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Recent Developments in Control and Simulation of Permanent Magnet Synchronous Motor Systems

Md Ali Azom [1], Md. Yakub Ali Khan [2]
[1] Department of Mechanical and Power Engineering, Nanjing Tech University, China
[2] Department of Electrical and Electronic Engineering, World University of Bangladesh, Uttara, Dhaka Bangladesh
Email: [1] aliajom786@gmail.com, [2] yakub.bimt@gmail.com
*Corresponding Author

Abstract—**This paper's main goal is to present a thorough analysis of current advancements in the simulation and control of Permanent Magnet Synchronous Motor (PMSM) systems. A crucial part of contemporary electrical drive systems, the Permanent Magnet Synchronous Motor (PMSM) finds extensive use in fields like industrial automation, renewable energy systems, and electric cars. This review examines the most current developments in PMSM system control and simulation, with a focus on cutting-edge modelling techniques, new control strategies, and the most recent simulation methods. It emphasizes how increasingly complex strategies like Model Predictive Control (MPC), Sliding Mode Control (SMC), and AI-based approaches have replaced more conventional ones like PID and vector control. Advanced control techniques like Field-Oriented Control (FOC) and MPC are used by Tesla and other EV manufacturers to maximize PMSM performance, guarantee smooth torque delivery, and improve energy economy. Siemens Gamesa wind turbines use PMSMs with reliable control systems for fault tolerance and maximum energy production in a range of wind conditions. The study also discusses the developments in simulation techniques, such as the incorporation of multi-physics models, real-time simulation, and the application of AI to improve simulation efficiency and accuracy. More realistic modelling of PMSM systems in dynamic contexts is now possible thanks to recent developments in simulation approaches, such as Multiphysics models and real-time simulations. These simulations are combined with sophisticated control algorithms to give real-time input while the system is operating, which speeds up fault finding and optimization. This procedure is further improved by AI-based simulation tools, which forecast system behavior's under varied circumstances and spot possible problems before they arise. It is described how these advancements affect PMSM performance, including increased fault tolerance, robustness, and efficiency. The study concludes by highlighting the significance of integrating cutting-edge control and simulation approaches for optimal performance in PMSM systems, as well as important research issues and prospects.**

Keywords—***Control, Simulation, Permanent Magnet, Motor Systems, Challenges***

I. INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) have become integral to modern industries due to their superior performance, efficiency, and reliability compared to other motor types. Because of their high-power density, small size, and superior torque-to-weight ratio, these motors are perfect for applications that demand energy efficiency and precision control.

In the automobile industry, PMSMs are essential components of hybrid electric vehicles (HEVs) and electric cars (EVs), allowing for improved performance while using less energy [1]. They are essential to renewable energy systems like solar trackers and wind turbines because they generate power reliably and efficiently. Additionally, PMSMs are frequently utilized in industrial automation for conveyor systems, robots, and CNC machines, where their resilience and ability to precisely place objects are essential [2]. PMSMs are the go-to option for crucial applications in medical and aeronautical systems, like MRI scanners and surgical robots, because to their high dependability and minimal maintenance needs. The significance of PMSMs keeps increasing as companies move toward automation and more energy-efficient technologies, highlighting the necessity for sophisticated control and simulation methods to fully realize their potential. Multiphysics simulations have high computational requirements, particularly when combining mechanical, thermal, and electromagnetic models. When there is a large dynamic load or very low speed, sensor less control methods are not very accurate. In order to optimize PMSM designs for thermal reliability and energy economy, Tesla had to use hybrid modelling techniques, which cut down on computation time.

The nonlinear dynamics, parameter sensitivity, and reliance on exact control techniques of Permanent Magnet Synchronous Motors (PMSMs) make them difficult to manage and simulate. Controlling PMSMs is made more difficult by their intrinsic nonlinear features, which include temperature-dependent fluctuations, magnetic saturation, and back electromotive force (EMF). Advanced control strategies that can adapt to dynamic changes in operating conditions are necessary to address these nonlinearities [3]. Accurate understanding of factors such as rotor position, resistance, and inductance is crucial for PMSM performance. Control precision and efficiency can be weakened by variations in these parameters brought on by aging, temperature changes, or inconsistent manufacturing. Accurate rotor position data is necessary for the efficient control of PMSMs, especially in field-oriented control (FOC) and vector control. For Permanent Magnet Synchronous Motors (PMSMs), Field-Oriented Control (FOC) is a popular motor control technique that allows fine torque and speed control by independently regulating the magnetic flux and torque-producing components. While sensor less approaches may experience decreased accuracy at low speeds or under variable load situations, sensor-based systems raise issues with cost and dependability [4]. High-speed, high-precision control is required for applications like robotics and electric cars, which can be difficult because controllers must compute quickly and respond in real time. Accurate models that take into consideration mechanical, thermal, and electromagnetic interactions are necessary for high-fidelity simulation of PMSM systems. Creating such thorough models can be time-consuming and computationally costly. Furthermore, it might be difficult to make sure that simulation findings match actual behavior, especially when it comes to digital twin creation and hardware-in-the-loop (HIL) testing. Hardware-in-the-Loop (HIL) is a simulation technique that eliminates the requirement for actual prototypes by connecting a physical controller to a simulated motor and system environment. This enables real-time testing and validation. Communication, data processing, and cybersecurity issues arise when PMSMs are integrated into Industry 4.0 settings and IoT-enabled devices. Furthermore, incorporating artificial intelligence and machine learning into control systems requires a substantial investment of time and knowledge [5]. Continuous improvements in control algorithms, real-time simulation tools, and sturdy hardware platforms are needed to address these issues and allow PMSMs to reach their maximum potential in a variety of applications.

This paper's main goal is to present a thorough analysis of current advancements in the simulation and control of Permanent Magnet Synchronous Motor (PMSM) systems. Improvements in control strategies and modeling techniques are necessary to optimize PMSM performance, efficiency, and reliability as they continue to play a crucial role in a variety of sectors. By providing insights into cutting-edge methodologies and their uses, this paper seeks to close the gap between developing technology and real-world applications. This essay discusses several different subjects, such as principles of PMSM functioning and modeling [6].

comprehensive review of both traditional and contemporary control techniques. Thorough rundown of the platforms and simulation tools utilized in PMSM research. new developments, such how AI and IoT are helping to advance PMSM technologies. Examples and case studies of PMSM uses across a range of sectors.

II. FUNDAMENTALS OF PMSM SYSTEMS

In a variety of applications, Permanent Magnet Synchronous Motors (PMSMs) are well known for their accuracy, dependability, and efficiency. grasp their outstanding performance requires a grasp of their structure and guiding principles. The electromagnetic interaction between the rotor and stator magnetic fields is the basis for the operation of permanent magnet synchronous motors, or PMSMs [7]. A revolving magnetic field is produced when the stator windings receive a three-phase alternating current (AC). Synchronous speed is the speed at which the rotor, which is equipped with permanent magnets, rotates in synchronization with this rotating field. The rotor is driven by torque, which is produced by the interaction of the magnetic fields [8]. PMSM efficiency depends on accurate stator current management, which is usually accomplished using methods like Direct Torque management (DTC) or Field-Oriented Control (FOC). These techniques efficiently coordinate the current and magnetic fields to maximize torque production and reduce losses. In order to facilitate appropriate commutation and speed regulation, an inverter also transforms the DC power source into a three-phase AC input for the stator. PMSMs are very effective and appropriate for applications requiring great performance and precision because of their precise control and magnetic field synchronization [9].

The high torque-to-weight ratio of PMSMs makes them desirable for applications like robotics and electric cars that call for small and light designs. High efficiency is attained because there are no current rotor losses because the rotor generates its magnetic field using permanent magnets rather than an external power source [10]. Variable-speed applications can benefit from PMSMs' broad operating speed range, which includes both constant torque and constant power regions. PMSMs have a high-power factor because they use less reactive power, which increases energy efficiency and lowers system losses overall. Since temperature changes can alter the characteristics of permanent magnets and winding resistance, performance is dependent on the motor's thermal behavior. For high-performance applications like industrial automation and precision machinery, the capacity to swiftly adjust to variations in load and speed is crucial [11]. For applications like medical equipment that need to run smoothly, less harmonic distortion and less acoustic noise are essential. Effective control, especially in Field-Oriented Control (FOC) and vector control schemes, require precise knowledge of the rotor position. There are two ways to implement the PMSM drive: (i) open loop control and (ii) closed loop control. Fig. 1 displays the PMSM drive's implementation block diagram. For Permanent Magnet Synchronous Motors (PMSMs) to operate as efficiently as possible, an accurate parameter estimate is essential. Important variables that directly affect control techniques and motor efficiency include converters, load, and sensing elements. The process of parameter estimates, and validation is much improved by the combination of Field-Oriented Control (FOC) and Hardware-in-the-Loop (HIL) systems, bolstering the argument.

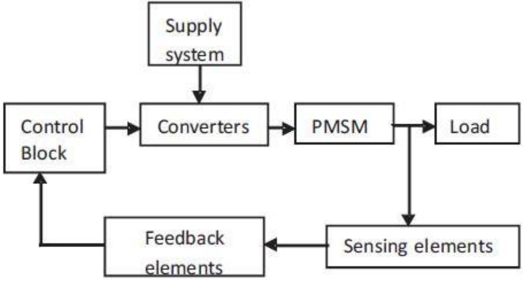

Fig. 1. Parameter estimation of permanent magnet synchronous motor

For Permanent Magnet Synchronous Motors (PMSMs), parameter estimation is crucial to performance optimization and the application of sophisticated control techniques. To precisely estimate important characteristics including resistance, inductance, flux linkage, and thermal properties, a variety of methods, instruments, and algorithms are used. Although they are computationally costly, offline methods such as Finite Element Method (FEM) simulations using programs like ANSYS Maxwell or COMSOL Multiphysics and experimental testing [12]. Nonlinearities such cogging torque, temperature-induced fluctuations, and magnetic saturation must be adjusted for via controllers. Control algorithms must be robust against modifications in motor properties (such as resistance and inductance) brought on by age or temperature variations. Reliable performance in mission-critical applications requires ongoing operation even in the face of faults, such as electrical disruptions or sensor failures. Advanced control algorithms, particularly for battery-powered systems like electric vehicles, should concentrate on reducing energy usage while preserving performance. PMSMs can provide optimal performance in a variety of demanding industrial and commercial applications by concentrating on these critical performance factors and following exact control specifications [13].

III. CONTROL STRATEGIES FOR PMSMS

Traditional control techniques are essential to the functioning of Permanent Magnet Synchronous Motors (PMSMs), offering efficiency and stability in a range of applications. Because of their ease of use and efficiency, Field-Oriented Control (FOC) and Proportional-Integral (PI) controllers are popular among these techniques. In PMSM control systems, PI controllers are frequently used to control torque, current, and speed. By modifying the control inputs, they reduce the discrepancy between the intended and actual values of a parameter, like rotor speed [14]. While the integral term gradually removes steady-state mistakes, the proportional term corrects faults instantly based on their magnitude. PI controllers are appropriate for a wide range of industrial applications due to their ease of implementation and computational efficiency. However, dynamic conditions or changes in parameters can cause their performance to deteriorate, necessitating careful adjustment for best outcomes.

The variable-frequency drive (VFD) control technique known as vector control, or field-oriented control (FOC), identifies the stator currents of a three-phase AC or brushless DC electric motor as two orthogonal components that can be represented by a vector. The torque and magnetic flux of the motor are determined by two different components. The drive's control system uses the torque and flux references provided by the speed control to determine the associated current component references shown in Fig. 2. The motor's outstanding dynamic performance and efficient operation are guaranteed by this decoupling [15]. Applications requiring exact speed and torque control, such robotics and electric cars, are better served by FOC. Notwithstanding its efficiency, FOC necessitates precise rotor position sensing and parameter expertise, which can make the system more complex. Both FOC and PI controllers are fundamental techniques in PMSM control, providing harmony of performance, dependability, and ease of use. To satisfy the requirements of contemporary applications, more sophisticated control strategies have been developed because of their shortcomings in managing nonlinearities and parameter variations [16]. Permanent Magnet Synchronous Motors (PMSMs) are increasingly using Model Predictive Control (MPC), a sophisticated control technique, due to its capacity to manage multi-variable control requirements, nonlinearities, and system restrictions. In contrast to conventional control techniques, MPC forecasts future behavior over a limited time horizon using a dynamic model of the motor. It solves a mathematical optimization problem at each control step to optimize control inputs, guaranteeing that the system maintains operational restrictions while attaining the intended performance [17]. The nonlinear dynamics of PMSMs, such as changes in parameters like resistance and inductance, are especially well-managed by MPC. Its predictive nature also enables it to anticipate changes in operating conditions and correct for disturbances, which makes it ideal for high-performance applications like robotics and electric vehicles. A reliable nonlinear control method that is frequently used to manage Permanent Magnet Synchronous Motors (PMSMs) is Sliding Mode Control (SMC). SMC works by pushing the system states in the direction of a predetermined sliding surface in the state space and keeping them there despite outside disruptions or ambiguities in the parameters. The sliding surface is made to guarantee the motor's intended performance, including exact speed or torque control [18].

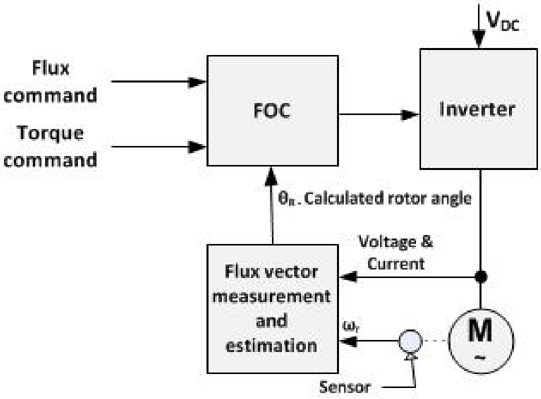

Fig. 2. Vector control of motor

SMC's resilience to external disturbances and parameter fluctuations is one of its main benefits, which makes it appropriate for PMSM systems with nonlinearities like magnetic saturation or temperature-induced changes. SMC guarantees that the system rapidly converges to the sliding surface and remains there, attaining precise and stable control, by employing discontinuous control law. It's critical to weigh the benefits, drawbacks, and applicability of different control strategies for Permanent Magnet Synchronous Motors (PMSMs) according to the demands of the application [19]. A comparison of several popular control techniques, such as Sliding Mode Control (SMC), Field-Oriented Control (FOC), Model Predictive Control (MPC), and Proportional-Integral (PI) control, is shown below. The requirements of the PMSM application determine which control method is best. While FOC or MPC will be advantageous for high-performance applications like robotics or electric vehicles, PI control may be adequate for low-cost and less demanding jobs. SMC provides a potent answer for settings where resilience to disturbances is essential. Several variables, including system complexity, computational resources, and performance needs, will always determine the best option [20].

IV. SIMULATION TECHNIQUES FOR PMSM SYSTEMS

The design, analysis, and optimization of Permanent Magnet Synchronous Motors (PMSMs) and their control schemes heavily rely on simulation tools and platforms. Before a motor is physically implemented, engineers and researchers can use these tools to model the motor, simulate its behavior under different operating conditions, and optimize its performance. MATLAB/Simulink is a widely used platform for modeling, simulating, and analyzing dynamic systems, including PMSMs [21]. It offers a comprehensive suite of toolboxes and built-in blocks that allow users to design control algorithms, simulate motor behavior, and visualize system responses. Simulink provides graphical, block-based modeling, making it easy to represent complex systems with minimal coding. MATLAB/Simulink provides specialized toolboxes for motor control, including Field-Oriented Control (FOC) and Model Predictive Control (MPC), allowing users to design and test control algorithms. Supports detailed simulations of both electrical and mechanical components of PMSMs, including rotor dynamics, torque generation, and control systems. With Simulink Real-Time, engineers can implement hardware-in-the-loop (HIL) simulations and validate algorithms on real hardware. Modeling Flexibility: It provides the flexibility to model both detailed electrical characteristics of the PMSM and system-level dynamics, making it suitable for testing various designs and control strategies [22]. Fig. 3 shows an illustrative comparison between the proposed method and traditional methods. In the next section, experimental verification and further analysis are carried out using simulation data.

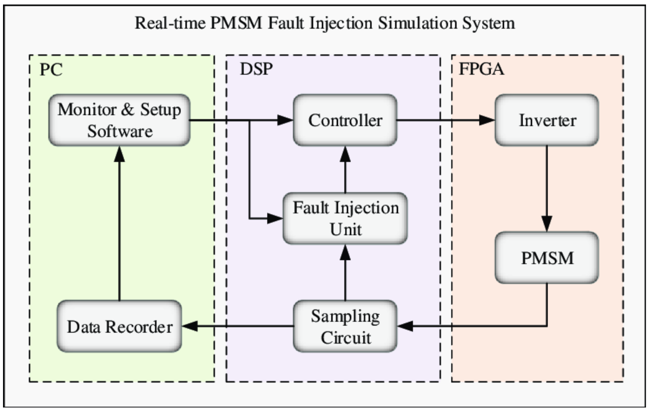

Fig. 3. Schematic diagram of real-time PMSM fault injection simulation

Precise mathematical modelling is necessary for Permanent Magnet Synchronous Motors (PMSMs) to guarantee effective control and realistic simulation for practical applications. Two main topics are covered in this section dynamic models expressed in state-space form and models of voltage and current. A PMSM's equivalent circuit model is used to derive its voltage equations. These formulas explain the connection between the windings' resistance, back electromotive force (EMF), and applied voltage. The interaction of the stator resistances and inductances affects the current dynamics. These dynamics are essential for figuring out how well the motor can generate torque and maintain stability under different load scenarios. Advanced control techniques like Model Predictive Control (MPC) and observer design for parameter estimation are made possible by state-space models. Additionally, they play a crucial role in the analysis of stability margins, transient behaviors, and real-time control performance [23].

PMSMs may be precisely simulated under a range of operating situations by integrating these mathematical models, opening the door to improved efficiency and reliable performance in applications such as renewable energy systems and electric vehicles. A strong computational tool that is frequently used for the electromagnetic simulation of permanent magnet synchronous motors (PMSMs) is finite element analysis (FEA). Designing and evaluating the intricate relationships inside PMSMs requires FEA, which offers comprehensive insights into how well they function in a range of operational scenarios [24]. The magnetic flux density, field dispersion, and motor interactions can all be precisely calculated thanks to FEA. This is crucial for assessing the rotor, stator, and permanent magnets' performance.

Engineers can calculate copper losses, eddy current losses, and core losses using FEA. These computations aid in maximizing motor efficiency and pinpointing regions in need of development. To ensure smooth operation and reduce vibrations, FEA offers precise forecasts of electromagnetic forces, torque ripples, and cogging torque. Thermal models and electromagnetic simulations can be used to examine the effects of heat on motor performance, especially in situations requiring large currents or extended operation.

It is essential to incorporate control techniques into simulation frameworks when building and assessing Permanent Magnet Synchronous Motor (PMSM) systems. It guarantees that the motor will run effectively and dependably in a variety of situations, such as with different loads, speeds, and climatic factors. Simulation frameworks are used to create common control systems like Direct Torque Control (DTC) and Field-Oriented Control (FOC) [25]. To deal with non-linearities and parameter fluctuations, more sophisticated techniques like adaptive control and model predictive control (MPC) can be used [26]. Before deploying the motor in real-world applications, simulations allow for the fine-tuning of controller parameters, such as PI gains, to obtain optimal performance. A crucial first step in comprehending and improving the behaviour of PMSM systems under various operating situations is performance study using simulation. Engineers can anticipate and resolve problems with efficiency, thermal control, and dynamic response with the aid of simulations. Simulations evaluate the motor's performance under nominal, heavy, and light load scenarios. Current consumption, torque ripple, and speed stability are among the metrics that are assessed. Model situations that range from high-speed operation for maximum power production to low-speed operation for high-precision activities [27]. Analyse the thermal impact and efficiency at various speeds. identifies possible problems during the design stage, lowering the possibility of failure in practical applications. Virtual testing environments are provided, which removes the requirement for extensive prototyping [28]. Aids in optimising control algorithms, heat management systems, and motor design for optimal performance.

High processing demands for precise multi-domain models. Guaranteeing the accuracy of control models in co-simulation settings. Real-world uncertainties are taken into account in virtual simulations. Through the incorporation of sophisticated control techniques into simulation models and thorough evaluations under various operational scenarios, PMSM systems can be developed to satisfy the exacting requirements of contemporary applications such as industrial automation and electric cars [29].

V. RECENT DEVELOPMENTS IN PMSM CONTROL AND SIMULATION

The increasing need for dependable, high-performance, and energy-efficient motor solutions in fields like industrial automation, renewable energy systems, and electric vehicles has spurred major developments in the field of permanent magnet synchronous motor (PMSM) control systems in recent years. In order to overcome issues including nonlinearity, parameter sensitivity, and efficiency optimization, recent research has concentrated on improving control techniques. The following summarizes the main conclusions from current research and developments in PMSM control systems. FOC remains a cornerstone of PMSM control due to its ability to achieve high precision in torque and speed control. Recent studies emphasize the integration of real-time adaptive tuning to address parameter variations during operation. Zhao et al. (2023) proposed an improved FOC with an adaptive observer to enhance stability under variable loads. To reduce torque ripple and increase response time, DTC has developed with improved switching strategies and predictive control algorithms [30].

To improve transient performance, Singh et al. (2022) presented a hybrid DTC that blends traditional techniques with estimators based on neural networks. Recent studies demonstrate that MPC can manage multi-objective optimization, including preserving thermal balance and minimizing losses in PMSM systems [31]. An MPC framework was created by Nguyen et al. (2023) to reduce energy usage while maintaining reliable performance under a range of operational circumstances. Using observer-based techniques and machine learning algorithms, sensor less control solutions are growing in popularity to lessen reliance on physical sensors while preserving high accuracy in rotor position and speed prediction [32]. A novel Kalman filter-based observer for sensor less PMSM drives was presented by Li et al. (2023), which achieved improved robustness and a lower computing load. Fault-tolerant control systems have gained popularity as PMSMs are used in more important applications. Strategies to identify and address defects like open-phase or short-circuit problems without sacrificing performance have been the focus of research [33]. A redundancy-based control system that isolates problematic phases while preserving stable operation was proposed by Kumar et al. in 2022. For accurate simulation of thermal and electromagnetic behavior, recent developments have integrated control algorithms with finite element analysis (FEA). To maximize PMSM performance in electric vehicles, Patel et al. (2023) integrated an adaptive controller with FEA-based electromagnetic modelling. It is clear from examining and combining these developments that PMSM control systems are evolving towards more intelligent, resilient, and energy-efficient solutions that satisfy the intricate requirements of contemporary applications.

In PMSM control systems, the combination of machine learning (ML) and artificial intelligence (AI) has become revolutionary. Adaptive and predictive control systems are increasingly being designed using AI-driven algorithms, such as neural networks and reinforcement learning. These methods offer reliable issue diagnosis and mitigation, enhance energy efficiency, and optimize performance. Before implementing PMSM systems in real-world applications, control techniques must be tested and validated using real-time simulation [34]. To accommodate intricate, high-fidelity models, recent advancements have concentrated on decreasing simulation latency and boosting computational efficiency. Electrical, mechanical, and thermal models must be combined into a single modelling framework to fully comprehend PMSM performance. Accurate predictions of system behavior under various operational and environmental conditions are made possible by multi-physics models. A paradigm shift in PMSM technology has been brought about by developments in AI-driven control, real-time simulation, and multi-physics modelling. These developments support the dependability and sustainability of PMSM systems in a variety of applications in addition to improving performance and efficiency [35].

VI. CHALLENGES AND OPEN ISSUES

Because of the intricate interplay between their mechanical, thermal, and electromagnetic domains, PMSM systems are intrinsically nonlinear. Accurate modelling, control, and performance optimization are severely hampered by these nonlinearities [36]. Developing accurate control techniques is made more difficult by the nonlinear relationship between flux and current under magnetic saturation circumstances.

The efficiency of the system is impacted by extra nonlinear dynamics brought about by magnetic hysteresis and eddy currents, especially at high speeds or frequencies. Variations in parameters, environmental influences, and measurement technique constraints all contribute to uncertainty in PMSM models. Both electrical and thermal models are impacted by these uncertainties, which lessen their dependability and practicality [37]. Temperature, ageing, and load conditions all affect important characteristics including stator resistance, inductance, and permanent magnet flux linkage. Unpredictability in system behavior is introduced by external influences such as electromagnetic interference, mechanical vibrations, and temperature changes [38].

Developing robust and adaptive control techniques is a challenging undertaking due to nonlinearities and model uncertainty. In these circumstances, conventional linear control techniques might not work well enough. Instability can result from nonlinear dynamics, especially when operating at high speeds or loads. To maintain optimal performance, control techniques must take external disturbances and parameter fluctuations into account [39].

Even with advancements in PMSM modelling and control, there are still several unresolved problems that call for more study and creativity. creating models that faithfully depict PMSM systems' nonlinear behavior while avoiding undue computational loads. It is still difficult to identify and compensate for model uncertainties in real time, especially for high-speed applications.

For Permanent Magnet Synchronous Motor (PMSM) systems to accurately simulate their real-world behavior, electrical, mechanical, and thermal models must be integrated into a coherent multi-physics simulation framework. It is difficult to integrate results from specialized software for the mechanical (e.g., vibration modelling), thermal (e.g., heat transfer simulations), and electrical (e.g., electromagnetic finite element analysis) domains. Multi-physics models will be much more useful in PMSM system design and optimization if these issues are resolved [40].

VII. APPLICATIONS OF PMSM IN VARIOUS INDUSTRIES

Electric vehicles (EVs) frequently use permanent magnet synchronous motors (PMSMs) because of their excellent torque-to-weight ratio, small size, and great efficiency. The performance and dependability of PMSMs in EV applications have been greatly improved by the incorporation of sophisticated control and simulation techniques.

By precisely managing torque and speed, advanced control techniques including field-oriented control (FOC) and model predictive control (MPC) increase energy efficiency during drive cycles. To ensure optimal performance, these solutions can be tested under various road conditions using simulation models.

Predicting heating effects and improving cooling system designs are made easier by simulations that combine electrical and thermal models. This improves longevity and dependability by guaranteeing the motor runs within safe thermal bounds.

Effective motor control lowers power losses, which immediately increases EV range. Precise simulations of PMSM dynamics aid in the improvement of energy utilizations strategies, which in turn extend battery life [41].

Because of their great efficiency, dependability, and versatility in operating speeds, permanent magnet synchronous motors, or PMSMs, are being used more and more in renewable energy systems, especially in wind turbines. Even under challenging environmental circumstances, performance has significantly improved because of the integration of PMSMs with wind energy systems.

With direct-drive wind turbines, PMSMs are perfect because they do not require a gearbox. This improves system reliability, lowers maintenance needs, and streamlines the mechanical design especially in offshore wind farms with difficult access. When paired with cutting-edge control techniques like field-oriented control (FOC), the intrinsic properties of PMSMs allow for effective operation at varying wind speeds, maximizing energy capture and minimizing energy losses [42].

Extreme weather conditions such excessive humidity, temperature swings, and exposure to salt are ideal for PMSMs. Precise mechanical and thermal models aid in design optimization to guarantee robustness and dependability under such conditions [43]. PMSMs greatly enhance the dependability and sustainability of renewable energy systems, especially in the expanding wind energy industry, by fusing high efficiency, sturdy architecture, and sophisticated control systems.

VIII. FUTURE TRENDS AND DIRECTIONS

Because of their high efficiency and fine control capabilities, PMSM drives are expected to become more and more integrated into renewable energy systems like solar and wind. Because PMSMs can adapt to changing operating circumstances, they are perfect for intermittent renewable energy sources. Future developments will concentrate on better energy storage management, hybrid renewable systems that combine several energy sources, and optimising PMSM motors for smooth grid integration [44]. PMSM drive control and monitoring are being revolutionised by IoT-enabled systems, which offer real-time insights into system health and performance. By using real-time simulation, operating parameters can be dynamically changed, increasing productivity and decreasing downtime. By enabling self-learning and adaptable systems, artificial intelligence (AI) has the potential to completely transform PMSM control. Real-time control strategy optimisation is possible using AI-based algorithms that take operational and environmental changes into consideration [45]. PMSM drive simulation tools are developing to reduce computational overhead and increase accuracy. More thorough system analysis will be made possible by emerging methods such hybrid multi-physics models that combine mechanical, thermal, and electrical elements. By tackling these tendencies, PMSM technology will keep up with the needs of contemporary applications, spurring innovation in a variety of sectors and enhancing sustainability, performance, and dependability [46].

IX. DISCUSSION

The efficiency, dependability, and adaptability of Permanent Magnet Synchronous Motor (PMSM) systems in a range of applications have been greatly enhanced by recent developments in control and modelling. A strong framework for maximizing PMSM performance has been made possible by the combination of sophisticated control tactics, creative modelling approaches, and state-of-the-art simulation tools.

The accuracy and dynamic reactivity of PMSM systems have been improved by contemporary control techniques such vector control, direct torque control, and model predictive control. PMSMs can now manage complicated operating conditions and fluctuating loads thanks to the significantly enhanced adaptive control brought about by the integration of machine learning and artificial intelligence. The sophistication of fault-tolerant control systems has increased, guaranteeing continuous operation even in vital applications such as renewable energy systems and electric automobiles. In the design and study of PMSM systems, simulation has played a crucial role. Motor design can now be optimized thanks to the comprehensive insights into electromagnetic behaviors that Finite Element Analysis (FEA) has supplied. Control system design has benefited from the efficient dynamic simulations made possible by state-space models and dq-axis transformations. Even with these developments, several obstacles still exist. The accuracy of electrical models is nevertheless impacted by high-frequency harmonics, nonlinearities in magnetic materials, and model uncertainties. Similarly, it is still difficult to predict dynamic thermal behaviors under fluctuating loads and acquire accurate thermal characteristics. Another drawback is the computational demands of intricate simulations, like those utilizing multi-physics models or FEA, especially for real-time applications.

Real-time control and the Internet of Things are becoming increasingly important in PMSM applications, according to recent trends. Predictive maintenance and dynamic adjustments are made possible by IoT-enabled equipment, increasing productivity and decreasing downtime.

Additionally, self-learning and self-optimizing PMSMs are being made possible by AI-based adaptive control systems. The advancement of distributed and cloud-based simulation methods holds promise for resolving computing issues and facilitating large-scale, real-time simulations. The incorporation of multi-physics models, which integrate mechanical, thermal, and electrical elements into a single modelling framework, is among the most important recent advancements. Deeper understanding of the functionality and dependability of PMSM systems in practical settings has been made possible by this all-encompassing approach. Innovations in PMSM have been fueled in large part by the cooperation between simulation and control. While simulations allow for virtual prototyping, which cuts down on development time and expenses, control strategies guarantee operational stability and efficiency. By bridging the gap between theoretical models and real-world applications, the ability to simulate multi-physics interactions has ensured that PMSM systems operate dependably in a variety of settings.

In conclusion, recent advancements in PMSM simulation and control have greatly expanded their capabilities, making them essential in a variety of industries, from renewable energy systems to electric automobiles. The performance, dependability, and sustainability of PMSM systems will be further improved by ongoing research and innovation in this area, guaranteeing their continued relevance in a fast-changing technological environment.

X. CONCLUSION

The performance, efficiency, and dependability of Permanent Magnet Synchronous Motor (PMSM) systems have been significantly improved by developments in control and simulation methodologies. To meet the intricate needs of diverse industries, this review emphasizes the significance of contemporary control systems such vector control, direct torque control, and AI-based adaptive methods. The dynamic response, accuracy, and fault tolerance of PMSM systems have been greatly enhanced by these control techniques, which qualify them for demanding applications such as industrial automation, renewable energy systems, and electric vehicles. A deeper comprehension of PMSM behavior under various operating situations has been made possible by the incorporation of advanced simulation approaches, such as state-space modelling, multi-physics frameworks, and finite element analysis. Higher performance and dependability have been ensured by optimizing motor design, thermal control, and mechanical durability thanks in large part to these simulation models. Notwithstanding the advancements, problems still exist, including high-frequency harmonics, nonlinearities in magnetic materials, and the processing needs of real-time simulations. Energy losses are further decreased by recent developments in motor design, such as the use of rare-earth magnets with higher magnetic flux densities. In electric vehicles (EVs), for example, PMSMs can reach up to 96% efficiency, reducing energy waste and extending driving range. More developments in adaptive control techniques, computational efficiency, and modelling accuracy are needed to overcome these obstacles. Future research and innovation in PMSM systems could go in encouraging areas thanks to emerging trends including real-time simulations, AI-driven optimization, and IoT-enabled systems. In conclusion, the possibilities of PMSM systems have been redefined by the combination of sophisticated control strategies and thorough simulation approaches. PMSMs will continue to be at the forefront of contemporary applications thanks to ongoing research and integration of cutting-edge technologies, supporting technological advancement in a variety of fields and promoting sustainability and energy efficiency.

REFERENCES

[1] R. Krishnan, “Permanent magnet synchronous and induction motor drives,” *CRC Press*, 2017, https://doi.org/10.1201/9781420014235.

[2] V. Alex, A. Rammohan, “Drive control strategies for PMSM drives in electric vehicles,” *Green Machine Learning and Big Data for Smart Grids*, pp. 185-197, 2025, https://doi.org/10.1016/B978-0-443-28951-4.00014-9.

[3] O. E. Özçiflikçi, M. Koç, S. Bahçeci, S. Emiroğlu, “Overview of PMSM control strategies in electric vehicles: a review,” *International Journal of Dynamics and Control*, vol. 12, no. 6, pp. 2093-2107, 2024, https://doi.org/10.1007/s40435-023-01314-2.

[4] T. Orlowska-Kowalska *et al*., "Fault Diagnosis and Fault-Tolerant Control of PMSM Drives–State of the Art and Future Challenges," *IEEE Access*, vol. 10, pp. 59979-60024, 2022, https://doi.org/10.1109/ACCESS.2022.3180153.

[5] A. Milecki, P. Nowak, “Review of fault-tolerant control systems used in robotic manipulators,” *Applied Sciences*, vol. 13, no. 4, p. 2675, 2023, https://doi.org/10.3390/app13042675.

[6] C. Liu and Y. Luo, "Overview of advanced control strategies for electric machines," *Chinese Journal of Electrical Engineering*, vol. 3, no. 2, pp. 53-61, 2017, https://doi.org/10.23919/CJEE.2017.8048412.

[7] P. Tang, Z. Zhao, H. Li, “Transient Temperature Field Prediction of PMSM Based on Electromagnetic-Heat-Flow Multi-Physics Coupling and Data-Driven Fusion Modeling,” *SAE International Journal of Advances and Current Practices in Mobility*, vol. 6, no. 4, pp. 2379-2389, 2024, https://doi.org/10.4271/2023-01-7031.

[8] S. Zhao, F. Blaabjerg and H. Wang, "An Overview of Artificial Intelligence Applications for Power Electronics," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 4633-4658, 2021, https://doi.org/10.1109/TPEL.2020.3024914.

[9] M. Furmanik, L. Gorel, D. Konvičný, P. Rafajdus, “Comparative study and overview of field-oriented control techniques for six-phase PMSMs,” *Applied Sciences*, vol. 11, no. 17, p. 7841, 2021, https://doi.org/10.3390/app11177841.

[10] A. Veltman, D. W. Pulle, R. W. De Doncker, “Fundamentals of electrical drives,” *Springer*, vol. 345, 2016, https://doi.org/10.1007/978-3-319-29409-4.

[11] V. Teymoori, M. Kamper, R. J. Wang, R. Kennel, “Sensorless control of dual three-phase permanent magnet synchronous machines—A review,” *Energies*, vol. 16, no. 3, p. 1326, 2023, https://doi.org/10.3390/en16031326.

[12] S. Sakunthala, R. Kiranmayi and P. N. Mandadi, "A Review on Speed Control of Permanent Magnet Synchronous Motor Drive Using Different Control Techniques," *2018 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS)*, pp. 97-102, 2018, https://doi.org/10.1109/ICPECTS.2018.8521574.

[13] M. A. Hannan, J. A. Ali, P. J. Ker, A. Mohamed, M. S. H. Lipu and A. Hussain, "Switching Techniques and Intelligent Controllers for Induction Motor Drive: Issues and Recommendations," *IEEE Access*, vol. 6, pp. 47489-47510, 2018, https://doi.org/10.1109/ACCESS.2018.2867214.

[14] J. Zhang, W. Zhan and M. Ehsani, "Diagnosis and Fault-Tolerant Control of Permanent Magnet Synchronous Motors With Interturn Short-Circuit Fault," *IEEE Transactions on Control Systems Technology*, vol. 31, no. 4, pp. 1909-1916, 2023, https://doi.org/10.1109/TCST.2023.3239426.

[15] D. F. Valencia, R. Tarvirdilu-Asl, C. Garcia, J. Rodriguez and A. Emadi, "Vision, Challenges, and Future Trends of Model Predictive Control in Switched Reluctance Motor Drives," *IEEE Access*, vol. 9,

pp. 69926-69937, 2021, https://doi.org/10.1109/ACCESS.2021.3078366.

[16] M. Monadi, M. Nabipour, F. Akbari-Behbahani and E. Pouresmaeil, "Speed Control Techniques for Permanent Magnet Synchronous Motors in Electric Vehicle Applications Toward Sustainable Energy Mobility: A Review," *IEEE Access*, vol. 12, pp. 119615-119632, 2024, https://doi.org/10.1109/ACCESS.2024.3450199.

[17] Y. Lu, Z. Jiang, C. Chen, Y. Zhuang, "Energy efficiency optimization of field-oriented control for PMSM in all electric system," *Sustainable Energy Technologies and Assessments*, vol. 48, p. 101575, 2021, https://doi.org/10.1016/j.seta.2021.101575.

[18] P. G. Carlet, A. Favato, S. Bolognani and F. Dörfler, "Data-Driven Continuous-Set Predictive Current Control for Synchronous Motor Drives," *IEEE Transactions on Power Electronics*, vol. 37, no. 6, pp. 6637-6646, 2022, https://doi.org/10.1109/TPEL.2022.3142244.

[19] M. F. Elmorshedy, W. Xu, F. F. M. El-Sousy, M. R. Islam and A. A. Ahmed, "Recent Achievements in Model Predictive Control Techniques for Industrial Motor: A Comprehensive State-of-the-Art," *IEEE Access*, vol. 9, pp. 58170-58191, 2021, https://doi.org/10.1109/ACCESS.2021.3073020.

[20] K. Ullah, J. Guzinski, A. F. Mirza, "Critical review on robust speed control techniques for permanent magnet synchronous motor (PMSM) speed regulation," *Energies*, vol. 15, no. 3, p. 1235, 2022, https://doi.org/10.3390/en15031235.

[21] X. Sun, L. Chen and Z. Yang, "Overview of Bearingless Permanent-Magnet Synchronous Motors," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 12, pp. 5528-5538, 2013, https://doi.org/10.1109/TIE.2012.2232253.

[22] J. Peng, M. Yao, "Overview of predictive control technology for permanent magnet synchronous motor systems," *Applied Sciences*, vol. 13, no. 10, p. 6255, 2023, https://doi.org/10.1109/JAS.2022.105851.

[23] T. Li, X. Sun, G. Lei, Y. Guo, Z. Yang and J. Zhu, "Finite-Control-Set Model Predictive Control of Permanent Magnet Synchronous Motor Drive Systems—An Overview," *IEEE/CAA Journal of Automatica Sinica*, vol. 9, no. 12, pp. 2087-2105, 2022, https://doi.org/10.1109/JAS.2022.105851.

[24] S. Suganthi, R. Karpagam, "Dynamic performance improvement of PMSM drive using fuzzy-based adaptive control strategy for EV applications," *Journal of Power Electronics*, vol. 23, no. 3, pp. 510-521, 2023, https://doi.org/10.1007/s43236-023-00594-3.

[25] Y. Yin *et al*., "Disturbance and Uncertainty Attenuation for Speed Regulation of PMSM Servo System Using Adaptive Optimal Control Strategy," *IEEE Transactions on Transportation Electrification*, vol. 9, no. 2, pp. 3410-3420, 2023, https://doi.org/10.1109/TTE.2022.3227070.

[26] T. Pajchrowski, K. Zawirski, "Application of artificial neural network for adaptive speed control of PMSM drive with variable parameters," *COMPEL-The international journal for computation and mathematics in electrical and electronic engineering*, vol. 32, no. 4, pp. 1287-1299, 2013, https://doi.org/10.1109/TIE.2018.2826480.

[27] A. T. Nguyen, M. S. Rafaq, H. H. Choi and J. -W. Jung, "A Model Reference Adaptive Control Based Speed Controller for a Surface-Mounted Permanent Magnet Synchronous Motor Drive," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 12, pp. 9399-9409, 2018, https://doi.org/10.1109/TIE.2018.2826480.

[28] L. Dang, N. Bernard, N. Bracikowski and G. Berthiau, "Design Optimization with Flux Weakening of High-Speed PMSM for Electrical Vehicle Considering the Driving Cycle," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 12, pp. 9834-9843, 2017, https://doi.org/10.1109/TIE.2017.2726962.

[29] F. Yi *et al*., "Response Analysis and Stator Optimization of Ultrahigh-Speed PMSM for Fuel Cell Electric Air Compressor," *IEEE Transactions on Transportation Electrification*, vol. 9, no. 4, pp. 5098-5110, 2023, https://doi.org/10.1109/TTE.2022.3216925.

[30] M. Y. A. Khan, "Enhancing Electric Vehicle Performance: A Case Study on Advanced Motor Drive Systems, Integration, Efficiency, and Thermal Management," *Control Systems and Optimization Letters*, vol. 3, no. 1, pp. 20-27, 2025, https://doi.org/10.59247/csol.v3i1.152.

[31] K. S. Gaeid, T. Al Smadi, U. Abubakar, "Double control strategy of PMSM rotor speed-based traction drive using resolver," *Results in Control and Optimization*, vol. 13, p. 100301, 2023, https://doi.org/10.1016/j.rico.2023.100301.

[32] K. Jankowska, M. Dybkowski, "Design and analysis of current sensor fault detection mechanisms for PMSM drives based on neural networks," *Designs*, vol. 6, no. 1, p. 18, 2022, https://doi.org/10.3390/designs6010018.

[33] S. Yin, H. Luo and S. X. Ding, "Real-Time Implementation of Fault-Tolerant Control Systems With Performance Optimization," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 5, pp. 2402-2411, 2014, https://doi.org/10.1109/TIE.2013.2273477.

[34] W. Qiu, X. Zhao, A. Tyrrell, S. Perinpanayagam, S. Niu and G. Wen, "Application of Artificial Intelligence-Based Technique in Electric Motors: A Review," *IEEE Transactions on Power Electronics*, vol. 39, no. 10, pp. 13543-13568, 2024, https://doi.org/10.1109/TPEL.2024.3410958.

[35] A. Murali, R. S. Wahab, C. S. R. Gade, C. Annamalai, U. Subramaniam, "Assessing finite control set model predictive speed controlled PMSM performance for deployment in electric vehicles," *World Electric Vehicle Journal*, vol. 12, no. 1, p. 41, 2021, https://doi.org/10.3390/wevj12010041.

[36] J. Ren, Y. Ye, G. Xu, Q. Zhao and M. Zhu, "Uncertainty-and-Disturbance-Estimator-Based Current Control Scheme for PMSM Drives With a Simple Parameter Tuning Algorithm," *IEEE Transactions on Power Electronics*, vol. 32, no. 7, pp. 5712-5722, 2017, https://doi.org/10.1109/TPEL.2016.2607228.

[37] M. Y. A. Khan, "A Review of Analysis and Existing Simulation Model of Three Phase Permanent Magnet Synchronous Motor Drive (PMSM)," *Control Systems and Optimization Letters*, vol. 2, no. 3, pp. 349-356, 2024, https://doi.org/10.59247/csol.v2i3.151.

[38] W. Xu, L. Wang, Y. Liu, F. Blaabjerg, "Improved rotor flux observer for sensorless control of PMSM with adaptive harmonic elimination and phase compensation," *CES Transactions on Electrical Machines and Systems*, vol. 3, no. 2, pp. 151-159, 2019, https://doi.org/10.30941/CESTEMS.2019.00021.

[39] X. -F. Qin and J. -X. Shen, "Mathematical Modeling of High-Speed PMSM Considering Rotor Eddy Current Reaction Effect," *IEEE Transactions on Energy Conversion*, vol. 38, no. 4, pp. 2947-2958, 2023, https://doi.org/10.1109/TEC.2023.3288608.

[40] M. Marchesoni, M. Passalacqua, L. Vaccaro, M. Calvini, M. Venturini, "Performance improvement in a sensorless surface-mounted PMSM drive based on rotor flux observer," *Control Engineering Practice*, vol. 96, p. 104276, 2020, https://doi.org/10.1016/j.conengprac.2019.104276.

[41] J. Li, T. Akilan, "Global attention-based encoder-decoder LSTM model for temperature prediction of permanent magnet synchronous motors," *arXiv*, 2022, https://doi.org/10.48550/arXiv.2208.00293.

[42] A. Perera and R. Nilsen, "Recursive Prediction Error Gradient-Based Algorithms and Framework to Identify PMSM Parameters Online," *IEEE Transactions on Industry Applications*, vol. 59, no. 2, pp. 1788-1799, 2023, https://doi.org/10.1109/TIA.2022.3219041.

[43] S. Chen, Q. Zhang, S. Huang, "Electromagnetic-thermal integration design of permanent magnet synchronous motor for electric vehicle," *International Journal of Rotating Machinery*, 2019, https://doi.org/10.1155/2019/9653231.

[44] L. Cao, Z. Wu, "On-line detection of demagnetization for permanent magnet synchronous motors," *Machines*, vol. 10, no. 5, p. 354, 2022, https://doi.org/10.3390/machines10050354.

[45] S. Huang, G. Wu, F. Rong, C. Zhang, S. Huang and Q. Wu, "Novel Predictive Stator Flux Control Techniques for PMSM Drives," *IEEE Transactions on Power Electronics*, vol. 34, no. 9, pp. 8916-8929, 2019, https://doi.org/10.1109/TPEL.2018.2884984.

[46] W. Huang, J. Wang, J. Zhao, L. Zhou and Z. Zhang, "Demagnetization Analysis and Magnet Design of Permanent Magnet Synchronous Motor for Electric Power Steering Applications," *2020 IEEE 1st China International Youth Conference on Electrical Engineering (CIYCEE)*, pp. 1-6, 2020, https://doi.org/10.1109/CIYCEE49808.2020.9332771.