these standards, fostering a transition to greener and more sustainable practices [4].
- **Integration with Renewable Energy Systems:** Energy-efficient electric motors play a crucial role in the integration of renewable energy systems. As the world increasingly relies on sources like solar and wind power, the variability of these sources requires adaptable and efficient electric motors for energy conversion. By improving efficiency, electric motors contribute to the effective utilization of renewable energy, making these systems more reliable and viable.
- **Technological Innovation and Economic Competitiveness:** The pursuit of energy efficiency in electric motors drives technological innovation. Industries that invest in and adopt energy-efficient technologies gain a competitive edge in the marketplace. The development and implementation of cutting-edge motor technologies contribute to economic growth, job creation, and the establishment of a sustainable industrial ecosystem.

In summary, the significance of energy-efficient electric motor technologies extends beyond immediate energy savings. It encompasses environmental stewardship, economic advantages, compliance with regulations, and the facilitation of a transition toward cleaner and more sustainable energy systems. As the world grapples with the challenges of resource scarcity and climate change, the adoption of energy-efficient electric motor technologies stands as a pivotal step toward a more sustainable and resilient future.

## II. PERMANENT MAGNET SYNCHRONOUS MOTOR AND ITS WORKING

A Permanent Magnet Synchronous Motor (PMSM) represents a specific class of synchronous motor where the rotor, instead of being wound with coils and supplied with current, integrates permanent magnets. These magnets generate a fixed magnetic field, while the stator winding produces a rotating magnetic field, resulting in the synchronous rotation of the rotor. PMSMs are recognized for their exceptional attributes such as high efficiency, power density, and precise control capabilities, rendering them well-suited for diverse applications including electric vehicles, robotics, and industrial machinery. A Permanent Magnet Synchronous Motor (PMSM) is an electric motor variant that employs permanent magnets in the rotor instead of traditional electromagnets. This design choice enhances the motor's efficiency, power density, and controllability. PMSMs find widespread use in applications where high-performance, precision control, and energy efficiency are paramount [5].



## Permanent Magnet Synchronous Motor Construction

Fig 1. Permanent Magnet Synchronous Motor

## 2.1 Key Features of PMSMs:

- **Permanent Magnets in the Rotor:** The rotor of a PMSM houses permanent magnets, typically crafted from materials like neodymium or samarium-cobalt. These magnets maintain their magnetic properties, creating a consistent magnetic field without requiring external power. This design contributes to the motor's elevated efficiency and power density.
- **Synchronous Operation:** PMSMs operate in sync with the frequency of the AC power supply. The rotor rotates at the same frequency as the rotating magnetic field produced by the stator windings. This synchronous operation ensures efficient power conversion and precise control over the motor's speed and torque.
- **High Efficiency:** The incorporation of permanent magnets eliminates energy losses linked to the generation of a magnetic field in traditional motors. This results in heightened efficiency, as the magnetic field in the rotor is pre-established, reducing overall power consumption and heat generation in the motor [5].
- **Precise Control:** PMSMs afford precise control over speed, torque, and position, making them suitable for applications requiring accurate and responsive motor performance. Advanced control strategies, such as Field-Oriented Control (FOC) and Direct Torque Control (DTC), are often employed to optimize motor operation.
- **Compact and Lightweight Design:** The absence of a rotor winding and the use of high-strength permanent magnets contribute to a more compact and lightweight motor design. This is particularly advantageous in applications where space and weight considerations are critical, such as in electric vehicles and aerospace [5].

## Applications:

PMSMs find applications across a spectrum of industries, including:

- **Electric Vehicles (EVs):** PMSMs are prevalent in electric propulsion systems for vehicles due to their high efficiency and power density [6].
- **Industrial Automation:** PMSMs drive various industrial machinery and automation systems, offering precise control over rotational motion.
- **Renewable Energy Systems:** PMSMs play a role in wind turbines and other renewable energy applications where efficiency and reliability are crucial [6].
- **Consumer Electronics:** They are utilized in appliances and devices where compact design and energy efficiency are imperative.
- **Sensor less Control (Optional):** Some PMSMs implement sensor less control methods, eliminating the need for additional sensors to detect rotor position or speed. Sensor less control relies on algorithms that estimate the rotor position based on the motor's electrical characteristics, reducing complexity and cost.

In summary, Permanent Magnet Synchronous Motors (PMSMs) provide an alluring combination of high efficiency, precise control, and compact design, positioning them as a preferred choice for a diverse array of applications in the contemporary electric and electronic landscape. Their contribution to advancing energy-efficient technologies and promoting sustainable practices underscores their significance in the evolving field of electric motor technologies [7].

## 2.2 Components of a Permanent Magnet Synchronous Motor (PMSM):

- **Rotor:** The rotor stands as a pivotal element in a PMSM, housing permanent magnets typically crafted from materials like neodymium-iron-boron (NdFeB) or samarium-cobalt (SmCo). These permanent magnets create a steadfast magnetic field, and their configuration determines critical motor characteristics such as torque and efficiency. The rotor plays a key role in transforming electrical energy into mechanical energy.
- **Stator:** The stator, the stationary part surrounding the rotor, comprises windings, usually in the form of coils, connected to the power supply. Energizing these windings with three-phase alternating current (AC) generates a rotating magnetic field. The interplay between the stator's rotating field and the rotor's fixed magnetic field induces rotor rotation, resulting in mechanical motion [8].
- **Power Electronics (Inverter):** Critical for the conversion of direct current (DC) power from the source into the three-phase AC power necessary for the motor, power electronics, often in the form of an inverter, are integral. The inverter regulates the amplitude and frequency of the AC power supplied to the stator windings, ensuring precise motor operation.
- **Position or Speed Sensors (Optional):** Certain PMSM applications may incorporate position or speed sensors to provide feedback for accurate control. These sensors detect rotor position or speed and relay this information to the motor controller. However, modern PMSMs may implement sensor less control methods, negating the necessity for these additional sensors [8].
- **Encoder (Optional):** In applications requiring high precision in position control, an encoder may be added to the motor shaft. The encoder furnishes detailed information about the rotor's position, enabling precise control and feedback.
- **Bearings:** Supporting the rotor and facilitating its rotation within the stator, bearings play a crucial role. Proper bearing design is essential for minimizing friction and ensuring smooth and efficient motor operation.
- **Housing/Frame:** Encasing and safeguarding the internal components, the housing or frame provides structural support and often includes features for heat dissipation, maintaining optimal operating temperatures [9].

- Cooling System (Optional): In high-performance applications, especially those with high power levels, a cooling system may be integrated to dissipate heat generated during operation. This ensures that the motor remains within its temperature limits for optimal performance and longevity.
- Understanding the functions and interactions of these components is paramount for designing and optimizing Permanent Magnet Synchronous Motors for specific applications. Each component significantly contributes to the motor's overall performance, efficiency, and reliability [9].

### 2.3 Working Principles of PMSM

The working principles of a Permanent Magnet Synchronous Motor (PMSM) involve the interaction of magnetic fields, specifically the fixed magnetic field produced by permanent magnets in the rotor and the rotating magnetic field generated by the stator windings. Here's a step-by-step explanation of the working principles:

- Permanent Magnets in the Rotor: The rotor of a PMSM contains permanent magnets, typically made of materials like neodymium or samarium-cobalt. These magnets generate a constant magnetic field within the rotor, and this magnetic field remains fixed in space [10].
- Stator Windings and AC Power: The stator, which surrounds the rotor, consists of windings connected to a three-phase alternating current (AC) power supply. When the AC power is applied to the stator windings, it produces a rotating magnetic field. The frequency of this rotating field is determined by the frequency of the AC power supply.
- Synchronous Rotation: The key principle of a PMSM is synchronous operation. The rotor, with its fixed magnetic field, attempts to align itself with the rotating magnetic field produced by the stator. This synchronization occurs because the magnetic field generated by the stator induces forces on the rotor's magnets, compelling them to align with the stator's magnetic field.
- Torque Production: As the rotor aligns itself with the rotating stator magnetic field, a torque is produced. This torque is a result of the magnetic forces between the fixed rotor magnets and the rotating stator magnetic field. The torque causes the rotor to follow the rotation of the stator, and mechanical motion is generated [10].
- Sine-Wave Control (Field-Oriented Control): In advanced control strategies like Field-Oriented Control (FOC), the stator current is controlled to be in phase with the rotor magnetic field. This allows for precise control of torque and speed. The concept of FOC involves transforming the three-phase currents into a two-coordinate system (d-q coordinates), making the control of torque and flux more straightforward.
- Sensorless Control (Optional): Some PMSM applications implement sensorless control methods. In sensorless control, algorithms are employed to estimate the rotor position based on the motor's electrical characteristics. This eliminates the need for additional position or speed sensors [11].
- Control of Speed and Torque: By controlling the amplitude and frequency of the stator currents, the speed and torque of the PMSM can be accurately regulated. This precise control is essential for applications requiring specific performance characteristics, such as in electric vehicles, robotics, and industrial automation.

In summary, the working principles of a PMSM involve the synchronized interaction between the fixed magnetic field of the rotor and the rotating magnetic field produced by the stator. This synchronous operation, combined with advanced control strategies, allows for precise control over speed, torque, and position, making PMSMs suitable for a wide range of applications.

## III. ADVANTAGES AND CHALLENGES

### 3.1 Advantages of Permanent Magnet Synchronous Motors (PMSMs):

- High Efficiency: PMSMs are recognized for their exceptional efficiency, attributed to the absence of rotor windings and reduced copper losses. The use of permanent magnets ensures a more direct conversion of electrical energy to mechanical energy.
- Precise Control: PMSMs provide precise control over speed, torque, and position. Advanced control strategies, such as Field-Oriented Control (FOC), enable accurate and dynamic control, making them suitable for applications requiring fine-tuned performance.
- Compact and Lightweight Design: The elimination of rotor windings and the incorporation of high-strength permanent magnets contribute to a more compact and lightweight motor design. This is advantageous in applications where space and weight are critical factors, such as in electric vehicles and robotics.
- High Power Density: PMSMs exhibit high power density, delivering a substantial amount of power for their size and weight. This feature makes them suitable for applications demanding a high power-to-weight ratio, such as in aerospace and electric propulsion systems.

- **Reduced Maintenance:** The simplicity of the PMSM design, with fewer moving parts and no rotor windings, leads to reduced maintenance requirements. This simplicity can result in longer operational lifespans and lower overall operating costs.
- **Energy Savings:** The inherent efficiency of PMSMs contributes to energy savings, making them environmentally friendly and cost-effective in the long run. This is particularly crucial in applications where energy efficiency is a primary concern, such as in electric vehicles and renewable energy systems.
- **Suitability for Regenerative Braking:** PMSMs are well-suited for regenerative braking systems in electric vehicles, acting as generators during braking and converting kinetic energy back into electrical energy, thereby improving overall system efficiency.

### 3.2 Challenges of Permanent Magnet Synchronous Motors (PMSMs):

- **Material Costs:** The cost of rare-earth materials, including neodymium and samarium-cobalt used in permanent magnets, can impact the overall cost of PMSMs. Fluctuations in these material prices can influence the economic feasibility of using PMSMs in certain applications.
- **Temperature Sensitivity:** PMSM performance is sensitive to temperature variations, with high temperatures risking demagnetization of permanent magnets or increased electrical resistance, affecting motor efficiency. Cooling systems may be necessary for some applications.
- **Demagnetization Risk:** Operating a PMSM at high currents or under specific fault conditions may pose a risk of demagnetization of the permanent magnets. Proper design and control strategies are necessary to mitigate this risk and ensure long-term motor stability.
- **Complex Control Algorithms:** Implementing advanced control algorithms, such as Field-Oriented Control (FOC), can be complex and may require sophisticated control systems. This complexity can increase costs and pose challenges in terms of system integration and maintenance.
- **Sensitivity to Parameter Variations:** PMSM control systems are sensitive to variations in motor parameters like temperature and magnetic characteristics. Accurate parameter identification and compensation mechanisms are essential for maintaining optimal performance.
- **Rare-Earth Dependency:** The reliance on rare-earth materials for permanent magnets, particularly neodymium, raises concerns about environmental impact and geopolitical considerations associated with the mining and supply chain of these materials.
- **Difficulty in Disposal:** The disposal of rare-earth magnets poses environmental challenges due to their composition. Establishing proper recycling and disposal methods is crucial to minimize environmental impact.

While Permanent Magnet Synchronous Motors (PMSMs) offer numerous advantages, addressing associated challenges is crucial for their widespread adoption and long-term sustainability in various applications. Ongoing research and technological advancements aim to mitigate these challenges and enhance the overall performance of PMSMs.

## IV. CONCLUSION

In conclusion, this review has delved into the intricate realm of Permanent Magnet Synchronous Motors (PMSMs), emphasizing their pivotal role in the landscape of electric motor technologies. With their high efficiency, precise control capabilities, and compact design, PMSMs emerge as crucial contributors to the ongoing quest for energy efficiency and sustainability across diverse applications. The exploration of fundamental principles, design considerations, and control strategies has furnished a comprehensive understanding of PMSMs' workings. The inherent advantages, including high efficiency, precise control, and reduced maintenance, position PMSMs as frontrunners in applications spanning from electric vehicles to industrial automation and renewable energy systems. Nevertheless, the challenges faced by PMSMs, such as material costs, temperature sensitivity, and rare-earth dependency, underscore the necessity for continuous research and development endeavors. Addressing these challenges is imperative for unlocking the full potential of PMSMs and ensuring their sustainable integration into various applications.

Looking to the future, emerging trends like advanced materials, innovative design approaches, and the integration of PMSMs with smart grid technologies present exciting opportunities. Coupled with ongoing efforts to enhance control algorithms and address environmental concerns, these trends promise to further elevate the performance and applicability of PMSMs in the dynamic landscape of electric motor technologies. In essence, this review serves as a roadmap for researchers, engineers, and practitioners navigating the complexities of PMSMs. By synthesizing current knowledge, addressing challenges, and envisioning future possibilities, this paper contributes to the ongoing discourse on PMSMs, fostering a deeper understanding of their role in shaping a more energy-efficient and sustainable future. As we embrace the potential of Permanent Magnet Synchronous Motors, the journey towards greener, more efficient electric motor technologies persists, marking a significant step towards a more sustainable and technologically advanced world.

## REFERENCES

1. Chen, Y., Liang, S., Li, W., Liang, H., & Wang, C. (2019). Faults and diagnosis methods of permanent magnet synchronous motors: A review. *Applied Sciences*, 9(10), 2116.
2. Li, T., Sun, X., Lei, G., Guo, Y., Yang, Z., & Zhu, J. (2022). Finite-control-set model predictive control of permanent magnet synchronous motor drive systems—An overview. *IEEE/CAA Journal of Automatica Sinica*, 9(12), 2087-2105.

3. Ullah, K., Guzinski, J., & Mirza, A. F. (2022). Critical review on robust speed control techniques for permanent magnet synchronous motor (PMSM) speed regulation. *Energies*, 15(3), 1235.
4. Cai, B., Hao, K., Wang, Z., Yang, C., Kong, X., Liu, Z., ... & Liu, Y. (2021). Data-driven early fault diagnostic methodology of permanent magnet synchronous motor. *Expert Systems with Applications*, 177, 115000.
5. Sun, X., Shi, Z., Lei, G., Guo, Y., & Zhu, J. (2019). Analysis and design optimization of a permanent magnet synchronous motor for a campus patrol electric vehicle. *IEEE Transactions on Vehicular Technology*, 68(11), 10535-10544.
6. Qu, L., Qiao, W., & Qu, L. (2020). Active-disturbance-rejection-based sliding-mode current control for permanent-magnet synchronous motors. *IEEE Transactions on Power Electronics*, 36(1), 751-760.
7. Yu, Y., Huang, X., Li, Z., Wu, M., Shi, T., Cao, Y., ... & Niu, F. (2021). Full parameter estimation for permanent magnet synchronous motors. *IEEE Transactions on Industrial Electronics*, 69(5), 4376-4386.
8. Ganguli, S., Kumar, A., Kaur, G., Sarkar, P., & Rajest, S. S. (2021). A global optimization technique for modeling and control of permanent magnet synchronous motor drive. *Innovations in Information and Communication Technology Series*, 074-081.
9. Sun, Y., Zhang, S., Chen, G., Tang, Y., & Liang, F. (2020). Experimental and numerical investigation on a novel heat pipe based cooling strategy for permanent magnet synchronous motors. *Applied Thermal Engineering*, 170, 114970.
10. Xiao, D., Nalakath, S., Rotilli Filho, S., Fang, G., Dong, A., Sun, Y., ... & Emadi, A. (2020). Universal full-speed sensorless control scheme for interior permanent magnet synchronous motors. *IEEE Transactions on Power Electronics*, 36(4), 4723-4737.
11. Hao, Z., Yang, Y., Gong, Y., Hao, Z., Zhang, C., Song, H., & Zhang, J. (2021). Linear/nonlinear active disturbance rejection switching control for permanent magnet synchronous motors. *IEEE Transactions on Power Electronics*, 36(8), 9334-9347.
12. Yang, Yang, Qiang He, Chunyun Fu, Shuiping Liao, and Peng Tan. "Efficiency improvement of permanent magnet synchronous motor for electric vehicles." *Energy* 213 (2020): 118859.