

Review of Electrical and Thermal Modeling Techniques for Three-Phase PMSM Drives

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Abstract—The objective of this paper is to present a thorough examination of electrical and thermal modelling approaches for three-phase PMSM drives, emphasizing their methods, potential, and constraints. Modern electric drives now rely heavily on Permanent Magnet Synchronous Motors (PMSMs), which are found in renewable energy systems, industrial automation, and electric cars. PMSM drives must be accurately modelled to maximize performance, guarantee dependability, and increase operational longevity. The methods, advantages, and disadvantages of electrical and thermal modelling approaches for three-phase PMSMs are thoroughly examined in this paper. To forecast electromagnetic behavior and drive efficiency, the electrical modelling section examines dynamic dq-axis transformations, finite element methods (FEM), equivalent circuit models, and sophisticated AI-driven techniques. The function of thermal modelling tools in controlling heat dissipation and halting thermal degradation is examined. These techniques include lumped parameter models, coupled electro-thermal models, and computational fluid dynamics (CFD). The trade-offs between these models' practical usability, computational complexity, and accuracy are highlighted by a comparative comparison. Incorporating trade-offs between accuracy, complexity, and usability into modelling methods for three-phase Permanent Magnet Synchronous Motor (PMSM) drives offer a comprehensive viewpoint that strikes a compromise between performance and usefulness. Current issues are noted in the review, including the requirement for real-time adaptive models and the incorporation of multi-physics effects. New developments are highlighted as promising paths to improve PMSM modelling, including AI-based simulations and digital twin technologies. The goal of this study is to provide researchers and engineers with a thorough resource that will direct the creation of reliable and effective PMSM drive systems. The review's findings and insights have the potential to influence a variety of applications, spur innovation in PMSM drives, and aid in the global shift to sustainable technologies and electrification.

Keywords—*Electrical Modeling, Thermal Modeling, Techniques, Three-Phase PMSM, Challenges, Advantages*

I. INTRODUCTION

The high-performance electric motors known as Permanent Magnet Synchronous Motors (PMSMs) are renowned for their dependability, efficiency, and small size. In contrast to traditional motors, PMSMs reduce energy losses and do not require external stimulation because they use permanent magnets in the rotor. Their exceptional power-to-weight ratio, high torque density, and superb speed control are some of their distinctive qualities that make them perfect

for demanding applications. PMSMs are widely utilized in robotics, industrial automation, electric vehicles (EVs), and renewable energy systems where durability, accuracy, and energy efficiency are essential. PMSMs are positioned as a key technology in contemporary electrification and sustainable energy solutions because of these attributes. They are now essential components of many contemporary applications, such as industrial motors, renewable energy systems, and electric cars. PMSMs are perfect for energy-sensitive applications because of their great energy efficiency, which is a result of their elimination of excitation currents and decreased rotor losses. A compact motor design with a high power-to-weight ratio is made possible by the use of permanent magnets, which is especially advantageous in applications such as electric vehicles. A few important research gaps are intended to be filled by the evaluation of electrical and thermal modelling approaches for three-phase Permanent Magnet Synchronous Motor (PMSM) drives. It first addresses the dearth of thorough frameworks that combine thermal and electrical modelling, which are frequently examined separately despite their connection. This review's main goals are to assess and contrast current electrical and thermal modelling methods, pinpoint their advantages and disadvantages, and suggest ways to best integrate them for increased dependability and performance. A roadmap for creating reliable, scalable, and useful models that are suited to the various requirements of PMSM applications in sectors like industrial automation, renewable energy, and electric vehicles is also provided by the review, which also attempts to highlight trade-offs between complexity, accuracy, and usability.

For precise automation and robotics applications, PMSMs provide smooth and accurate torque control. Longer operational lifespans and cheaper maintenance costs result from the removal of brushes and slip rings, which also lessen wear and strain [1]. Because of their great efficiency and capacity to deliver significant torque at low speeds, PMSMs are frequently seen in EVs. This increases the vehicle's range and energy efficiency. Better incorporation into EVs' space-constrained contexts is made possible by their small size. PMSMs aid in the transition to sustainable transport and lower emissions. PMSMs make accurate motion control possible in automation and manufacturing, which is crucial for robotics, conveyor systems, and CNC machines. In industrial settings, its capacity to sustain steady performance

under various load scenarios guarantees operational reliability.

Because of their effectiveness and broad speed range, PMSMs are essential to the production of wind and hydroelectric power, which optimizes energy capture. They are essential to distributed generating systems, which improve the stability and efficiency of the grid. PMSMs are appropriate for aerospace applications, including actuators and auxiliary power units, because to their high-power density and dependability [2]. PMSMs offer quiet, accurate, and reliable functioning in medical devices including ventilators and MRI scanners. The limits of PMSM performance are constantly being pushed by developments in manufacturing processes, control algorithms, and materials. It is anticipated that innovations like AI-driven control systems, improved cooling systems, and high-temperature permanent magnets would increase their range of uses. PMSMs are positioned to continue to be a key technology advancing the development of advanced and sustainable systems because of their remarkable efficiency, portability, and dependability [3].

For three-phase Permanent Magnet Synchronous Motor (PMSM) drives to operate as efficiently and dependably as possible, accurate electrical and thermal modelling is essential. A thorough grasp of the motor's dynamic behavior, including current, voltage, and electromagnetic torque generation, is made possible by electrical modelling, which guarantees accurate control across a range of operating circumstances [4]. This is especially crucial for applications where responsiveness and efficiency are critical, such as industrial automation and electric vehicles. Conversely, thermal modelling sheds light on the motor's internal heat production and dissipation. Thermal models aid in the prevention of overheating, material deterioration, and component failure by detecting possible hot thermal spots and forecasting temperature increases. Together, these models help to increase energy efficiency, save maintenance costs, and prolong the life of PMSM motors.

Finding the most popular modelling techniques, assessing their precision and computing complexity, and emphasizing their usefulness in actual situations are the main goals. By showcasing new developments like coupled multi-physics models and AI-driven simulations, the review also aims to close the gap between theoretical developments and practical implementations [5].

A detailed review of current developments in modelling and control tactics for Permanent Magnet Synchronous Motor (PMSM) systems is the goal of this paper. PMSMs' great efficiency, dependability, and accuracy put them at the forefront of contemporary applications, including industrial automation, electric vehicles, and renewable energy systems. An analysis of cutting-edge modelling and simulation techniques, including multi-physics modelling, hardware-in-the-loop (HIL) systems, and finite element analysis (FEA). Their capacity to forecast mechanical, thermal, and electrical behaviors in practical settings is the main focus. Discussion on the integration of control and simulation for PMSM systems, highlighting the importance of holistic approaches for design, optimization, and performance evaluation. Analysis of particular use cases to demonstrate the usefulness of sophisticated control and simulation techniques, such as

robotics, electric cars, and renewable energy systems. For scholars, experts in the business, and technicians looking to expand their knowledge of PMSM systems and help shape the upcoming advancements in motor control and simulation, this review is an invaluable resource [6].

II. BASIC PRINCIPLES OF PMSM

The rotor, stator, and permanent magnets are the three main parts of a permanent magnet synchronous motor (PMSM) shown in Fig. 1, and each is essential to the motor's functioning. The PMSM's revolving component, the rotor has permanent magnets installed on or incorporated within it. By producing a steady magnetic field without the need for external stimulation, these permanent magnets increase efficiency and lower losses. There are two types of rotor designs: interior, in which the magnets are integrated within the rotor, and surface-mounted, in which they are attached to the rotor's outside. The torque characteristics and thermal performance of the motor are influenced by the design decision [7]. The motor's stator, which houses the windings, is its stationary component. When alternating current (AC) is applied to these windings, which are usually set up in three-phase designs, a spinning magnetic field is produced. The synchronous torque that powers the motor is created by the interplay of the rotor's steady magnetic field and the stator's rotating magnetic field. Laminated silicon steel sheets are frequently used to build the stator in order to reduce eddy current losses and increase efficiency. The permanent magnets used in the rotor are typically made from rare-earth materials such as neodymium-iron-boron (NdFeB) or samarium-cobalt (SmCo). These materials offer high magnetic strength and thermal stability, enabling the motor to achieve a high-power density and excellent performance across a wide range of operating conditions. The arrangement and orientation of these magnets directly influence the motor's magnetic flux distribution and efficiency. Together, the rotor, stator, and permanent magnets form a highly efficient and compact system that delivers high torque, smooth operation, and superior energy efficiency, making PMSMs ideal for applications like electric vehicles, industrial drives, and renewable energy systems.

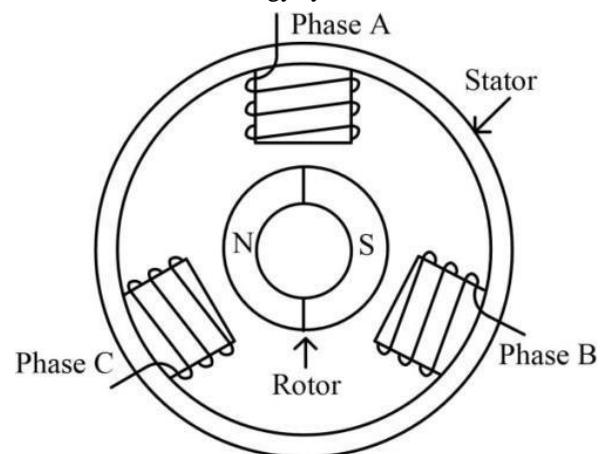


Fig. 1. Basic structure of PMSM [8]

The interaction between the stator's revolving magnetic field and the rotor's permanent magnets' continuous magnetic field is what drives the operation of a three-phase Permanent

Magnet Synchronous Motor (PMSM). Because of the windings' spatial arrangement and the time-varying nature of the current, a three-phase alternating current (AC) delivered to the stator windings produces a spinning magnetic field. The rotor rotates synchronously and without slip as a result of the torque this revolving magnetic field applies to it. Modern PMSMs frequently employ sophisticated control strategies like Direct Torque Control (DTC) and Field-Oriented Control (FOC) to regulate the motor's operation. By separating the stator current into the parts that produce flux and torque, these techniques allow for exact control of the motor's torque and speed. For high-performance applications where responsiveness, accuracy, and efficiency are crucial, such industrial automation and electric cars, this degree of control is necessary [9]. Three-phase Permanent Magnet Synchronous Motors (PMSMs) are commonly controlled using Direct Torque Control (DTC) and Field-Oriented Control (FOC), each of which has unique benefits and drawbacks. Low-speed, high-torque applications can benefit from DTC's easier installation, quick dynamic response, and decreased reliance on motor settings. Nevertheless, it has poor performance at high speeds, variable switching frequency, and excessive torque ripple. FOC, on the other hand, offers precise control by separating flux and torque, guaranteeing outstanding performance over a broad speed range, including flux weakening, and smooth operation with minimal torque ripple. However, FOC's dependence on sophisticated microcontrollers makes it more complicated, necessitates precise parameter estimation, and raises implementation costs.

Because of their operational principles, PMSMs have intrinsic advantages such high efficiency, compact design, and exceptional torque characteristics, which make them a popular choice in many contemporary applications.

The design, analysis, and optimization of Permanent Magnet Synchronous Motors (PMSMs) relies on modelling to increase their reliability, efficiency, and performance. Engineers can predict the motor's electrical, magnetic, and thermal behavior under a variety of operating conditions with precise modelling, eliminating the need for extensive physical prototyping [10]. This reduces the cost of development while also accelerating the design process. For example, electrical modelling makes it possible to simulate dynamic performance, including torque, speed, and current responses, which gives information about how the motor would act under various load scenarios or control schemes. Conversely, thermal modelling is essential for comprehending how heat is generated and dissipated within the motor, assisting in the identification of any thermal hotspots, and preventing overheating, which may result in material failure or deterioration [11]. For applications requiring high performance and dependability, such electric vehicles, industrial automation, and renewable energy systems, integrated multi-physics modeling—which integrates electrical, thermal, and magnetic analysis is especially crucial. These versions guarantee reliable functioning in a variety of conditions and assist maximize the motor's efficiency. Furthermore, by clearly knowing the properties and characteristics of the motor, accurate modelling facilitates the use of sophisticated control strategies like Field-Oriented Control (FOC).

III. CONTROL STRATEGIES FOR PMSM

When planning and optimizing the performance of complicated systems, such as Permanent Magnet Synchronous Motors (PMSMs), simplified models of control systems are essential. By lowering computational and analytical complexity, these representations preserve the system's fundamental behavior while enabling engineers to concentrate on important dynamics. The PMSM's three-phase currents and voltages are converted into a two-axis (direct and quadrature) rotating reference frame using the dq-axis model. By separating torque and flux control, this simplification makes it possible to create effective controllers such as Field-Oriented Control (FOC). It simplifies the management of sinusoidal variables by treating them as DC-like quantities. Simplified models make it easier to analyze stability and performance using traditional control approaches like frequency response and root locus by linearizing the nonlinear PMSM equations around an operational point. Model predictive control (MPC) and proportional-integral-derivative (PID) controller tuning require this [12].

Over time, numerous control techniques have been devised to govern the operation of PMSMs. A summary of these control techniques is depicted in Fig. 2. State-space models that incorporate inputs (voltages), outputs (torque, speed), and system states (currents, rotor position) can be used to depict PMSM dynamics. Compact in size, this representation facilitates sophisticated control concepts such as observer-based state estimation and optimal control. Simplified models lessen the computational load on embedded processors in real-time control systems. In order to ensure prompt reaction and accurate functioning, quick control loops are implemented using approximate models without compromising precision. In simulation environments, simplified representations are frequently employed to test control strategies. They enable quick prototyping and iterative control algorithm improvement by striking a compromise between accuracy and computing economy. Engineers can create effective and efficient control systems for PMSMs because to simplified representations, which makes them appropriate for a variety of applications such as industrial automation, robotics, and electric cars. They ensure dependable and high-performance operation by striking a balance between system complexity and realistic implementation [14]. By increasing efficiency, dependability, and durability, the combination of electrical and thermal modelling has greatly enhanced PMSM performance in a number of important applications. Combining electrical and thermal models, for instance, helps electric vehicles (EVs) maximize motor drive performance while avoiding overheating under high torque demands, which increases range and prolongs battery life. Integrated modelling predicts and mitigates thermal stresses in PMSMs subjected to changing loads, ensuring optimal energy conversion and dependable operation in renewable energy systems like wind turbines.

IV. ELECTRICAL MODELING TECHNIQUES

A common mathematical method in the control of Permanent Magnet Synchronous Motors (PMSMs) is the dq-axis transformation, sometimes referred to as the park

transformation. To align the three-phase stator currents (or voltages) with the rotor's magnetic field, they must be converted from a stationary ABC-frame to a spinning dq-frame. By reducing the intricate, time-varying three-phase system to a two-coordinate system the direct (d) axis and the quadrature (q) axis this transformation makes it easier to analyze and manage PMSMs. The component of the current or voltage that corresponds to the magnetic flux of the rotor is represented by the d-axis, while the perpendicular component is represented by the q-axis. This transformation allows torque and flux to be independently controlled by making the PMSM's equations time-invariant in the rotating frame. This enables effective control of the motor's electromagnetic torque, which is especially advantageous for Field-Oriented Control (FOC) and Model Predictive Control (MPC). The capacity of dq-axis transformation to improve control precision and computing efficiency makes it relevant. Decoupling torque and flux management enhances motor response time and performance [15]. Control methods are made simpler by converting time-dependent sinusoidal changes into steady-state values in the rotating frame. Achieving the ideal current distribution reduces losses and improves total energy efficiency. For high-performance motor control in contemporary PMSM applications, such as industrial drives, electric cars, and renewable energy systems, dq-axis transformation is still a vital tool.

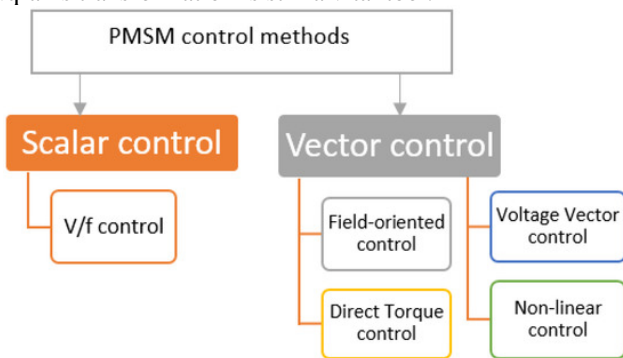


Fig. 2. Control techniques of PMSM [13]

Initiatives to employ PMs in large motors with a rating of at least 1 MW are also in place. As a result, PM motors are employed in many different applications, ranging from massive PM synchronous motors for ship propulsion (such as icebreakers, navy frigates, cruise ships, and medium-sized cargo boats) to stepping motors for watches. Fig. 3 shows a schematic diagram of an electric vehicle with a PMSM drive. A popular mathematical framework for simulating and evaluating dynamic systems, such as Permanent Magnet Synchronous Motor (PMSM) drives, is the state-space representation. This method offers a condensed and methodical technique to express the behavior of the PMSM in terms of a collection of differential equations of the first order. Advanced control techniques and simulations are made possible by the state-space model, which represents the dynamics of the motor in matrix form. The state-space model of PMSM drives captures the mechanical and electrical equations that control the motor. These consist of the electromagnetic torque generation and the voltage-current relationships in the dq-axis. Through the inclusion of system factors including inertia, resistance, back-EMF constants, and inductance, the model offers a thorough explanation of the

motor's operation. The state-space method is especially useful for making it easier to design sophisticated controllers like observers or Linear Quadratic Regulators (LQR). It makes it possible to simulate dynamic responses under many conditions with efficiency [17].

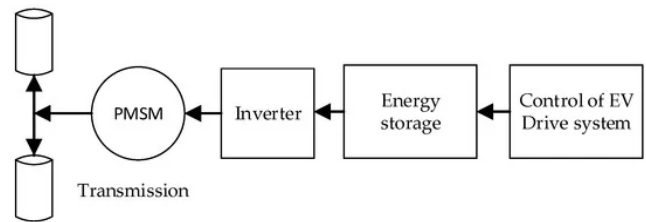


Fig. 3. Electrical modeling techniques of PMSM [16]

Aids in researching the motor drive system's transient behavior and stability. In contemporary applications, state-space modelling is essential for optimizing PMSM drives for high performance, efficiency, and dependability in a variety of sectors, including robotics, renewable energy, and electric cars. Temperature affects the stator windings' resistance, which affects electrical performance. The efficiency of the motor decreases as the temperature rises due to increased resistive losses (I^2R losses). Additionally, the air gap between the rotor and stator may change due to the thermal expansion of materials, which could influence the electromagnetic interaction and torque generation [18].

Mechanically speaking, extended exposure to high temperatures can result in thermal stress, which can wear out materials and perhaps cause adhesives, bearings, or insulation systems to fail. The longevity and dependability of the motor are jeopardized by this deterioration. Effective thermal management technologies are used to lessen these difficulties. These consist of strong design techniques, improved materials, and sophisticated cooling systems. In order to forecast temperature increases and modify operating parameters to guarantee performance stability, precise thermal modelling and monitoring are also necessary. In order to maximize PMSM efficiency, guarantee long-term dependability, and avoid irreversible damage such magnet demagnetization, temperature effects must be controlled [19].

V. THERMAL MODELING TECHNIQUES

Permanent Magnet Synchronous Motors' (PMSMs) dependability, efficiency, and performance are all greatly impacted by temperature. High temperatures can have a negative impact on the electrical characteristics, material qualities, and overall efficiency of the motor. The alteration in the permanent magnets' magnetic characteristics is one significant effect. The coercivity and remanence of permanent magnets, which are usually composed of rare-earth elements, decrease with increasing temperature. The motor's capacity to provide the necessary torque may be diminished by this deterioration, which may lead to partial or permanent demagnetization. Additionally, the magnet's operating point within its hysteresis loop may be shifted by high temperatures, which could result in decreased efficiency and possible loss of performance.

Temperature influences winding wire resistance, which in turn influences winding loss. Therefore, a two-way coupling between the temperature field and magnetic field can be used to illustrate the relationship between temperature and

winding loss. Fig. 4 depicts the procedure. To analyze Permanent Magnet Synchronous Motor (PMSM) systems holistically, electrical and thermal effects must be integrated. In PMSMs, thermal and electrical phenomena are inherently linked, with changes in one area having a substantial impact on the other. Accurate performance evaluation, reliability improvement, and motor operation optimization under a variety of circumstances are ensured by a thorough analysis including these factors. The motor's thermal behavior is directly impacted by electrical performance, which is defined by current flow, electromagnetic fields, and power losses. For instance, heat is produced via resistive losses (I^2R) in the stator windings, raising the motor's temperature. Electrical characteristics including resistivity, magnetism, and insulation integrity are subsequently impacted by this temperature increase. For example, copper's temperature-dependent resistivity causes higher losses, which lowers efficiency. Likewise, high temperatures have the potential to demagnetize permanent magnets, reducing their capacity to generate torque [21]. Mechanical strains brought on by thermal factors also affect electrical performance. Temperature-induced material expansion and contraction can modify the air gap between the rotor and stator, changing the dynamics of the motor and the magnetic coupling. These interactions emphasize how important it is to treat the thermal and electrical domains simultaneously. Multi-physics simulations and other integrated modelling techniques are essential to accomplishing this thorough study. To forecast how the motor would behave in actual operating circumstances, these models take into account thermal dynamics, electrical equations, and material characteristics.

In-depth simulations that capture the interaction of electrical and thermal effects are made possible by techniques such as the Finite Element Method (FEM), which offer important insights into system performance [22]. Engineers can create PMSMs with more efficiency, improved thermal stability, and increased dependability by combining electrical and thermal effects. This method guarantees that the motors run effectively under tough circumstances and allows for optimized performance across a range of applications, such as industrial automation, electric vehicles, and renewable energy systems.

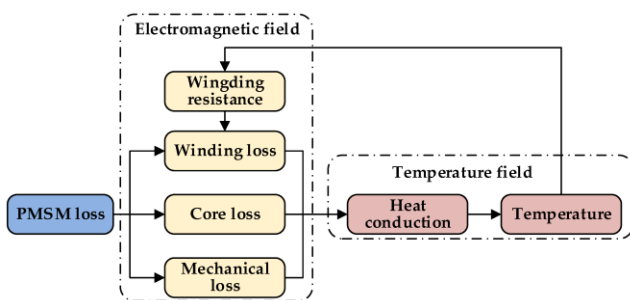


Fig. 4. Thermal modeling techniques of PMSM [20]

VI. COMPARISON OF MODELING TECHNIQUES

Comparison of electrical and thermal models in terms of accuracy, computational complexity, applicability to different scenarios and hardware-in-the-loop (hil) testing compatibility shown in Table 1.

Table 1. Comparison of electrical and thermal models in terms of Accuracy, Computational complexity, Applicability to different scenarios and Hardware-in-the-loop (HIL) testing compatibility

Parameter	Electrical Models	Thermal Models
Accuracy	<ul style="list-style-type: none"> - High accuracy with detailed models (e.g., FEM, dq-axis). 	<ul style="list-style-type: none"> - High accuracy for steady-state and transient analysis using CFD and FEM-based models. - Simplified thermal resistance network models reduce accuracy but provide quicker estimates.
Computational Complexity	<ul style="list-style-type: none"> - Simplified models lose precision for high-frequency or transient phenomena. - FEM-based models are computationally intensive, especially for 3D and high-frequency effects. - dq-axis and equivalent circuit models are simpler, suitable for real-time applications. 	<ul style="list-style-type: none"> - Simplified thermal network models reduce accuracy but provide quicker estimates. - CFD models are resource-intensive due to 3D geometry and fluid flow analysis. - Lumped parameter thermal network models have lower complexity and faster execution.
Applicability to Scenarios	<ul style="list-style-type: none"> - Best suited for electrical performance optimization (e.g., torque control, loss analysis, dynamic responses). - Applicable to steady-state and transient electrical phenomena. 	<ul style="list-style-type: none"> - Ideal for evaluating cooling system performance, material selection, and thermal effects on motor components. - Suitable for both air-cooled and liquid-cooled systems under various scenarios.
HIL Compatibility	<ul style="list-style-type: none"> - dq-axis and equivalent circuit models are compatible with HIL systems for real-time motor control testing. - FEM-based models are generally too complex for real-time HIL but can be simplified. 	<ul style="list-style-type: none"> - Thermal resistance network models are compatible with HIL for quick thermal estimation. - Detailed CFD models are not suitable for HIL due to high computational demands.

VII. CHALLENGES IN ELECTRICAL AND THERMAL MODELING

A. Electrical Modeling Challenges

The saturation properties of magnetic materials in PMSMs cause them to behave nonlinearly. Furthermore, ferromagnetic materials' intrinsic hysteresis effects alter the magnetic flux distribution and result in energy losses.

These phenomena have an impact on torque, efficiency, and overall performance estimates and make it more difficult to accurately simulate electromagnetic fields [23].

These nonlinearities can be captured by sophisticated finite element models (FEM) or specialized algorithms but doing so comes at the expense of more computational complexity.

Parasitic effects, core losses, and inverter switching all contribute to high-frequency harmonics [24]. These harmonics may cause the motor to vibrate, make noise, or lose more power.

Inaccuracies in performance prediction and control design arise from standard models' frequent assumption of perfect sinusoidal waveforms, which ignore harmonic influences [25]. Accuracy can be increased by using comprehensive electromagnetic simulations and harmonic analysis. These techniques might not be appropriate for real-time applications, though, because they demand more processing power.

B. Thermal Modeling Challenges

Precise values for factors like specific heat capacity, thermal conductivity, and heat transfer coefficients for motor components are necessary for accurate thermal modelling. These parameters, however, frequently change depending on the characteristics of the material, the methods used for production, and the operational environment [26].

Reliability and cooling system design are impacted by inaccurate thermal parameters, which cause variations in temperature forecasts.

Parameter accuracy can be increased through iterative calibration using real-world data, experimental approaches, and material characterization techniques. Nevertheless, these methods may need a lot of time and resources [27].

Variations in duty cycles, ambient factors, and operating loads cause dynamic changes in thermal behavior. There are many difficulties in capturing transitory thermal effects, such as abrupt temperature increases or cooling delays.

Underestimation of thermal strains and possible overheating hazards result from simplified steady-state models' failure to take dynamic thermal reactions into consideration [28].

Dynamic behaviors can be addressed using time-dependent models, such as lumped-parameter thermal models or transient finite element models. Nevertheless, these models are difficult to incorporate into real-time applications and demand a lot of processing power.

VIII. FUTURE TRENDS AND DIRECTIONS

Future studies will probably concentrate on combining models of fluid, mechanical, thermal, and electrical dynamics into a single Multiphysics framework. A thorough grasp of the relationships between the several phenomena in PMSMs, including mechanical stress, heat generation, and electromagnetic fields, will be possible thanks to this all-encompassing approach. It will be feasible to more precisely and effectively optimize PMSM performance by integrating several physical factors. Better designs, quicker simulations, and improved control tactics can result from this combination. The primary obstacle is the intricacy of integrating several areas, which raises computational requirements and may call for advanced software and powerful computers. The primary obstacle is the intricacy of integrating several areas, which raises computational requirements and may call for advanced software and powerful computers [29]. One important area of expansion will be the creation of hybrid multi-physics models, which will take advantage of developments in parallel computing and simulation platforms. Improved predicted accuracy will result from this, especially for applications used in challenging or changing contexts [30]. FEM can be used for dynamic parameter extraction (such as torque ripple or

inductance) or precomputed look-up tables that be fed into runtime simplified dq-axis control models.

One quickly expanding trend in PMSM analysis is the application of machine learning (ML) and artificial intelligence (AI) to real-time adaptive modelling [31]. Use historical data, such as temperature profiles, load circumstances, and cooling performance, to train machine learning (ML) techniques such as neural networks, regression models, or ensemble approaches. Researchers may provide open-source resources and standards to confirm the precision and effectiveness of reduced-order or hybrid models in various PMSM applications. AI can be used to optimize control systems, forecast motor behavior, and instantly modify electrical and thermal models in response to shifting variables (such as load or temperature). Faster reaction times, enhanced system functionality, and more precise forecasts in unpredictable circumstances will all be made possible by this [32]. The creation of more intelligent, self-optimizing systems can also be aided by the real-time model adjustment. Large datasets for training algorithms and reliable techniques for integrating these models into control systems are necessary for the implementation of AI-driven real-time modelling [33]. The models also need to be able to strike a balance between computational efficiency and accuracy. It will be essential to build data-driven models and deep learning algorithms for adaptive real-time control [34]. A lot of attention will be paid to AI solutions that can automatically identify system irregularities and forecast PMSM system breakdowns. Another exciting avenue is the use of AI-based predictive maintenance [35].

IX. DISCUSSION

The importance of precise and effective modelling to meet the expanding needs of contemporary applications like electric vehicles, industrial automation, and renewable energy systems is highlighted by the review of electrical and thermal modelling approaches for three-phase permanent magnet synchronous motor (PMSM) drives [36]. Every modelling technique has unique advantages and disadvantages, highlighting the necessity of choosing one carefully depending on the application's particular needs. The advantages of simpler equivalent circuit models, finite element method (FEM) models, and dq-axis transformation were highlighted in the conversation. For real-time control, dq-axis transformation is necessary, yet FEM models provide unmatched precision in representing intricate electromagnetic interactions. Nevertheless, the computational complexity of FEM restricts its use in dynamic or real-time settings. The advantages, limitations, and suitable applications for different modeling techniques used in PMSMs shown in Table 2.

Despite being less precise, simplified equivalent circuit models are nonetheless very useful for designing control systems because of their effectiveness and simplicity of integration [37]. The accuracy and complexity of the thermal modelling methods under consideration, such as computational fluid dynamics (CFD), lumped-parameter thermal networks (LPTNs), and finite element thermal models, varied. Although CFD models are more computationally expensive, they offer deep insights into heat dissipation mechanisms, whereas LPTNs strike a balance

between simplicity and predictive power [38]. The need of thermal modelling goes beyond performance optimization to guarantee system dependability, especially in the face of harsh weather conditions and fluctuating operating loads.

Table 2. Comparison of modeling techniques, highlighting their strengths, drawbacks, and most suitable use cases for PMSM applications

Modeling Technique	Advantages	Limitations	Suitable Applications
dq-Axis Transformation	<ul style="list-style-type: none"> - Simplifies analysis and control of PMSMs. - Enables decoupled torque and flux control. 	<ul style="list-style-type: none"> - Assumes ideal motor conditions (e.g., sinusoidal waveforms). - Limited for non-linear or complex geometries. 	<ul style="list-style-type: none"> - Real-time motor control (e.g., FOC). - Low-complexity applications needing basic motor analysis.
Finite Element Method (FEM)	<ul style="list-style-type: none"> - High accuracy in analyzing electromagnetic fields, losses, and performance. - Captures non-linear effects. 	<ul style="list-style-type: none"> - Computationally intensive. - Requires expert knowledge and advanced software tools. 	<ul style="list-style-type: none"> - Motor design and optimization. - Applications requiring detailed electromagnetic analysis (e.g., EVs).
Computational Fluid Dynamics (CFD)	<ul style="list-style-type: none"> - Accurate thermal and fluid flow analysis for cooling system optimization. - Identifies hot spots. 	<ul style="list-style-type: none"> - High computational cost. - Requires detailed geometry and boundary conditions. 	<ul style="list-style-type: none"> - Cooling system design for high-performance motors (e.g., aerospace and EVs). - Thermal failure analysis.
Lumped Parameter Thermal Networks (LPTNs)	<ul style="list-style-type: none"> - Computationally efficient for thermal analysis. - Captures overall temperature distribution. 	<ul style="list-style-type: none"> - Less accurate than CFD for complex geometries. - Requires parameter tuning for accuracy. 	<ul style="list-style-type: none"> - Real-time thermal monitoring and control. - Applications require quick thermal evaluations.

There are inherent difficulties with both thermal and electrical modelling. High-frequency harmonics, nonlinearities in magnetic materials, and the effects of temporal and spatial fluctuations in the motor's operating circumstances must all be taken into account in electrical models. Accurately capturing changing thermal behaviors and determining exact material properties are challenges for thermal models. These difficulties highlight how crucial it is to develop modelling techniques and include creative ideas. An intriguing possibility for comprehensive study is presented by the integration of multi-physics models, which allow mechanical, thermal, and electrical phenomena to be considered simultaneously. Another new trend that promises improved accuracy and responsiveness in control and performance optimization is the application of AI and machine learning for real-time and adaptive modelling [39].

The importance of modelling approaches in developing PMSM technology is emphasized in this review. Future research can propel the creation of reliable and effective PMSM systems suited for a variety of applications by resolving current constraints and utilizing developments in processing power and artificial intelligence. It is anticipated that this all-encompassing strategy would open the door to

more intelligent, dependable, and high-performing drive systems.

X. CONCLUSION

To maximize the efficiency and dependability of three-phase permanent magnet synchronous motor (PMSM) drives, the review emphasizes the critical role that both electrical and thermal modelling methodologies play. Important conclusions emphasize how crucial precise electrical models like finite element methods (FEM) and dq-axis transformations are for capturing the complex electromagnetic interactions that control motor performance. The stability and longevity of systems are also guaranteed by thermal models, such as lumped-parameter thermal networks (LPTN) and computational fluid dynamics (CFD), which offer crucial insights into heat dissipation and temperature distribution. Combining thermal and electrical models becomes a crucial tactic for comprehensive analysis and performance improvement. While thermal models reduce the hazards of overheating, efficiency loss, and magnet demagnetization, electrical models concentrate on enhancing operational efficiency, dynamic responsiveness, and precision control. A thorough grasp of interdependent electrical and thermal behaviors is made possible by combining these methods, especially when dealing with fluctuating loads and harsh climatic circumstances. Applications such as electric vehicles, where high efficiency and thermal stability are crucial, and renewable energy systems, where dependability in challenging conditions is essential, demonstrate the importance of this integrated modelling approach. Future developments, such as AI-driven adaptive modelling and multi-physics simulations, promise to significantly improve PMSM drive capabilities and guarantee their continuous use in cutting-edge and contemporary technologies. Combining electrical and thermal models can help design smarter, more reliable, and energy-efficient PMSM systems that meet the needs of high-performance and sustainable applications by tackling the issues and utilizing developments.

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