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SURVEY

Advancements in Flux Switching Machine Optimization: Applications and Future Prospects

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ABSTRACT Flux switching machines play a crucial role in emerging sectors such as renewable energy, electric vehicles, and the aerospace industry. Recent advancements have underscored their potential for achieving high torque density, effective heat management, and flux-weakening capabilities. This paper provides a comprehensive review of the design optimization of these machines, offering a unique contribution, as no previous attempts have delved into a detailed exploration of various optimization techniques specific to this technology. Special attention is given to state-of-the-art technologies related to multi-objective optimization and the performance analysis of the three variants: permanent magnet, wound-field, and hybrid excited. The review highlights and compares several optimization strategies from recent research, revealing research gaps in integrating advanced control algorithms, thermal, vibroacoustic, and structural models into the optimization design process of these machines. Furthermore, this review identifies essential trends in optimization development, offering valuable insights and future perspectives for these machines across diverse applications.

INDEX TERMS Algorithms, design optimization, electric machines, electric vehicles, energy efficiency, finite element analysis, machine learning, prototypes, renewable energy sources, robustness, torque.

I. INTRODUCTION

In recent years, there has been significant progress in the design and manufacture of flux switching machines (FSMs), attracting attention both in academic research and industrial applications. FSMs, a type of doubly salient machine, share a rotor design similar to that of switched reluctance machines (SRMs). FSMs are suitable for high-speed applications owing to their exceptional mechanical robustness [1]. This suitability is particularly pronounced when low-loss soft magnetic materials are employed instead of silicon steel laminations [2].

FSMs are characterized by stators that incorporate permanent magnets (PMs) and/or DC field windings alongside the armature windings. This configuration gives rise to three primary types of FSMs:1) permanent magnet FSM (PMFSM), which use stator-mounted permanent magnets to generate magnetic flux. The rotor has no windings and relies on the stator magnets. 2) The Wound-field FSM (WFFSM) employs field windings on the stator instead of permanent magnets. Direct current is supplied to these windings to create magnetic flux, and 3) Hybrid-Excitation FSM (HEFSM), which combines permanent magnets and field windings on the stator. The permanent magnets contribute to the initial magnetic field, whereas field windings provide additional control [3], [4].

The magnetic flux generated by the PMs and/or DC field windings in the FSMs was linked to the armature windings. As the rotor moves, the magnitude and direction of this flux linkage change, resulting in the generation of

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an almost sinusoidal waveform known as back electromotive force (EMF). This characteristic allows the FSMs to operate using sinusoidal currents [5]. FSMs exhibit high air-gap flux density, which contributes to their high torque density [6].

FSMs have attracted significant interest for emerging applications, including elevators, synchronous condensers, electric and hybrid electric vehicles (EV/HEVs), wind generators, electric boats, and aerospace. This heightened interest is driven by the robust structure, high torque density, high efficiency, flux-weakening capabilities, and simple thermal management offered by the FSMs [7], [8], [9], [10]. Despite the advantages offered by FSMs, they have certain drawbacks, including notable cogging torque and ripples, resulting in noticeable vibrations owing to their double-salient nature. In addition, FSMs exhibit lower power factors owing to cross-coupling effects and their stator-mounted configurations [11], [12], [13], [14]. Therefore, conducting design optimization studies is critical for improving the static and dynamic performances of FSMs.

In recent decades, various novel FSM have been proposed, including segmented FSMs [7], [8], double-stator FSMs [15], [16], double-rotor FSMs [17], [18], skewed teeth FSMs [19], [20], linear FSM configurations [21], [22], axial flux FSMs [23], [24], and outer-rotor FSMs [14], [25], [26]. For example, a novel segmented 12/8 FSM with an excited outer rotor is proposed in [26]. This configuration places eight magnets of the same polarity within the rotor segments, enhancing the winding space and torque density and reducing the stator magnetic saturation. The optimized model achieved a 42.6% reduction in the torque ripple. Additionally, [20] demonstrated that the skewed-FSM outperformed the skewed-SRM in terms of the torque capacity, torque ripple, saturation tolerance, and power factor. Similarly, [16] compared a double-stator FSM (DS-FSM) with a DC-excited Vernier reluctance machine (DC-VRM), both rated at 1.5 kW. The results indicate that the DS-WFFSM outperformed the DC-VRM in terms of efficiency and torque capability while also generating symmetric phase and sinusoidal quantities. Furthermore, [25] outlined the design and analysis of an outer-rotor FSM, highlighting its high torque density and efficiency, minimal torque ripple, and high overload capacity.

The novel FSM topologies showed remarkable improvements in various aspects of machine performance. As researchers delve deeper into their characteristics, it becomes evident that their optimization advancements hold the potential to address existing challenges and set new benchmarks in the field of electrical machines.

Previous studies have predominantly focused on deterministic optimization (DO) strategies integrated with multi-objective, multilevel, or multimode optimization methodologies [27], [28], [29]. For instance, in [28], the FSM was optimized using the DO method to reduce the cogging torque by focusing on the pole embraces of the stator and rotor. Similarly, [30] employed the DO approach to address ten design parameters with the aim of achieving maximum power output, average torque, and power density. Furthermore, [31] applied a DO method to optimize an FSM by refining three design parameters while maintaining the air gap and outer rotor radius to achieve the maximum power output. In addition, [32] introduced a multi-objective optimization method for FSMs that entailed two objectives, three constraints, and 16 design parameters in the optimization process. To mitigate computational costs and enhance optimization efficiency, [29] proposed a multilevel design optimization method in which optimization variables were divided into two levels, each optimized individually. A system-level optimization strategy using multi-objective and multilevel techniques was also presented in [24]. By employing particle swarm optimization to optimize the proportional-integral controller settings, this strategy increases the robustness of the control system. A multimode optimization strategy for EV applications was also suggested by [23], considering different motor operation modes based on driving cycles.

Despite significant progress in enhancing the performance of FSMs, it is essential to acknowledge unexplored areas in the current literature. The optimization of FSM designs, such as that of other electrical machines, represents a multi-objective, multidisciplinary, and nonlinear challenge characterized by unavoidable variables that introduce complexities to the industry. The effectiveness of the motor and drive system is significantly influenced by the manufacturing accuracy, which, in turn, is shaped by mechanical techniques and processing conditions, including actions such as punching or laser cutting [33], [34]. Unlike deterministic approaches, design optimization of FSM technology has not addressed manufacturing tolerances or the variability of environmental conditions for mass production. Another aspect to consider is the integration of control schemes into optimization processes, a practice primarily observed in specific cases such as [23] and [24]. Additionally, there is a notable absence of factors, such as acoustic noise, thermal effects, and stress profiles, in the multi-objective optimization of FSMs. These gaps underscore the necessity of developing sophisticated strategies and intelligent technologies to enhance the robustness and efficiency of FSM optimization.

To the best of our knowledge, this study represents a pioneering research endeavor to provide an overview of optimization methodologies, design trends, and advancements in FSMs. The primary focus of this research is to identify robust frontiers for improving the FSM performance and reliability across various industrial applications. Simultaneously, it aims to provide researchers and engineers with up-to-date information on state-of-the-art technologies for FSM design and optimization studies. By accomplishing these objectives, this review aims to enable professionals in the field to stay informed, well-equipped, and at the forefront of advancements in FSM technology.

The remainder of this paper is organized as follows. Section II categorizes the various variants of the FSMs and provides insights into their configurations and operating principles. Additionally, it highlights key performance metrics, including flux weakening and torque characteristics. Section III discusses outer-rotor flux-switching machines and their classification. In Section IV, a wide range of industrial applications of FSMs are presented. Section V compares the FSM with other electrical machines. Section VI reviews various performance metrics utilized as objective functions in FSM optimization. Section VII highlights the diverse optimization strategies employed in FSMs, as reported in the existing literature, while identifying the research gaps in the survey. Section VIII explores state-of-the-art technologies utilized in other electric machines, offering potential trends for optimizing FSMs. Section IX outlines the emerging trends and opportunities in FSM design and optimization. Finally, Section X presents the relevant conclusions.

II. VARIANTS OF FLUX SWITCHING MACHINES

Flux-switching machines (FSMs) present a novel solution for addressing the challenges encountered in rotor-mounted machines. Conventional rotor-mounted machines, such as permanent magnet machines, wound field machines, magnets, or field windings, are situated on the rotor. However, this arrangement poses several challenges. Retaining sleeves are necessary to protect permanent magnets in rotor-mounted machines from centrifugal forces at high speeds. These forces can lead to magnet demagnetization or complete failure, adding complexity to the machine design and increasing manufacturing costs [36]. FSMs address this challenge by relocating permanent magnets or direct-current (DC) electromagnets to the stator instead of the rotor. This eliminates the need to retain sleeves and simplifies the machine design. Moreover, the stator-mounted magnets in FSMs offer superior thermal dissipation. In contrast to rotor-mounted magnets, which may face heat dissipation issues due to nearby components, stator-mounted magnets permit more effective cooling mechanisms. This efficient heat dissipation reduces the risk of demagnetization and ensures an optimal performance [36], [37].

Generating the required field flux in rotor wound field machines without slip rings or brushes is challenging. Typically, rotor-mounted machines use slip rings and brushes to establish electrical connections with the field windings [38]. However, their use has disadvantages such as increased friction, wear, and maintenance requirements.

In FSMs, the field windings are positioned on the stator, eliminating the necessity for slip rings and brushes. This enables a direct current supply to the field windings through stationary connections, thereby eliminating the challenges associated with rotating electrical connections. Consequently, machine construction and operation are simplified to reduce maintenance demands and enhance overall reliability [1]. By employing PMs or DC electromagnets on the stator, FSMs offer advantages over rotor-mounted machines, including the elimination of retaining sleeves, improved thermal dissipation, and the avoidance of slip rings and brushes. These advantages contribute to enhanced performance, reliability, and efficiency of various FSM applications. The three FSM variants based on the excitation modes are the PMFSM, WFFSM, and HEFSM, as illustrated in Fig. 1. A concise description of their configuration, operating principle, flux-weakening capability, and torque characteristics is presented as follows:

1) PMFSM:

- Configuration: PMFSM utilizes permanent magnets on the stator to produce the magnetic flux, with no windings present on the rotor.
- Operating Principle: The stator's permanent magnets establish a magnetic field that interacts with the rotor, as illustrated in Fig. 2. By regulating the stator current, it is possible to modulate the flux linkage between the stator and rotor, leading to torque generation [21].
- Flux Weakening Capability: PMFSMs generally exhibit a more limited ability for flux weakening in comparison to other FSM variants. Nevertheless, they can achieve partial flux weakening by regulating stator current [4].
- Torque Ripples: PMFSMs typically experience minimal torque ripples owing to the presence of permanent magnets, which maintain a consistent magnetic field.

2) WFFSM:

- Configuration: WFFSMs employ field windings on the stator instead of permanent magnets. These field windings are energized with direct current (DC) to generate the necessary magnetic flux.
- Operating Principle: The magnetic field is generated by the stator field windings, which interact with the rotor as depicted in Fig. 3. Precise control of the stator current allows for modulation of the flux linkage between the stator and rotor, thereby facilitating torque generation.
- Flux Weakening Capability: WFFSMs provide superior flux weakening capability in comparison to PMFSMs. The stator current can be precisely controlled to weaken the magnetic flux, thus enabling extended speed range and enhanced control.
- Torque Ripples:WFFSMs are prone to increased torque ripples because of their double-salient configuration, potentially leading to noticeable vibrations [39].

3) HEFSM:

- Configuration: HEFSMs integrate both permanent magnets and field windings on the stator, utilizing both PMs and DC field windings to generate the necessary magnetic field [1].
- Operating Principle: The rotor interacts with the combined magnetic field generated by the permanent magnets and field windings, leading to torque generation as depicted in Fig. 4. By manipulating the stator currents of both permanent magnets and field windings, flux linkage can be controlled to attain the desired torque [2].
- Flux Weakening Capability: HEFSMs provide advanced flux weakening capability attributed to the combined influence of permanent magnets and field windings.

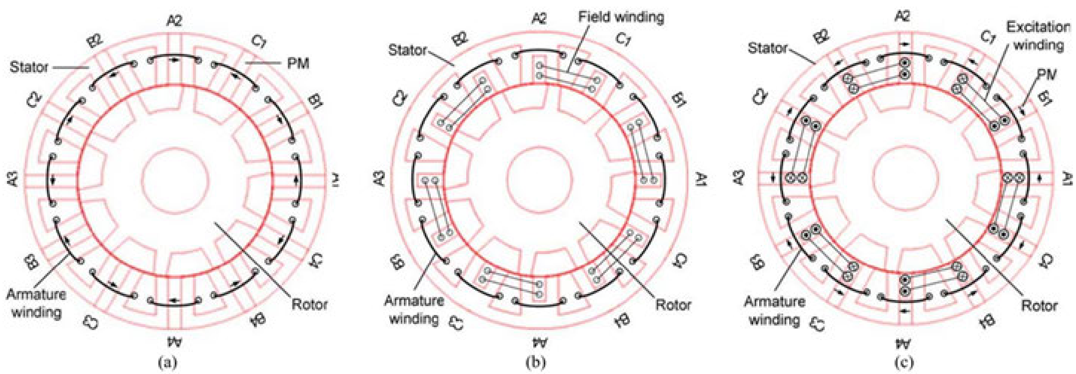

FIGURE 1. Variants of the flux-switching machines. (a) PMFSM, (b) WFFSM, and (c) HEFSM [35]. The figure provides an overview of the various types of FSMs by visually depicting their winding connections. In these machines, the stator contains strategically positioned sources, such as permanent magnets in the PMFSM, field windings in the WFFSM, and a combination of permanent magnets and field windings in the HEFSM. These sources play a vital role in shaping the magnetic flux distribution and the overall machine performance.

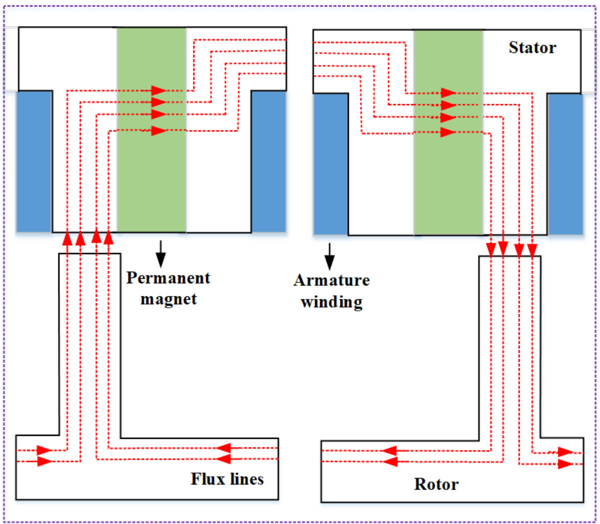

FIGURE 2. Operating Principle of PMFSM: This figure emphasizes the fundamental operational concept of a PMFSM, with a particular focus on the polarity switching of flux linkage to facilitate efficient energy conversion.

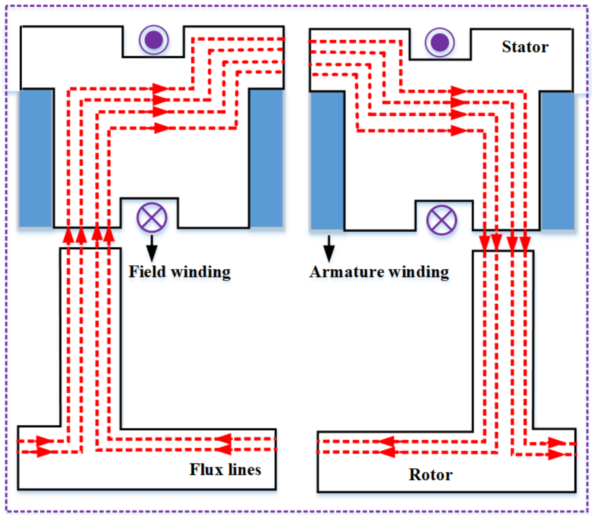

FIGURE 3. Operating Principle of WFFSM: This figure illustrates the strategic toroidal arrangement of field windings that generates bipolar flux-linkage patterns, defining the unique flux-switching behavior characteristic of WFFSMs.

This feature enables a broader range of operating speeds and superior control over machine performance [40].

- Torque Ripples: HEFSMs display torque ripples comparable to WFFSMs because of their double-salient construction. Nevertheless, the incorporation of permanent magnets and field windings contributes to partial mitigation of torque ripples [3], [41].

III. OUTER ROTOR FLUX SWITCHING MACHINES

In recent years, Outer Rotor Flux Switching Machines (OR-FSMs) have garnered significant attention in the field of electrical engineering owing to their unique designs and versatile applications. OR-FSMs offer several advantages, including a high torque density, improved efficiency, and reduced cogging torque [42]. Their outer rotor design facilitates effective cooling and enhances thermal performance [43]. However, challenges such as complex manufacturing processes and potential rotor imbalances must be addressed to achieve optimal performance. This section provides an exploration of various classifications of OR-FSMs and discusses their practical applications in different industries.

A. CLASSIFICATIONS OF OUTER ROTOR FLUX SWITCHING MACHINES

Outer rotor flux-switching machines (OR-FSMs) can be classified based on several key factors, including rotor topology, winding configuration, and operational mode. The rotor topology classification distinguishes between surface-mounted and interior-mounted permanent magnets, each of which has its own advantages and limitations. Winding configuration classifications encompass single-layer and double-layer windings, which influence torque production and winding complexity. Operational mode classifications involve self-excitation and separate-excitation modes, where the former eliminates the need for external field-current sources. The versatility of OR-FSMs lends them various applications in diverse industries. In automotive applications

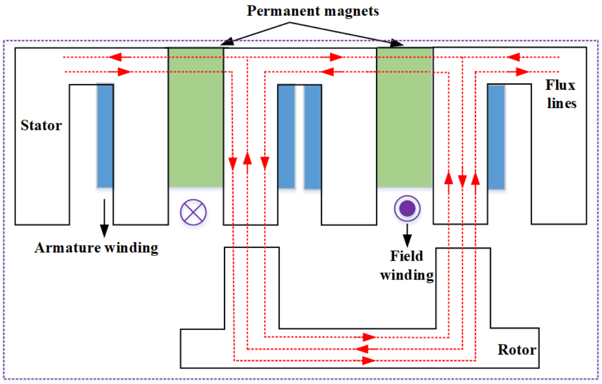

FIGURE 4. Operating Principle of HEFSM: This figure demonstrates the interaction between the combined magnetic field generated by magnets and field windings with the rotor. Additionally, it illustrates the flexibility of modifying the flux linkage to achieve the desired torque by controlling the polarity and amplitude of the current.

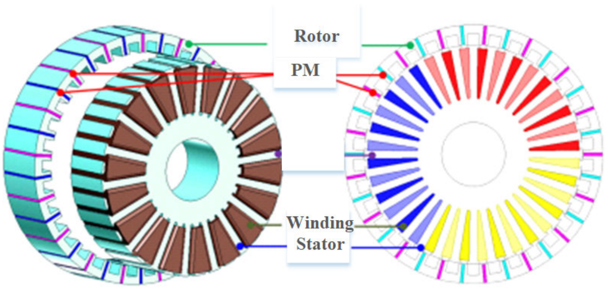

FIGURE 5. Configuration of an OR-PMFSM with a 12/22 pole configuration [25]. Each PM is enclosed between two "U"-shaped rotor parts. The figure provides insight into the machine's structure and design features.

[25], [42], [43], OR-FSMs are used in electric vehicles for propulsion owing to their compact design and high torque density. Renewable energy systems [31] and [44] serve as generators in small-scale wind turbines and hydroelectric power plants owing to their efficient energy-conversion capabilities. Additionally, OR-FSMs can be employed in industrial automation, robotics, and aerospace applications for precise motion control and actuation. This section highlights research efforts in the field of OR-FSM technology.

An outer-rotor PMFSM (OR-PMFSM) tailored for EV applications was introduced by [25]. In this design, each permanent magnet is securely positioned between two rotor pieces with a "U" shape, as depicted in Fig. 5. The optimization of the OR-PMFSM was conducted via a three-step process aimed at enhancing the output torque, minimizing torque ripple, and achieving high efficiency. Analysis of the performance of the optimized OR-PMFSM reveals favorable attributes, such as a sinusoidal back electromotive force (EMF) waveform, desirable torque behavior, robust overload capacity, and elevated efficiency. These merits make the proposed machine a promising choice for direct driving applications.

A comparative analysis was conducted between the OR-PMFSM and its counterpart, the inner rotor PMFSM (IR-PMFSM), for wind power applications, as outlined in [44]. The static analysis revealed that the IR-PMFSM

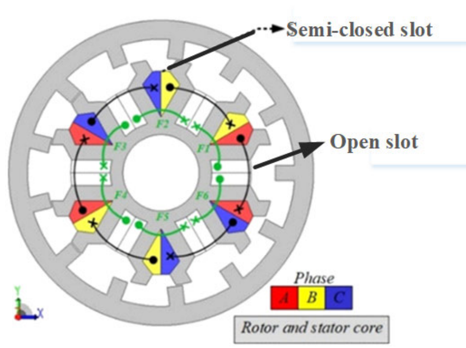

FIGURE 6. Configuration of an OR-WFFSM employing a 12/13 pole configuration [43]. The machine was designed for a high-power factor, featuring strategic semi-closed slots for armature coils and an open slot stator for field excitation. These design elements minimize flux pulsation and torque ripple, while improving average torque output.

delivered a 47.93% increase in the rated power, 2.83% higher efficiency, 56.91% reduction in the cogging torque, and significantly lower torque ripples by 83.18%. Performance assessments under rated and overload conditions demonstrate that the IR-PMFSM outperforms its OR-PMFSM counterpart, delivering 1.47 times more power. The analysis concludes that the IR-PMFSM can operate across a broad speed range to satisfy higher power specifications while maintaining an efficiency exceeding 90% for wind-power generation purposes.

Nevertheless, in [45], an innovative approach was presented by introducing an outer rotor design featuring a consequent pole permanent-magnet machine with an H-type modular stator core. The primary objective of this design is to attain an enhanced average torque while simultaneously minimizing the cogging torque, torque ripple, and harmonic content of the flux linkage and back EMF. Through a comprehensive analysis, the proposed design is evaluated under varying stator flux gaps, revealing that the incorporation of flux gaps in the H-type stator core not only elevates the electromagnetic performance but also improves the flux concentration. Moreover, the utilization of the H-type modular stator structure results in physical isolation of adjacent phases, thereby decoupling the flux between these phases. This effect leads to an enhancement in the self-inductance, while weakening the mutual inductance, resulting in improved fault tolerance. Finally, the study highlights the effectiveness of the proposed design, underlining its capacity to achieve a remarkable 91.69% increase in the average torque, accompanied by reduced cogging and torque ripples.

The methods detailed in [44] were employed to ascertain the optimal configuration of an OR-WFFSM featuring a segmented rotor, considering metrics such as torque-to-volume and torque-to-mass ratios as well as fault-tolerant capabilities essential for aerospace applications. This investigation involved the exploration of diverse slot/segment configurations and geometric machine parameters. Additionally, an initial thermal analysis was conducted to ensure that the winding temperatures remained within acceptable limits. The outcome reveals that the best design is the 36-slot-21

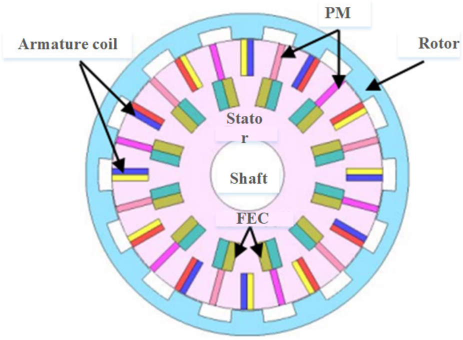

FIGURE 7. Configuration of an OR-HEFSM featuring a 12/14 pole configuration [42]. The inclusion of FEC acts as a secondary flux source, enhancing maximum torque and power capabilities through variable flux control.

segmented model, which achieves a notably sinusoidal back EMF, along with a smooth and high average torque.

Furthermore, as highlighted in [43], a novel outer-rotor WFFSM (OR-WFFSM) with a stator combining semi-closed and open slots was introduced to enhance power factor and torque performance. Owing to the use of a semi-closed slot for the armature coils, the designed OR-WFFSM shown in Fig. 6 shows a high power factor. The field-excitation coil topology was chosen because it effectively reduces leakage reluctance, which results in flux pulsation. Consequently, the torque ripples have less impact, and the average torque increases. The efficiency of the recommended OR-WFFSM was examined through a thorough investigation of stator slot and rotor pole combinations. According to a simplified mathematical formulation, the most feasible combinations were 12S/7P (stator slot/rotor poles), 12S/11P, 12S/13P, and 12S/17P. According to the preliminary FEA-based comprehensive electromagnetic performance, 12S/13P provides the highest average torque of 4.62 Nm, which was considered for further research and optimization using GA. The optimized configuration achieved a maximum output power of 3.22 kW with an efficiency of 87.7%. Finally, a comparison with a state-of-the-art model showed substantial enhancements in average torque, torque ripples, machine weight, and torque density. The optimization of a 12Slot 14Pole outer-rotor HEFSM for an in-wheel direct-drive EV is detailed in [42]. The initial design of the machine is shown in Fig. 7 underwent iterative refinement using a deterministic optimization approach. The optimized design achieved superior torque and power density, with values of 335.08 Nm and 5.93 kW/kg, respectively. These performance metrics are superior to those of the inner rotor HEFSM and interior permanent magnet synchronous machine (IPMSM) designs for EVs. Furthermore, the proposed machine successfully reduced the permanent magnet weight to 1.0 kg compared with the magnetic material employed in existing IPMSM designs.

Furthermore, a novel topology of an OR-HEFSM with a unique homopolar iron core and high-temperature superconducting (HTS) coil was proposed in [31]. Regulation of the flux linkage becomes feasible by adjusting the field current within the HTS field coil. This innovative arrangement enhances the appeal of the outer-rotor flux-switching machine, offering enhanced capability for flux regulation. It is relevant in various domains, including electric propulsion systems and wind power generation setups, which demand robust machine architectures and exceptional flux control capabilities. Nevertheless, owing to the integration of HTS field coils, it is imperative that future research focuses on the development of a robust cooling system and protective measures to ensure the practical realization of this machine configuration.

In conclusion, the diverse classifications and applications of Outer rotor flux switching machines (OR-FSMs) underscore their significant potential across various industries. Understanding these classifications and their respective advantages and challenges contributes to harnessing the full potential of OR-FSMs for various engineering applications. The pursuit of innovative configurations and integration with emerging technologies such as advanced power electronics and cutting-edge control algorithms offers a pathway for amplifying the performance and broadening the applications of OR-FSMs. As research on OR-FSM technology continues to evolve, there is a growing need for robust optimization strategies to further enhance their performance.

IV. APPLICATIONS OF FLUX SWITCHING MACHINES

FSMs have gained attention for their suitability for a wide range of applications across different industries. These applications include elevator systems [21], low-speed wind generators [10], synchronous condensers [46], more-electric aircraft systems [47], and electric vehicle (EV) propulsion [48]. In particular, the outer-rotor configuration of FSMs has been proposed for EV applications, offering benefits such as a nearly sinusoidal back-EMF waveform and a high torque output at low speeds. The robustness and adaptability of FSMs make them suitable for challenging operating environments in aerospace, automotive, marine, and wind energy applications [49], [50]. FSMs, owing to their high torque density and capability for high-speed operation, are particularly well suited for wide-speed constant-power operations [31]. The applications of FSMs are grouped into three main categories in this study, which are discussed in the following subsections.

A. APPLICATION IN TRANSPORTATION SYSTEMS

In [51], a comparison was made between a prototype PMFSM (based on the topology shown in Fig. 1(a)) and an interior permanent magnet (IPM) motor used in the 2004 Prius hybrid electric vehicle (HEV). The test motor was constructed using 200 laminations of 35H210 steel stacked to a height of 70 mm. Fig. 8 presents the open-circuit flux density distribution of the two motors at the maximum flux linkage value. The Prius-IPM motor had varying flux density in different regions, with the stator teeth ranging from 1.0 T to 1.2 T and the rotor yoke between 1.3 T and 1.4 T, except in the region with a higher saturation iron bridge. In

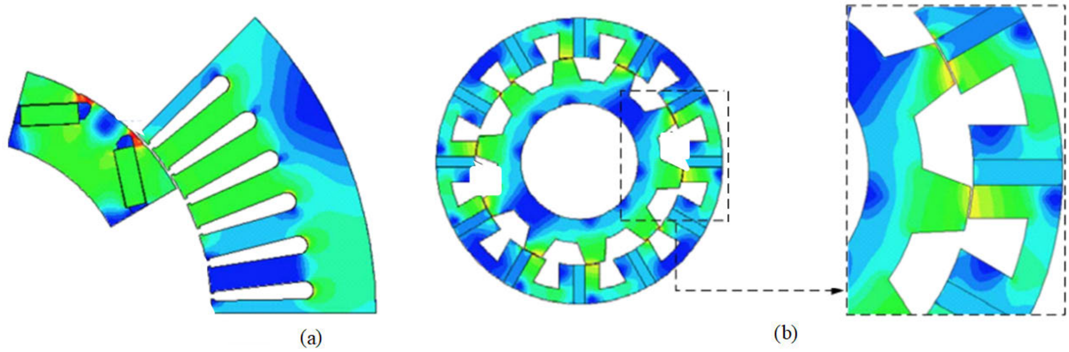

FIGURE 8. Comparison of open circuit magnetic flux density distribution of two permanent magnet machines. (a) Prius-IPM. (b) FSM [51]. The Prius-IPM motor features a stator teeth design with magnetic flux density ranging from 1.0 T to 1.2 T, and the rotor yoke ranges between 1.3 T and 1.4 T, except in the higher saturation iron bridge region. In contrast, the FSM exhibited a significantly higher flux density (approximately 2.0 T at the stator and rotor teeth tips. This higher flux density contributes to enhanced torque density performance and overall efficiency, making the FSM well-suited for automotive applications.

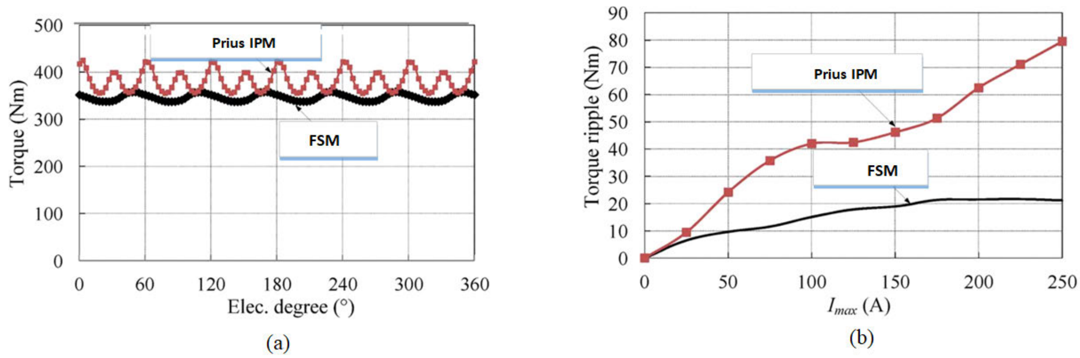

FIGURE 9. Torque performance of two permanent magnet machines. (a) Torque waveform versus electrical degree of the two motors. (b) Peak-to-peak torque ripple [51]. The figure underscores the suitability of FSMs for high-speed applications with precise torque response, minimized torque ripples, and mechanical robustness even in challenging operating conditions.

contrast, the PMFSM exhibited a significantly higher flux density (approximately 2.0 T in the stator and rotor teeth tips, enabling a high torque density performance and overall efficiency for automotive applications. Understanding the magnetic characteristics, including flux density, is crucial for optimizing the PMFSM design and ensuring reliable operation. Furthermore, Fig. 9 confirm the suitability of the PMFSM for high-speed applications with excellent torque response, minimal fluctuations, and enhanced dynamic performance. This improved precision reduces vibrations and noise, thereby enhancing the user experience. Additionally, the PMFSM exhibits mechanical integrity, enabling operation under demanding conditions such as high centrifugal forces and temperature variations. These results validate the effectiveness of FSMs in transportation, positioning them as a promising choice for electric vehicles, hybrid electric vehicles, and aerospace systems.

In [52], a comprehensive investigation was conducted on a three-phase field-excited FSM specifically designed for future HEV-drive applications. The stator of the motor was meticulously crafted using electromagnetic steels and comprised a distinctive field MMF source along with armature coils, while the rotor was constructed using iron stacks. The primary objective behind the motor's design is to attain remarkable power and torque densities surpassing 3.50 kW/kg and 210 Nm/m3, respectively, thereby positioning it as a competitive alternative to the widely employed interior permanent magnet synchronous (IPMS) motors in HEVs. Impressively, the robust rotor structure of the motor facilitated the realization of an impressive maximum achievable speed of 20,000 rpm.

A novel design was introduced in [8] for an EV/HEV motor, namely the segmented PM consequence pole HEFSM with a flux bridge. This design aims to enhance the flux modulation and regulation capabilities while significantly reducing the consumption of PMs by 46.52% and the associated PM cost by 46.48%. Notably, this design also eliminates stator leakage flux, thereby achieving a highly efficient and cost-effective FSM solution for EV/HEV applications.

In [53], the authors proposed a novel 12-slot-10-pole HEFSM for traction drives in HEVs. The field excitation coil in the stator is wound radially in the radial direction. The design of this machine aims to satisfy several crucial specifications. These include achieving a maximum torque of 210 Nm with a reduction gear ratio of 4:1, delivering a maximum power output of 123 kW, attaining a power density exceeding 3.5 kW/kg, and enabling a maximum rotational speed of 20,000 rpm. These specifications are comparable to the restrictions and requirements of interior permanent magnet synchronous motors (IPMSMs) used in vehicles, such as LEXUS RX400h. The final results demonstrate that the designed HEFSM can achieve a torque density similar to that of an existing IPMSM installed in a commercial SUV-HEV.

These studies highlight the development of innovative FSM designs with improved performance, reduced cost, and enhanced efficiency for electric- and hybrid-vehicle applications.

B. APPLICATION IN RENEWABLE ENERGIES

In the field of renewable energy, FSMs have also been investigated for wave energy harvesting and wind-generator applications. For wave energy harvesting, rotational electric generators used in wave generation systems typically require complex gearing equipment. However, linear generators driven directly by the reciprocation of sea waves offer higher efficiency than rotational systems. FSMs have been studied for their application in wave-energy conversion systems [55].

In [54], the design process involved the development of 12/10 WFFSM and 12/14 PMFSM models specifically tailored for wind-generator applications, as shown in Fig. 10. This study focused on evaluating the performance feasibility of these machines as alternatives to rare-earth permanent magnets, particularly in the context of industrial-scale wind power generation at both small-(10 kW) and large-scale (3 MW) power levels. These findings suggest that simply substituting rare-earth PMs with rare-earth-free materials does not enhance the high torque ripple effects typically associated with FSMs. The study also showed that, at a power level of 10 kW, the ferrite PMFSM outperformed other machine configurations in terms of torque ripple and active mass. At the 3 MW power level, the WFFSMs demonstrated better torque densities, while the ferrite PMFSMs exhibited lower torque ripple values, resulting in cost reductions for WFFSMs in industrial-scale wind generator applications.

In [56], a synchronous generator design aimed at reducing the voltage regulation under load conduction and increasing the power density was proposed. The air-gap flux density of the machine was higher and controllable compared to that of a linear generator (PMFSM) with pure permanent magnets. The tubular structure of the generator helped eliminate the lateral edge effect, and a multitooth structure with multitooth poles was adopted and reviewed for its effects.

In [57], a combination of finite element analysis-based optimization and experimental testing was employed to evaluate two unique nonconventional, nonoverlapping FSM designs for medium-speed wind generator drivetrains. This study focuses on large-scale applications and sub-scaled power levels. The two machines compared were a 10/12 pole/slot WFFSM and 16/18 wound-rotor synchronous machine (WRSM). Through experimentation, it was demonstrated that both generators could efficiently adjust their generated output power in response to varying wind resources. However, the WRSM exhibited a better efficiency range owing to improved regulation of the generator terminal voltage when operating in a direct grid-connected mode.

These studies highlight the exploration of FSMs for wave energy harvesting and wind generator applications and demonstrate their potential for efficient and sustainable renewable energy conversion.

C. APPLICATION IN AEROSPACE INDUSTRY

The demand for high-power-density machines in the electric transport industry, particularly in all-electric aircraft applications, presents an opportunity for research and development of machine topologies that are lightweight and highly efficient [17]. FSMs offer potential solutions to meet the challenges in the aerospace industry's machine applications, with a focus on high-power density.

In the context of aircraft power generation, hybrid machines are preferred owing to their high power density and flux control capabilities. These inherent characteristics facilitate the utilization of more dependable diode bridge rectifiers, rendering them well suited for DC power generation across a wide range of speeds [35]. However, the high remnant voltage of hybrid machines raises safety concerns, particularly in critical applications such as aircraft power generation. To address this issue, wound-field machines are often used. In [47], the authors introduced a design methodology for a HEFSM tailored for aircraft DC power generation. The primary goal was to strike a delicate balance between safety considerations and achieve a high performance. The HEFSM design incorporates a stator composed of CoFe sheets and a rotor composed of SiFe sheets. Despite its small remnant flux linkage, the optimized design of the HEFSM exhibited outstanding performance with a remarkable power-to-weight ratio.

Moreover, in [17], a groundbreaking proposal was presented for a new 1 MW 20-pole/15-slot double rotor FSM tailored for all-electric aircraft applications. This motor design incorporates high-temperature superconducting (HTS) field coils and a sophisticated thermal management system. Notably, the motor featured an air-core stator, utilized an aluminum Litz wire for the armature conductors, and employed a YBCO high-temperature superconducting material for the field coils. The armature winding and field coils were designed to operate at temperatures of 95 K and 65 K, respectively. The newly devised motor demonstrated exceptional performance. It boasted an impressive active part power density of 29.3 kW/kg and a specific power density (including support structure, mechanical components, and HTS) of approximately 18.5 kW/kg. Moreover, the motor achieved a remarkable efficiency of at least 98.7%. These findings hold immense promise for the aviation industry, firmly positioning the FSM as a potential front runner for future aircraft power-generation systems.

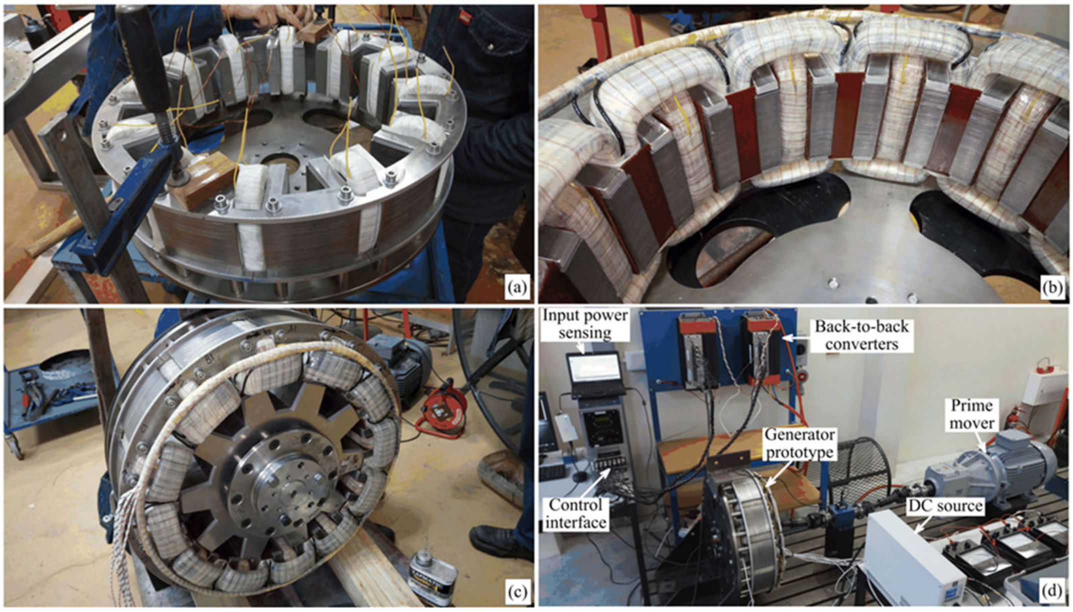

FIGURE 10. Prototype development and testing of FSM. (a) Manufacturing parts. (b) Varnished coils. (c) Assembled machine. (d) Experimental rig [54]. The Study shows the performance feasibility of alternative FSM to rare-earth permanent magnets for wind power generation at small-scale (10 kW) and large-scale (3 MW).

Overall, the development of FSMs with high power densities and advanced features, such as hybrid configurations and the integration of high-temperature superconducting materials, holds great potential for addressing the specific requirements of electric transport industries, including all-electric aircraft applications.

V. COMPARISON OF FLUX SWITCHING MACHINES WITH OTHER MACHINE TYPES

This section presents a comparison of FSMs with other well-known machine types such as Switched Reluctance Machines (SRMs) and Synchronous AC (Syn. AC), induction machines (IMs), and Direct Current (DC) machines. Each machine type was evaluated across various key performance parameters to determine their respective strengths and weaknesses. This comparison aims to provide a comprehensive understanding of how FSMs are compared with other widely used machines in the field of electrical engineering.

- Efficiency: FSMs tend to have high efficiency levels, especially in optimized configurations, owing to their improved flux paths and reduced losses [1]. SRMs also exhibit good efficiency, particularly for high-speed applications [58]. Syn. AC machines and IMs can achieve respectable efficiency levels [59], whereas DC Machines often have lower efficiency owing to commutation losses [60].
- Torque Density: FSMs are known for their relatively high torque density due to the unique utilization of both permanent magnets and field windings [35]. This enables them to achieve higher torque outputs in compact designs. SRMs also exhibit good torque density, although not as high as that of FSMs [61]. Syn. AC machines and IMs have a moderate torque density [62], whereas DC Machines typically have a lower torque density owing to their commutation mechanisms [63].
- Cost: FSMs often require more complex control systems and manufacturing processes, leading to relatively higher initial costs [11]. SRMs and Induction Machines are typically more cost-effective in terms of manufacturing. Syn. AC Machines can vary in cost, depending on their control and construction [62]. DC Machines generally have lower manufacturing costs, but can be less efficient in certain applications [60].
- Power Factor Control: FSMs and SRMs offer inherent power factor control capabilities due to their variable reluctance nature [11], [64]. Syn. AC and induction machines can also provide some level of power factor control through control strategies [62], [65]. DC Machines typically require external power factor correction mechanisms [66].
- Thermal Capability: FSMs' robust construction and efficient thermal paths contribute to good thermal performance [12]. SRMs also exhibit good thermal behavior owing to their simple structures [67]. Syn. AC machines and IMs have acceptable thermal capabilities [68], [69], whereas DC Machines might require additional cooling measures for higher-power applications [70], [71].
- Construction: The complex construction of FSMs, particularly the HEFSM variant, is known for their relatively high torque density due to the unique utilization of both permanent magnets and field windings [6], [7], [9]. This allows them to achieve higher torque outputs within compact designs, which can make them bulkier than the SRMs and IMs. SRMs are relatively simple

to construct, whereas Syn. AC machines can vary in complexity based on the type (synchronous reluctance, synchronous permanent magnet, etc.) [72]. IMs have a straightforward construction and DC machines are relatively simple [63], [73].

In summary, FSMs exhibit notable advantages in terms of torque density, efficiency, and power-factor control. However, they tend to have higher manufacturing costs and more complex construction, particularly in the case of HEFSM variants. SRMs offer comparable torque density and efficiency with simpler construction. Syn. AC and Induction machines provide moderate performance across various parameters, whereas DC machines are suitable for specific applications with lower efficiency requirements. Understanding these comparative aspects helps engineers make informed decisions regarding the most suitable machine type for their specific requirements.

VI. IMPROVEMENT OF FSM TECHNOLOGY

Accurate modeling and performance analysis are crucial for the initial design of electrical machines [13]. During this process, various key factors are considered as objective functions to improve the performance of FSM technology. These objectives encompass maximizing the torque, power factor, and efficiency while minimizing the torque ripple and mitigating the radial force to reduce the acoustic noise and vibration of the machine. By considering and optimizing these key factors during the design process, engineers aim to develop FSMs that deliver high torque, improved power factor and efficiency, reduced torque ripple, and minimized acoustic noise and vibration. By implementing these improvement strategies, researchers and engineers aim to enhance the overall performance and reliability of FSMs, making them more suitable for a wide range of applications, from electric vehicles and renewable energy systems to aerospace applications. This section offers a comprehensive review of improvement strategies for FSMs, drawing upon selected studies from various authors in the field.

A. TORQUE IMPROVEMENT

Torque production in FSM relies on controlling the flux path within the machine by switching the magnetic field between different rotor poles. This control over the magnetic flux creates a varying magnetic field in the air-gap. The air-gap field harmonics, including the fundamental component responsible for the primary torque generation and higher harmonics owing to the structure of the rotor, play a crucial role [11]. Torque is produced through the precise positioning of the rotor and magnetic field switching, inducing currents in the stator windings, leading to Lorentz forces, and utilizing harmonics to modulate the torque [5]. Maximizing the generated torque is a key objective in FSM design, which involves optimizing various aspects of the machine to achieve the highest possible torque output. Two main approaches can be adopted to enhance the torque capability of FSMs: design variable optimization and structural modifications [74]. In design variable optimization, the design parameters of the machine are optimized without altering the basic machine topology, which is a commonly used approach in conventional FSMs. Structural modifications involve topological changes and can be categorized into magnet design modifications (such as rotor PMs, parallel PMs, v-shaped PMs, and Halbach arrangements), partitioned rotor/stator modifications, and stator lamination changes (including c-core, E-core, and multitooth core) [74], [75].

The torque equation considers multiple factors affecting the machine torque but does not separate the phase-specific contributions. It uses a lumped parameter approach, combining all phase effects for overall torque. Electric machines typically have multiple phases (often three), each contributing to the total torque based on the phase currents, winding, and magnetic interactions. The analytical torque equation proposed in [76] and employed in [15] is expressed as follows:

$$T_e = \frac{\sqrt{2}\pi^2}{4}\frac{P_r}{P_s}K_s K_d \Lambda_0^2 A_s B_g D_{\text{out}}^2 L_{\text{st}} c_s \eta, \tag{1}$$

where D_{out} denotes the stator outer diameter, T_e represents the electromagnetic torque, Λ_0 signifies the split ratio, N_s refers to the number of slots for the phase windings, k_d is the leakage, A_s denotes the electrical loading of the phase windings, B_g indicates the peak airgap flux density, K_s represents the winding factor, η signifies the efficiency, k_L relates to the aspect ratio, and c_s corresponds to the stator tooth arc factor. A more detailed explanation of the modification of (1) concerning the wound-field variant was provided in [15]. It is important to highlight that the torque equation can be further modified based on the specific variant and configuration of the FSM.

Equation (1) shows that various design parameters collectively affect the electromagnetic torque of FSMs. Among these parameters, certain geometrical factors have the greatest influence. The outer diameter of the stator is a critical factor because of its quadratic relationship in the equation. Changes in the stator diameter result in nonlinear variations in the torque output. Additionally, the number of pole pairs determines the machine's pole configurations, influencing the magnetic interactions, and consequently, the torque production. The winding factor K_s influences the stator-rotor field coupling. The split ratio Λ_0 governs the winding distribution and flux, thereby affecting the torque. Electrical loading A_s alters the current capacity, magnetic field, and torque. The air-gap flux density B_g affected the magnetic force and torque. The stack length L_{st} and stator tooth arc factor c_s alter the geometry and flux, thereby impacting the torque. These factors collaboratively determine the electromagnetic torque output, with the stator diameter standing out owing to its quadratic influence, highlighting its significance in optimizing the torque performance.

In [75], a novel PMFSM with dual sets of magnet arrangements was proposed, resulting in a significantly improved torque density by increasing the working harmonic content of the MMF. The effects of geometric parameters on the average torque and cogging torque were also investigated, demonstrating a 30.8% increase in torque density, 79.4% reduction in cogging torque, and 15.6% improvement in power factor compared to the conventional counterpart.

The authors of [77] presented a partitioned stator hybrid excited machine with a DC-biased sinusoidal current. This machine utilizes consequent pole permanent magnets for PM excitation on the inner stator, while an integrated dual three-phase winding on the outer stator produces wound and armature fields simultaneously by injecting a sinusoidal current with DC bias. The proposed machine outperformed existing series and parallel machines in terms of torque.

The torque density, defined as the machine's average torque to its volume (in Nm/m^3), and the specific torque, which represents the ratio of the average torque to machine weight (in Nm/kg), can also be used as an optimization function. Overall, research efforts have focused on optimizing FSM design variables, exploring structural modifications, and utilizing optimization techniques to improve the torque performance and density in FSM technology [3], [54], and [78].

B. POWER FACTOR AND EFFICIENCY IMPROVEMENT

The power factor is a crucial parameter in electrical machines, as it indicates the efficiency of power transfer by measuring the phase relationship between the voltage and current. A higher power factor signifies more efficient utilization of electrical energy and improved performance [79]. In FSMs, the power factor can be enhanced to increase the energy efficiency.

The low air-gap flux density excited by permanent magnets is often the primary cause of low power factor. Different permanent-magnet topologies have been explored to improve the power factor by enhancing the air-gap flux density. Spoke-type PMs, Halbach PMs, and consequent-pole PMs have been identified as contributing factors to improving the power factor by improving the air-gap flux density [74], [79]. Similarly, studies have shown that the power factor of an FSM can be enhanced by reducing the leakage flux and modifying the phase-phase axial separation [80]. Other techniques for enhancing the power factor in FSM were investigated in [3], [57], [81], and [82].

Efficiency is a crucial factor in the performance of electrical machines as it measures the effectiveness of converting electrical power into mechanical power. To improve the efficiency, design optimization techniques are applied to minimize losses in various components of the machine, including the core, windings, and mechanical parts. This optimization process helps to maximize the conversion of the input electrical power into a useful mechanical output. In the case of FSMs, minimizing losses is a key strategy for enhancing the efficiency. One approach is to select appropriate materials for machine construction. Copper

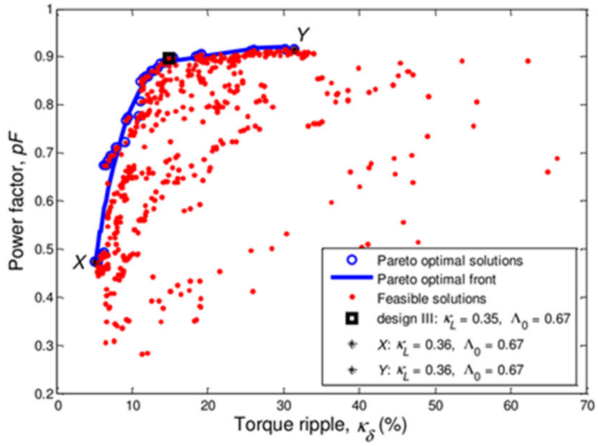

FIGURE 11. Pareto optimal front of power factor and torque ripple [15]. The figure reveals the trade-off between higher power factor performance and lower torque ripple values, characterized by the curving and stretching of the front in the feasible design space.

magnet wires are commonly used for coils owing to their high thermal conductivity, high current-carrying capacity, and low electrical resistivity compared with alternatives such as aluminum [83]. Additionally, the core loss can be reduced by utilizing low-loss magnetic steel materials such as 6.5% high silicon steel, low-loss silicon steel, laminated amorphous alloy, or high-resistivity soft magnetic composites [83], [84].

In [22], a novel double-sided linear HEFSM with a yokeless secondary structure is proposed for long-stroke applications. The elimination of the secondary yoke in this innovative design reduces its volume, resulting in a more compact machine. Furthermore, cost reduction was achieved by using ferrite magnets with a reduced volume compared with conventional designs. Despite operating within the same volume constraint and electrical loading, the proposed model demonstrated higher efficiency and power factor.

C. TORQUE RIPPLES REDUCTION

Torque ripple refers to the fluctuation in torque output during each revolution of an electrical machine resulting from variations in the electromagnetic fields and their interactions between the rotor and stator [85]. Minimizing the torque ripple is crucial for achieving smooth and stable machine operation, as excessive fluctuations can lead to undesirable vibrations and noise. This objective is typically achieved through careful design of the machine's magnetic structure and control algorithms.

In particular, FSMs exhibit higher torque pulsations compared to other machine types because of the discrete nonlinear torque of each phase and the doubly salient structure of the machine [27], [54], [86], [87]. Reducing the torque ripple in FSMs has been an active area of research. Geometry and topology optimization are commonly used approaches to minimize torque ripple.

The torque ripple (TR) is given as:

$$TR = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}}, \quad (2)$$

where $T_{\max}$ denotes the maximum torque, $T_{\min}$ denotes the minimum torque, and T_{avg} denotes the average torque. The process of optimizing torque ripples in FSMs begins by addressing the following problem:

$$\text{Minimize: } f_m(x_m) \tag{3}$$
$$\text{Subject to: } h_m(x_m). \tag{4}$$

The design variables and constraints in the optimization process are denoted as x_m and h_m, respectively. The machine's optimization goal is represented by $f_m(x_m)$, which aims to minimize the torque ripple within this framework. It is formulated as:

$$f_m(x_m)_{\min} = \lambda_{w1} \frac{TR'}{TR(x_m)}, \tag{5}$$

where the weight coefficient and the initial value of the torque are represented as λ_{w1} and TR', respectively.

In the context of torque ripple minimization in flux-switching machines, it is crucial to ensure that the optimization process aligns with the practical operational constraints. This involves considering both geometrical and control parameters such as the stator outer diameter, slot width, current density, phase current, and rotor position. These design constraints prevent the machine from operating in regions that could potentially damage it or cause instability. For instance, phase-current constraints are important for maintaining thermal integrity and avoiding undesirable effects due to excessive current. Airgap length constraints are essential for preventing magnetic saturation. Balancing the minimization of torque ripples while satisfying these constraints requires a comprehensive optimization approach. By accounting for these operational limitations, the optimized solution will not only reduce torque ripples, but also ensure safe and reliable motor performance.

In [85], an analytical model was proposed to reduce the air-gap permeance variation and torque ripples in an 8-slots-6-poles single-phase electrically excited FSM. The rotor pole-shaping technique was employed to minimize the variation in the air-gap permeance. The proposed design resulted in a 71% reduction in magnetic flux harmonics, 48.5% suppression of back-EMF harmonics, 20% reduction in torque ripples, and 42.7% decrease in the cogging torque. Other studies have utilized parameters such as the arc angles of the rotor and stator poles, height of the rotor and stator poles, stator/rotor back iron thickness, number of phases, and stack length to minimize torque ripple in FSMs [27], [81], [97].

Fig. 11 presents the optimal data of the Pareto optimal front for a WFFSM designed for wind-energy applications, as reported in [15]. The analysis involved 2D FEA, combined with simple analytical formulations. The authors demonstrated that a higher power factor performance could be achieved at lower torque ripple values if the mass of the machine is not prioritized during the multi-objective design optimization process. The shape of the Pareto front in Fig. 5 indicates that a higher power factor estimation is obtained at lower torque ripple values, with the front curving away from the peripheral axes and stretching along both axes within a feasible design space. It should be noted that this approach oversimplifies the torque ripple calculations, which can limit the performance of the machine. A novel approach was introduced in [98]. This approach leveraged the principle of flux modulation to thoroughly analyze the torque ripple in a V-shaped permanent-magnet FSM. The analysis confirmed that the torque ripple predominantly originated from the 9th and 18th torque harmonics. By identifying the key design parameters associated with these harmonics as well as the leading airgap harmonics, this study focused on improving their generation principles. By implementing enhancements to these crucial design parameters, the 9th and 18th torque harmonics were effectively reduced, leading to significant suppression of the torque ripple from 42.15% to 20.17%. This notable reduction validates the efficacy of the proposed method in mitigating the torque ripple, thereby addressing a critical challenge in FSMs.

D. MITIGATION OF RADIAL FORCE AND VIBRATION

Radial forces occurring in electrical machines can induce mechanical vibrations and noise, which result from the interaction between the magnetic fields and the mechanical structure of the machine [99]. Various factors contribute to the vibration of the drive system, including torque ripple, power electronic device switching, torsional forces, and non-sinusoidal magnetic fields generated by permanent magnets [100], [101]. Particularly in PM machines, non-sinusoidal magnetic fields from permanent magnets, saturation effects of the iron core, and stator slotting create a complex harmonic magnetic field and rapidly change exciting forces [101].

To mitigate vibrations in FSMs, specific attention must be paid to high-amplitude and low-order exciting force components. Additionally, it is essential to compare the modal frequencies and frequencies of each order of exciting force to prevent beating vibrations or resonance [102]. Minimizing radial forces is of utmost importance to ensure smooth and reliable machine operation and enhance overall performance.

Extensive research has been conducted on unbalanced forces and vibrations in various types of electric machines including switched reluctance machines [102], [103], [104], fractional slot concentrated winding surface permanent magnet machines [99], [105], [106], induction machines [107], [108], wound-field synchronous machines [109], [110], and interior permanent magnet machines [101], [111], [112]. Different design approaches have been proposed to mitigate electromagnetic vibrations by modifying the geometric dimensions and topologies of the machines. These approaches include techniques such as pole width changing, pole shifting, adding auxiliary permanent magnets, and shaping or segmenting the permanent magnets. Adjusting the position and shape of the rotor poles allows for the redistribution of the air-gap flux and the directional elimination

TABLE 1. Popular optimization algorithms for efficient design of various types of electrical machines.

Optimization Technique	Description	Advantages	Limitations	Suitable Performance Improvements
Non-dominated Sorting Genetic Algorithm (NSGA-II)	This optimization method is extensively employed and incorporates an elitist strategy, utilizing the crowding distance operator to maintain diversity and the sorting operator to select Pareto-dominant solutions [88].	Multi-objective optimization	Requires tuning of parameters	Cogging torque reduction, torque ripple mitigation
Evolutionary Algorithm (EA)	It mimics the evolutionary process observed in species, drawing inspiration from the concept of natural selection. They can be regarded as a subcategory of Evolutionary Algorithms (EAs) [89].	Global search capability	Computational intensity	Efficiency improvement, torque enhancement
Deterministic Optimization (DO)	This employs the gradients of the objective function concerning the design parameters to direct the optimization iterations towards the optimal solution [90].	Convergence reliability	Limited to simple landscapes	Torque ripple reduction, efficiency enhancement
Particle Swarm Optimization (PSO)	It utilizes an evolutionary-based search approach and proves valuable for optimizing parameters in continuous, multidimensional search spaces [91].	Fast convergence	Local minima convergence	Torque output enhancement, efficiency improvement
Archive-based Multi-objective Genetic Algorithm (AMOGA)	This approach incorporates an archive and leader selection process commonly employed in Multi-objective Optimization [87], [90].	Pareto front solutions	Limited scalability	Cogging torque reduction, torque ripple mitigation
Online Optimization Method (OOM)	This method operates by gradually revealing input data and providing output at intermediate stages [92].	Real-time adaptation	May require complex modeling	Efficiency improvement, torque enhancement
Artificial Neural Network (ANN)	This computational algorithm, inspired by the biological nervous system, was employed for data modelling. Its design is influenced by the functioning of biological systems, and hence its name. It finds applications in scenarios in which extracting trends or detecting patterns is challenging [93].	Non-linear optimization	Training complexity	Efficiency enhancement, torque improvement
Differential Evolution (DE)	This method applies the weak-dominance concept to identify Pareto-dominant solutions and incorporates an enhanced crowding distance operator and a non-dominated sorting algorithm for result analysis [89].	Robust performance	Slower convergence	Torque ripple reduction, efficiency improvement
Response Surface Method (RSM)	This statistical tool constructs an empirical model of a response by considering input variables. The responses of various objectives are assessed at different points in space, allowing the evaluation of responses at additional points in the design space through interpolation [58].	Surrogate modeling	Limited accuracy	Torque enhancement, efficiency improvement
Nelder–Mead Optimization (NMO)	This heuristic optimization algorithm, similar to GA or PSO, is particularly suitable for addressing relatively simple optimization problems with few local minima and low dimensions ($n < 10$) [94].	Simple and reliable	May converge to local minima	Torque ripple reduction, efficiency enhancement
Design of Experiment (DoE)	This statistical optimization tool efficiently measures the impact of altering the geometrical design variables on the responses of the machines [83].	Systematic exploration	Limited to predefined factors	Cogging torque reduction, torque ripple mitigation
Latin Hyper Cube Sampling (LHS)	This method can be used to sample random numbers in which samples are distributed even [95].	Factor variation	Limited to specific designs	Torque enhancement, efficiency improvement
Taguchi Optimization (TO)	This approach is employed to determine the minimum number of experiments within the specified limits of factors and levels [94]. It utilizes the concept of orthogonal arrays to determine the required number of simulations for optimization [96].	Factor optimization	Assumes linear relationships	Cogging torque reduction, torque ripple mitigation

of specific-order air-gap flux harmonic components. Another method involves modifying the stator tooth, such as altering the tooth shape [106], introducing auxiliary slots on the stator tooth [112], or utilizing teeth with unequal widths [113]. These methods alter the air gap flux by modifying the permeability distribution in the air gap. Overall, these methods have demonstrated their effectiveness in mitigating vibrations. However, further research is required to enhance the understanding and mitigation of radial forces and vibrations in FSMs.

VII. OPTIMISATION OF FSMs AND RESEARCH GAPS

In this section, a comprehensive review that covers a wide range of techniques utilized in the optimization of electrical machines is provided. The objective was to offer a brief understanding of the approaches and methodologies employed to enhance the performance, efficiency, and overall design of electrical machines. Fig. 12 illustrates the optimization algorithms utilized in the design optimization of electrical machines and other electromagnetic devices [67]. These algorithms can be categorized into

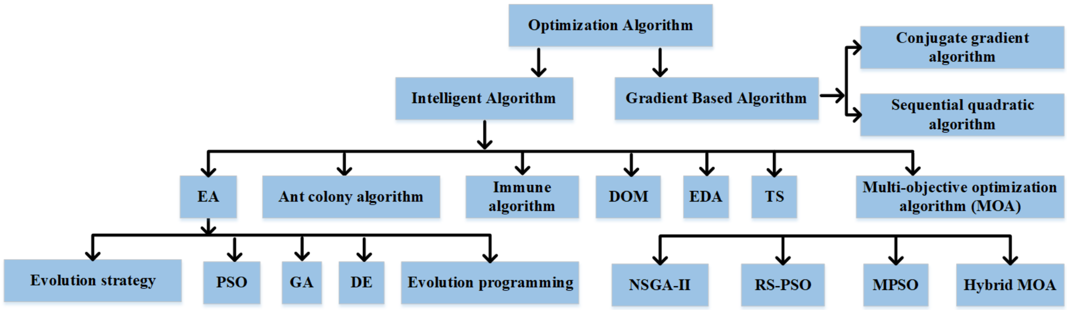

FIGURE 12. Evolutionary tree of optimization algorithms for electrical machine design. This figure presents the relationships and progression of optimization methods dedicated to enhancing the performance and efficiency of electrical machines. The interconnected branches illustrate how different optimization techniques have evolved and branched out over time to address the intricate challenges posed by electrical machine design optimization.

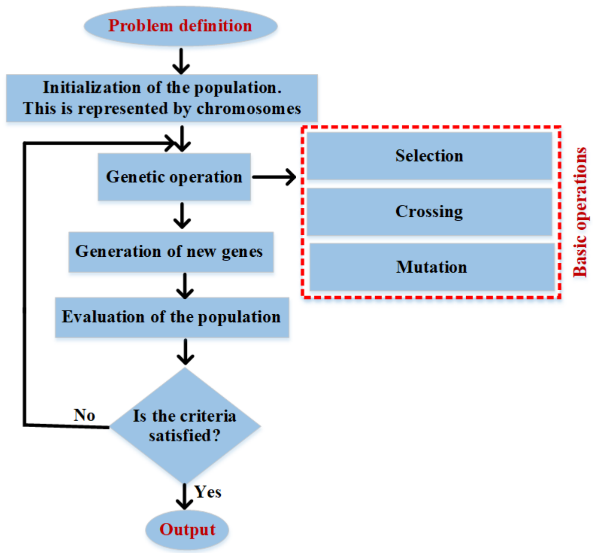

FIGURE 13. Flowchart of a general genetic algorithm. It shows different phases and termination criterion of the algorithm, which concludes upon reaching the threshold fitness solution.

two types: gradient-based algorithms (GBAs) and intelligent optimization algorithms (IOAs). It showcases a total of eighteen optimization algorithms utilized in electric machine design. These algorithms include the conjugate gradient algorithm (CGA), sequential quadratic programming (SQP) algorithm, estimation of distribution algorithm (EDA), immune algorithm, evolutionary algorithm (EA), evolution programming, evolution strategy, and ant colony algorithm. However, based on preliminary studies conducted in both academic and industrial fields, commonly preferred optimization algorithms include the conjugate gradient algorithm (CGA), sequential quadratic programming (SQP) algorithm, tabu search (TS), and deterministic optimization method (DOM). Furthermore, genetic algorithms (GA), differential evolution (DE) algorithms, and particle swarm optimization (PSO) are the three major subclasses of evolutionary algorithms (EA) frequently utilized. In the category of multi-objective algorithms (MOA), the widely used modified PSO (MPSO), non-dominated sorting genetic algorithm (NSGA II), hybrid multi-objective algorithm (hybrid MOA), and response Surface-PSO (RS-PSO) is among the four commonly employed optimization approaches [83], [91]. These algorithms have been effective for addressing multiple objectives simultaneously.

A general flowchart illustrating the optimization process of the GAs is shown in Fig. 13. The algorithm begins with a population of solutions represented by chromosomes. From this initial population, a new population, referred to as an offspring or children, is formed through three genetic operations: crossover, mutation, and selection. The parent solutions are selected based on their fitness, meaning that more suitable solutions have a higher chance of being reproduced in the evolutionary process. This process is repeated until certain conditions or criteria are met, such as the maximum iteration number [114].

To handle nonlinear constraints, an Augmented Lagrangian Genetic Algorithm (ALGA) is proposed in [56].

The optimization problem addressed by the ALGA is defined as follows:

$$\text{Minimize:} \quad f(x) \tag{6}$$

$$\text{Subject to:} \quad g_i(x) \leq 0, \quad i = 1, 2, \ldots, m \tag{7}$$

$$h_j(x) = 0, \quad j = 1, 2, \ldots, l \tag{8}$$

$$Ax \leq B \tag{9}$$

$$x_{\text{lb}} \leq x \leq x_{\text{ub}}. \tag{10}$$

The optimization problem considered in this method involves upper and lower limits, denoted as x_{ub} and x_{lb}, respectively, for the design variables. The constraints in this method can be categorized as nonlinear constraints, represented by (7) and (8), and linear constraints, represented by (9) and (10). To address these constraints, a sub-problem is formulated by combining nonlinear equality and inequality constraints with objective functions. This is achieved by using Lagrangian and penalty functions, resulting in the following formulation [56]:

$$R(x, \lambda, s, \rho) = f(x) - \sum_{i=1}^{m} \lambda_i s_i \log(s_i - g_i) + \sum_{j=1}^{l} \lambda_{j+m} h_j + \frac{\rho}{2} \sum_{j=1}^{n} h_j^2. \tag{11}$$

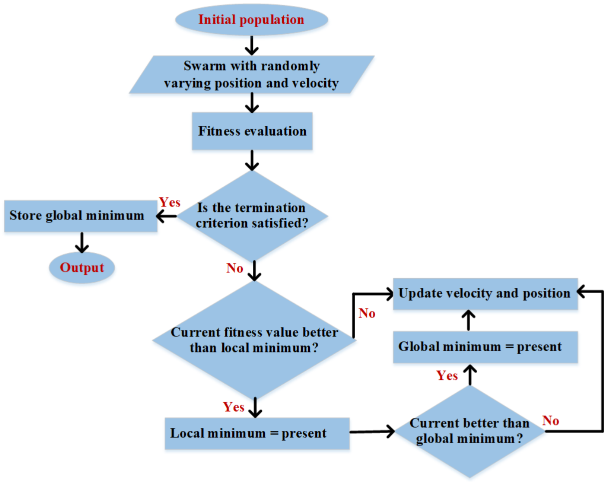

FIGURE 14. Flowchart of the particle swarm optimization algorithm. The algorithm progressively refines candidate solutions towards optimal solutions using swarm intelligence principles.

In the given algorithm, λ represents the estimate of the Lagrangian multiplier, s denotes a nonnegative shift, and ρ is the penalty parameter. The algorithm began with an initial value of ρ. GA is used to minimize a series of subproblems, where λ, s, and ρ are kept constant within each subproblem. Once a subproblem is minimized to the desired accuracy, the values of λ, s, and ρ are updated to form the next subproblem. This process continues until the termination criteria are satisfied. Consequently, the GA algorithm is capable of solving optimization problems that involve nonlinear equality and inequality constraints. Additionally, Fig. 14 illustrates a flowchart that depicts the particle swarm optimization (PSO) algorithm. In PSO, each particle (or individual) in a swarm is associated with a location within the design space. At each iteration, the particle locations are updated based on the velocity, which is determined by considering the best achieved positions of the particle and the global best position across the entire swarm. Mathematically, this can be expressed as [88]:

$$x_i^k = x_i^{k-1} + V_i^k, \tag{12}$$

$$V_i^k = wV_i^{k-1} + C_1 d_1(x_i^{\bar{k}} - x_i^{k-1}) + C_2 d_2(x^{\bar{k}} - x_i^{k-1}). \tag{13}$$

The velocity of the i-th particle at the k-th iteration is denoted by V_i^k and its position is represented as x_i^k, whereas the best global solution across all particles is $x_{\bar{i}}$. The cognitive learning factor is denoted by $C1$, where $C2$ represents the factor that connects the best global value to each particle. Random values between 0 and 1 are denoted by $d1$ and $d2$. The acceleration factor is denoted as w. As illustrated in Fig. 14, the algorithm begins by evaluating the fitness of a randomly generated population with random positions and velocities. The best local minimum of the population is stored and compared with that of the subsequent populations. The algorithm updates the velocities and positions of all particles based on equations (12) and (13). The algorithm continues to run until the termination conditions are satisfied [88].

Multiobjective optimization plays a crucial role in tailoring the design of FSMs to meet the diverse requirements of different industrial applications. In this approach, multiple performance indices of the FSMs are considered simultaneously. The solution candidates were then evaluated and processed in a distinct manner, as explained in the preceding section. By considering multiple objectives, the optimization process aims to find a set of solutions that represents a trade-off between different performance metrics, allowing for a more comprehensive and flexible design approach [91].

In multi-objective optimization of the FSM, the generic optimization model of the machine can be described as follows:

$$F_m = F[f_m(x_m)]_{\min}. \tag{14}$$

The boundary constraints are as follows:

$$h_m(x_i) \leq 0, k = 1, 2, , N_m. \tag{15}$$

$$\text{Min}X_i \leq X_i \leq \text{Max}X_i. \tag{16}$$

The optimization model of the FSM is denoted as F_m, whereas the objective function of the process is given as $f_m(x_m)$ which represents the optimization of various performance targets of the machine, such as the improvement of average torque, efficiency, torque density, and reduction of cogging torque and torque ripples.

$X_i = [x_m]$ is the design variable vector, which includes both geometrical and control parameters, such as the stator outer diameter, stack length, slot width, current density, phase current, and rotor position. These parameters play vital roles in maintaining a safe and reliable machine operation.

The upper and lower limits of X_i are denoted by MaxX_i and MinX_i, respectively. The boundary and the number of constraints are represented as h_m and N_m, respectively.

The corresponding objective function that involves the five performance criteria is formulated as follows:

$$f_m(x_m)_{\min} = \lambda_{w1}\frac{TR'}{TR(x_m)} - \lambda_{w2}\frac{\eta'}{\eta(x_m)} + \lambda_{w3}\frac{T'_{\text{cog}}}{T_{\text{cog}}(x_m)} - \lambda_{w4}\frac{T'_{\text{avg}}}{T_{\text{avg}}(x_m)} + \lambda_{w5}\frac{\text{cost}'}{\text{cost}(x_m)}, \tag{17}$$

where the torque ripple, efficiency, cogging torque, average torque, and cost of the machine are denoted as TR, η, T_{cog}, T_{avg}, and cost respectively. The weight coefficients are λ_{w1}, λ_{w2}, λ_{w3}, λ_{w4}, and λ_{w5}, and their initial values are denoted as TR', η', T'_{cog}, T'_{avg}, and cost′, respectively. The introduction of the weight coefficients ensures that the resulting solution not only achieves the desired performance improvements, but also maintains the operational feasibility and integrity of the machine. The objective function and constraints work in tandem to guide the optimization process towards an optimal design that balances performance metrics with real-world practicalities.

TABLE 2. Overview of optimization strategies for permanent magnet flux switching machines (PMFSMs). This table provides notable studies that delve into optimization methods and their practical applications of PMFSMs.

Topology	Opt.	Avg. Torq.	Cog. Torq.	Stress	Temp. Effect	Control Scheme	Eff./ Loss	P.F	Cost	Torq. Rip.	Industry App.	Val. Meth.	Ref.
12/10	GA	Yes	No	No	No	No	No	No	No	No	High power app.	Experiment	[115]
12/10	DO	Yes	Yes	No	No	No	No	No	No	Yes	Generic	Experiment	[27]
Linear PMFSM	RSM	No	No	No	No	No	Yes	Yes	No	No	Ropeless elevator system	Simulation	[21]
12/10	DO	No	Yes	No	No	No	No	No	No	No	Direct-drive wind power system	Experiment	[28]
12/22	RSM	Yes	No	No	No	No	No	No	No	Yes	HEV	Experiment	[116]
6/19	ANN		No	No	No	No		No	Yes	Yes	wind drives	Experiment	[25]
36/34	GA	Yes	No	No	No	No	Yes	No	No	Yes	EV	Simulation	[117]
6/8	PP	Yes	No	No	No	No	No	No	No		HEV	Simulation	[78]
12/10	RSM	Yes	Yes	No	No	No	No	No	No	Yes	HEV	Experiment	[118]
20/11	PSO	Yes	No	No	No	No	No	No	No	Yes	EV	Experiment	[119]
24/22	NMO	No	No	No	No	No	Yes	No	No	Yes	Direct-driven wind turbine	Simulation	[120]
Linear PMFSM	TO	No	No	No	No	No	No	No	No	No	Drive wave energy conv.	Simulation	[121]
22/24	NMO	No	No	No	No	No	No	No	Yes	No	Low-speed wind gen.	Simulation	[10]
12/14	TO	No	Yes	No	No	No	No	No	No	Yes	Counter-rotating wind turbine	Experiment	[122]
12/5	DO	Yes	Yes	No	No	No	Yes	No	No	No	EV	Simulation	[123]
24/22	MLO	Yes	No	No	No	No		No	No	Yes	Expanded speed app.	Experiment	[29]
24/10	RSM	Yes	No	No	No	No	Yes	No	No	No	HEV	Simulation	[49]

A Brief description of other popular optimization techniques used in the design of electrical machines is presented in Table 1. These algorithms play a vital role in improving the design of the electrical machines. GA and EA mimic natural selection to find optimal solutions. DOM focuses on non-dominated solutions for multi-objective optimization. PSO simulates the behavior of particles to explore the search space. AMOGA adapts the population size based on problem complexity. Other algorithms, such as Orthogonal OOM, ANN, DE, RSM, NMO, DoE, LHS, and TO contribute to optimizing electrical machine designs, each with their own unique approaches and advantages. These diverse optimization algorithms provide engineers with effective tools for optimizing the design of electrical machines for a wide range of applications.

Although various approaches such as the enumeration method (EM), RSM, and parametric scanning/optimization have been applied to address multi-objective design and optimization problems in FSMs, stochastic algorithms are commonly employed in the majority of the literature. These stochastic algorithms assess a large number of design candidates using randomly generated independent prime design variables. These variables typically involve critical geometric parameters of FSMs, such as magnet arc, magnet thickness, air gap diameter, stator tooth arc, stator-to-rotor copper loss ratio, stack length, split ratio of stator/rotor pole heights, stator and rotor tooth arcs, pole arc angles, auxiliary tooth width, rotor, and stator yoke thickness, and non-geometric factors such as current density and number of turns. The complete machine geometry was subsequently designed, and various performance indices were evaluated using techniques such as FEA simulations, multilevel models, or analytical models based on a magnetic equivalent circuit (MEC). These performance indices are incorporated into a scalar or vector objective function, and the next generation of prime design variables is generated using multi-objective optimization algorithms, such as genetic algorithms (GA), particle swarm optimization (PSO), and Tabu search (TS). This iterative process continued until the desired number of iterations was achieved. Finally, the optimal model performance indicators were validated through experimental tests or simulations, demonstrating significant enhancements in the targeted performance indices while minimizing their impact on others, as reported in previous studies.

TABLE 3. Overview of optimization strategies for wound-field flux switching machines (WFFSMs). This table provides notable studies that delve into optimization methods and their practical applications of WFFSMs.

Topology	Opt.	Avg. Torq.	Cog. Torq.	Stress	Temp. Effect	Control Scheme	Eff./ Loss	P.F	Cost	Torq. RIP.	Industry App.	Val. Meth.	Ref.
12/10	GA	No	No	No	No	No	Yes	Yes	No	No	Wind energy drives	Simulation	[15]
12/10	DO	Yes	No	No	No	No	Yes	No	No	No	All electric boat	Simulation	[124]
12/10	SM	No	No	No	No	No	No	No	No	Yes	Turbo synch. condenser	Experiment	[125]
12/13	DO	Yes	Yes	No	No	No	No	No	No	No	In-wheel direct drive	Simulation	[14]
12/10	DO	Yes	No	No	No	No	No	No	No	No	HEV and All electric boats	Simulation	[9]
12/10	GA	Yes	Yes	No	No	No	No	No	No	Yes	Medium-speed wind power gen.	Experiment	[57]
12/10	GA	Yes	No	No	No	No	No	No	No	Yes	Wind gen.	Experiment	[54]
12/13	DO	Yes	No	No	No	No	Yes	No	No	No	HEV	Simulation	[126]
10/8, 10/9, 10/11, and 10/12	GA	Yes	No	No	No	No	Yes	No	No	Yes	Wind energy	Experiment	[81]
24/17, 24/14	EM	Yes	Yes	No	No	No	Yes	No	No	No	Higher torque density	Experiment	[94]
12/10	EM	Yes	No	No	No	No	Yes	Yes	No	Yes	Wind energy drives	Simulation	[3]
5/7	LHS	Yes	No	No	No	No	No	No	No	No	Electric grid system	Simulation	[127]
Linear WFFSM	DO	Yes	No	No	No	No	No	No	No	Yes	Long stroke app.	Simulation	[128]
12/10	GA	Yes	Yes	No	No	No	No	No	No	Yes	Wind power gen.	Experiment	[129]
12/10	PO	No	Yes	No	No	No	No	No	No	No	Wind turbines	Simulation	[130]
12/10	DO	Yes	No	No	No	No	Yes	No	No	No	HEV	Experiment	[52]
12/10	SM	No	No	No	No	No	No	No	No	No	Synch. condenser	Experiment	[46]
12/7, 12/11, 12/13, and 12/17	GA	Yes	No	No	No	No	No	No	No	Yes	High speed app.	Simulation	[43]

Tables 2, 3, and 4 list the various multi-objective approaches that have contributed to the advancement of FSM technology. These tables provide information on PMFSM, WFFSM, and HEFSM, focusing on the machine topology, optimization strategy, performance indices for optimization, industrial applications, and validation methods. Additionally, Table 5 presents a review of the optimization strategies employed in different electrical machines with diverse objective functions. The abbreviated optimization algorithms SLO, EM, SM, SO, DO, PO, and MLO stand for system-level optimization, enumeration method, surrogate model, stochastic optimization, deterministic optimization, parameter optimization, and multilevel optimization, respectively.

In Table 5, the listed machines include SynREL, IPM, BLDC, AFPMM, VPMs, DRAFPMM, and SPMSM, representing synchronous reluctance machines, interior permanent magnet machines, brushless direct current motors, axial flux permanent magnet machines, vernier permanent magnet machines, dual-rotor axial flux permanent magnet machines, and surface permanent magnet synchronous motors, respectively.

Although significant progress has been made in enhancing the performance of electrical machines, this study focuses on evaluating the latest and most influential works. However, it is important to note that there are still substantial unexplored areas in the literature, and there is a continuous need for fast and highly accurate methods for FSM performance evaluation.

The optimization design gaps in FSMs, as revealed by the comparison between Tables 2, 3, and 4 and Table 5, can be summarized as follows:

- Limited integration of control schemes: There's a notable absence of the integration of control schemes for FSMs into the optimization processes, with only

TABLE 4. Overview of optimization strategies for hybrid excited flux switching machines (HEFSMs). This table provides notable studies that delve into optimization methods and their practical applications of HEFSMs.

Topology	Opt.	Avg. Torq.	Cog. Torq.	Stress	Temp. Effect	Control Scheme	Eff./ Loss	P.F	Cost	Torq. RIP.	Industry App.	Val. Meth.	Ref.
12/10	PSO	No	No	No	No	No	Yes	No	No	No	Aircraft DC power generation	Simulation	[47]
12/14	AMOGA	No	No	No	No	No	Yes	No	Yes	Yes	Elevators and industrial shredders	Experiment	[87]
12/10	DO	No	No	No	No	No	Yes	No	No	No	HEV	Simulation	[30]
10/18, 10/19, 10/21	PO	Yes	No	No	No	No	No	No	No	No	EV	Simulation	[131]
12/10	GA	No	No	No	No	No	No	No	Yes	No	Electric power train	Experiment	[7]
18/13	GO	Yes	Yes	No	No	No	No	No	No	Yes	HEV	Simulation	[8]
6/5, 6/7	GA	No	No	No	No	No	No	Yes	No	No	Machine tools	Experiment	[132]
Linear HEFSM	GA	No	No	No	No	No	Yes	No	No	No	Electric power train	Simulation	[133]
Linear HEFSM	GA	No	No	Yes	No	No	No	No	No	No	Direct drive long stroke applications	Experiment	[23]
18/15	DO	Yes	No	No	No	No	No	No	No	No	EV	Simulation	[31]
12/11	GA	Yes	Yes	No	No	No	No	No	No	Yes	In-wheel traction	Experiment	[97]
12/11	OOM	Yes	No	No	No	Yes	No	No	No	No	EV	Experiment	[23]
36/8	DO		No	No	No	No	No	No	No	No	Vehicle	Experiment	[134]
56/4, 6/4	GA	Yes	No	No	No		No	No	No	Yes	EV	Experiment	[24]
12/10	PSO	Yes	No	No	No	Yes	No	No	No	Yes	Electrical traction system	Experiment	[135]
12/10	DO	Yes	No	No	No	No	No	No	No	No	HEV	Simulation	[53]

TABLE 5. Compilation of optimization strategies for various electrical machines. The table presents a range of techniques aimed at improving the performance and design of different types of machines across various industrial applications.

Topology	Opt.	Avg. Torq.	Cog. Torq.	Stress	Temp. Effect	Control Scheme	Eff./ Loss	P.F	Cost	Torq. Rip.	Industry App.	Val. Meth.	Ref.
IM and Syn-Rel	GA	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Railway Traction	Simulation	[68]
IPM	SM	Yes	No	No	No	Yes	Yes	No	No	No	EV	Experiment	[136]
SRM	SM		No	Yes	No	No	No	No	No	No	Generic	Experiment	[137]
BLDC	MLO	Yes	No	No	Yes	Yes	Yes	No	No	Yes	Three-wheel motorcycle	Experiment	[70]
AFPMM	GA	Yes	Yes	No	No	No	Yes	No	No	No	Off-highway vehicles	Experiment	[138]
IPM	DE	Yes	No	Yes	No	No	No	Yes		Yes	aircraft electrification	Simulation	[139]
SPMSM	EM	Yes	No	Yes	Yes	No	No	No	No	Yes	Brake Systems	Experiment	[140]
VPM	MLO	Yes	No	No	No	No	No	Yes		Yes	Direct-drive	Experiment	[141]
DRAFPMM	SLO	Yes	No	Yes	Yes	Yes	Yes	No	No	No	electric aircraft propulsion	Simulation	[142]
SRM	EM	Yes	No	Yes	Yes	No	No	No	No	No	EV	Experiment	[143]

specific works such as [23] and [24] addressing this aspect.

- Under utilization of surrogate models: Surrogate models, which can be valuable for evaluating various

TABLE 6. Comparative analysis of Kriging, RSM, and RBF models. The comparison provides insights into the strengths and limitations of each modeling approach, aiding in the selection of the most appropriate technique for specific optimization tasks.

Model	Kriging	RSM	RBF
Equation	$y = q(x)'\beta + z(x)$	$y = X\beta + \varepsilon$	$y = \sum_{i=1}^{n} \beta_i H(\lVert x - x_i \rVert)$
Model complexity	High	Low	Middle
Parameter estimation	$\hat{\beta} = (Q'R^{-1}Q)^{-1}Q'R^{-1}Y$, $\sigma^2 = \frac{1}{n}(Y - Q\hat{\beta})R^{-1}(Y - Q\hat{\beta})$	$\hat{\beta} = (X'X)^{-1}X'Y$	$\hat{\beta} = H^{-1}Y$
Correlation functions	Gauss and exponent	None	None
Popular model basis functions	Constant, linear, and quadratic polynomials	Linear and quadratic polynomials	Gauss, multiquadratic, and inverse multiquadratic
Model features	Global trend and local deviation	Global trend (mean response)	Global trend
Estimation method	Best linear method (for β), and maximum likelihood (for σ^2)	Least square method	No error term

performance indices of FSMs, have not been extensively employed in the existing literature.

- Neglect of acoustic noise, thermal, and stress profiles: The multi-objective design and optimization of FSMs have not sufficiently considered critical factors such as acoustic noise, thermal effects, and stress profiles.
- Lack of optimization for fourier series coefficients: There's a lack of optimization efforts focused on multiple Fourier series coefficients to approximate current profiles and minimize acoustic noise and ripples in the machine.

These identified gaps underscore the pressing need for the development of advanced strategies and intelligent technologies that can enhance the robustness and efficiency of FSM optimization. The tables and analysis presented in this paper demonstrate the continued dedication of researchers and engineers to advancing the FSM technology, bringing it closer to widespread implementation.

VIII. STATE-OF-ART STRATEGIES

This section discusses several optimization techniques for electrical machines that have not been extensively utilized in FSM technology [13], [143], [144], [145]. By incorporating these techniques, researchers and engineers can unlock new possibilities and achieve further advancements in FSM optimization.

A. SURROGATE MODELS

Surrogate models offer an alternative to FEA for solving optimization problems that involve objectives and constraints. They provided a statistical approach to global optimization by training a mathematical model using a limited number of simulations conducted around the operating point. Surrogate models have the advantage of reducing the computational burden during the optimization process and have been proven effective, particularly for problems with a large number of variables [146], [147].

Three popular types of surrogate models have been widely employed in the optimization of other electrical machines: the Kriging model, response surface model (RSM), and radial basis functions (RBF). These models are compared in Table 6, based on various criteria [83].

In Table 6, y, Y, x, X, R, H, and Q, $q(x)$, ϵ, H, and $z(x)$ represent the coefficient matrix, sample response, matrix of sample response, sample input, matrix of correlation function, basis functions, structural matrix, basis function, random error, RBF function, Euclidean norm, and stochastic process, respectively. $z(x)$ has a mean of zero, variance of σ^2, and covariance related to the correlation function matrix. The Kriging model, RSM, and RBF are effective surrogate modeling techniques that have been successfully applied to different optimization scenarios. Each model has its own strengths and limitations such as computational efficiency, accuracy, and flexibility. The choice of the surrogate model depends on the specific requirements of the optimization problem and available resources.

Mathematically, the RSM and RBF are parametric models, meaning that their form is determined by a fixed set of parameters. On the other hand, the Kriging model is a semi-parametric model because it combines a deterministic term with a stochastic process term. This stochastic process allows the Kriging model to capture local nonlinearities more effectively than RSM and RBF models [83], [114]. The ability of the Kriging model to model local nonlinearities is a significant advantage, particularly in situations where the relationship between the variables and response is complex and varies across different regions of the design space. By incorporating both deterministic and stochastic process terms, the Kriging model can capture and represent these nonlinear relationships better, leading to more accurate and reliable predictions [67].

The RSM and RBF models are simpler in terms of their structure and parametrization. They are effective in modeling global trends and approximating the response surface but may struggle to capture local nonlinearities as effectively as the Kriging model. Ultimately, the choice between these surrogate models depends on the specific characteristics of the optimization problem, including the complexity of the system, availability of data, and trade-off between accuracy and computational efficiency.

Researchers and engineers can refer to Table 6 to understand the characteristics and suitability of each model for application in electrical machine optimization. In the context of FSM optimization, notable studies have employed surrogate models to improve the efficiency and effectiveness of the optimization process.

In [148], the authors focused on axial flux permanent magnet (AFPM) machines, where they implemented a two-level surrogate-assisted optimization algorithm. The algorithm consists of interior and exterior levels. The interior level, utilizing affordable kriging models, has explored hundreds of designs to identify the most promising candidates. The selected designs were then evaluated in the exterior loop using expensive 3-D FEA models. The objective functions are aimed at minimizing the active material mass and total losses during the rated operation. The results showed that the algorithm achieved optimal designs with significantly fewer FEA evaluations than conventional methods, demonstrating the effectiveness of surrogate-assisted optimization.

The authors in [149] focused on a segmented rotor switched reluctance machine (SSRM), in which surrogate models and genetic algorithms were employed for multimode optimization. The objective was to improve the performance of the SSRM in terms of high starting torque, low torque ripple, and high power generation efficiency under four different driving modes. Seven design variables were considered in the multi-objective optimization model. The study showed that the proposed method successfully enhanced the performance of the SSRM under all driving modes, indicating the potential of surrogate models and genetic algorithms for multimode optimization of electrical machines.

Furthermore, in [150], a large-scale high-speed PM synchronous machine was optimized using surrogate models based on various artificial neural networks (multilayer perceptron, support vector regression, and generalized regression neural network) and the classical Kriging model. These surrogate models were developed and evaluated using the NSGA-II optimization algorithm. The results demonstrated that the surrogate models significantly improved the effectiveness of the design optimization process, offering high accuracy. This study highlights the importance of surrogate models for large-scale machine optimization tasks. It is worth noting that although surrogate-assisted optimization has been applied successfully to other electrical machine optimization problems, its application to FSM optimization is relatively unexplored. Therefore, there is significant potential for the development and implementation of surrogate-based optimization strategies specifically tailored to FSMs.

B. MULTI-LEVEL OPTIMIZATION METHOD

The multilevel optimization method is a powerful approach for handling high-dimensional optimization problems. It involves dividing the initial design space into multiple lower-dimensional subspaces and sequentially optimizing the variables within each subspace. This method has been demonstrated to be highly effective in design optimization problems, offering several advantages, such as reducing the design cycle, lowering computational costs, and improving overall design efficiency [91]. The flowchart in Fig. 15 depicts the sequential steps involved in implementing the multilevel optimization method. The high-dimensional optimization problem involves both control method variables and structural parameters, posing a significant challenge. To address this complexity, a multilevel optimization approach is employed by dividing the design variables into three subspaces based on their impact on the optimization objectives. Each subspace was sequentially optimized through an iterative process until the convergence condition was satisfied. The effectiveness of this approach has been demonstrated in optimizing an SRM drive [64], where the significant parameters of the motor and controller for each driving mode were selected as optimization variables using sensitivity analysis. Correlation analysis was performed to simplify the optimization process by determining the coherence of the objective functions across all driving modes. A sequential Taguchi method was then applied to determine an optimal design with reduced sensitivity to noise factors, leading to significant reductions in torque ripple and overall performance enhancement. This multilevel optimization strategy has also been applied to various other electrical machines. For instance, in the optimization of an IPMSM [151], the Kriging model was used to approximate the finite element analysis, resulting in better performance, reduced torque ripple, and lower power loss with reduced computation cost.

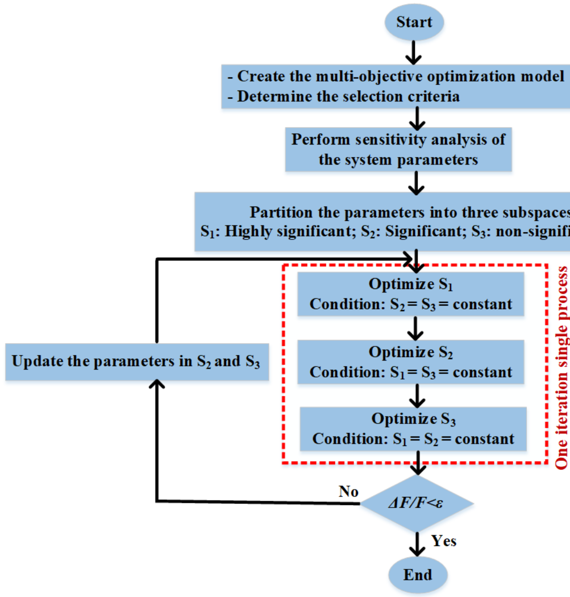

FIGURE 15. Flowchart of multi-level optimization method. This method is commonly employed to address the optimization challenges marked by a hierarchical structure. In such cases, decisions are made across various levels, guided by both upper-level and lower-level variables.

Moreover, a systematic multilevel optimization design and dynamic control strategy was proposed for a less-rare-earth hybrid permanent magnet motor [152], considering both motor design and control levels. The optimization process involved comprehensive sensitivity analysis, RSM, and GA. Each level focused on specific optimizations, leading to

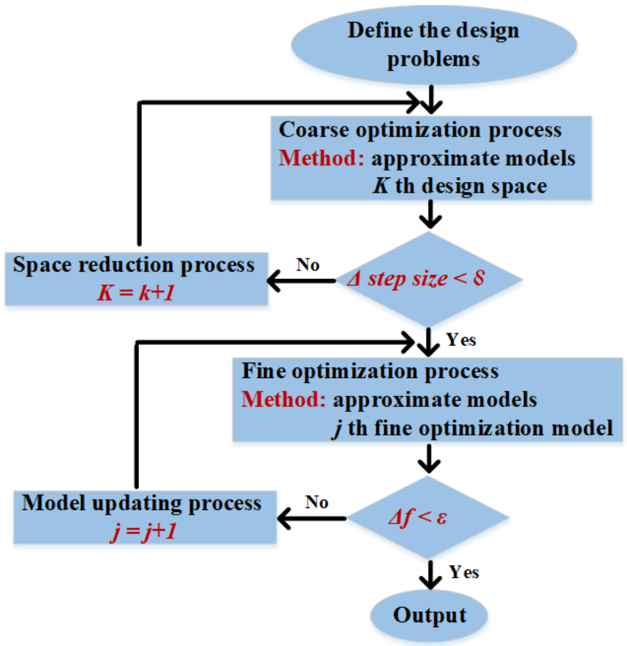

FIGURE 16. Flowchart of sequential optimization method. The method involves initiating experiments that inform subsequent ones, enabling the pursuit of broader optimization goals that extend beyond traditional cost minimization and profit maximization.

a machine with a high torque density, low torque ripple, high efficiency, and favorable overload capability. Simulation and experimental results validated the effectiveness of the proposed systematic optimization strategy.

Similarly, the multilevel design optimization method was utilized to obtain optimal parameters for an HEFSM [25], resulting in a machine with improved flux regulation capability and higher torque density compared to conventional designs.

Although this multilevel optimization technique has been applied to various electrical machines, it has not been researched specifically for the optimization of WFFSMs.

C. SEQUENTIAL OPTIMIZATION METHOD

The sequential optimization method, also known as sequential optimization, is an approach used to solve complex optimization problems by dividing them into a series of smaller and more manageable subproblems. In this method, the optimization process proceeds in a sequential manner, with each sub-problem being solved one after the other [88]. The sequential optimization method is particularly effective when dealing with high-dimensional optimization problems in which the number of design variables is large. By partitioning the design variables into subspaces based on their influence on the optimization objectives, the method allows for a more focused and efficient optimization process. Typically, the optimization of each subspace is performed iteratively, with the optimization algorithm moving from one subspace to the next, until a convergence condition is met. This iterative process helps to refine the design and improve the optimization objectives. This allows for systematic exploration of the design space, enabling the identification of optimal solutions [91].

The sequential optimization method has been successfully applied in various domains, including the optimization of electrical machines, such as SRMs, IPMSMs, and IMs. They have been used to improve the performance of these machines under different operating conditions, leading to enhanced efficiency, reduced torque ripple, and better overall performance. The effectiveness of the sequential optimization method lies in its ability to break down complex optimization problems into more manageable sub-problems. By addressing each subspace individually and iteratively refining the design, this method provides a systematic and efficient approach to optimization. This offers a promising avenue for future research and application in the field of flux-switching machines and other optimization-intensive domains [88].

FSMs, similar to other electromagnetic devices, have a vast initial design space that encompasses all possible design configurations. However, the optimal solution lies within the limited subspace of interest. Neglecting this aspect can lead to the analysis of a large number of samples from outside the relevant subspace during the optimization process, resulting in wastage of computational resources. In contrast to traditional intelligent algorithms, such as the GA and differential evolution algorithm (DEA), SOM can be seen as a space-to-space optimization strategy [13], [114]. The primary objective of SOM is to minimize waste by employing space-reduction techniques.

Fig. 16 provides an overview of the SOM flowchart, which consists of two main procedures: design space reduction and parameter optimization. The initial phase aims to efficiently narrow the initial design space to the relevant subspace using various space-reduction algorithms. The subsequent phase focuses on determining the optimal solution within the limited subspace of interest [144].

In [145], a fuzzy-based sequential Taguchi robust optimization method was proposed to enhance the overall performance of a five-phase PM hub motor for (EV).

Optimization objectives, such as high torque density, low torque ripple, efficiency, and fault-tolerant operation capability, were considered. The proposed method achieved improvements of 3% in maximum torque, 63% in torque ripple reduction, 21% in PM eddy loss and core loss reduction, -4.9% in maximum torque under single-phase fault operation, and 16% in torque ripple under single-phase fault operation.

In another study, the key parameters of a novel dual-armature flux-switching permanent magnet (DA-PMFSM) with different stator core shapes were sequentially optimized to maximize the average torque [146]. The optimized machine exhibited superior electromagnetic performance in terms of phase back-EMF, electromagnetic torque, overload capability, inductances, power factor, efficiency, and unbalanced magnetic force compared with the counterpart machine.

Furthermore, a combination of RSM and modified SOM has been employed to optimize the HEFSM [32]. The electromagnetic performance of the machine, including the back EMF, cogging torque, and output torque, was studied. The simulation results of the optimized model validated the effectiveness of the proposed optimization design strategy compared to the conventional model.

Notably, the SOM method has not yet been utilized in the context of WFFSM technology, presenting an opportunity for further research and application in this area.

D. ROBUST OPTIMIZATION METHOD

The Robust Optimization Method is an effective approach to address uncertainties and variations in design parameters, operating conditions, and external factors that can significantly impact the performance of FSMs. This method aims to find solutions that are less sensitive to these uncertainties, thereby ensuring the robustness and reliability of the optimized design. By considering worst-case scenarios and minimizing the effects of variations, robust optimization provides a means to achieve stable and consistent performance under different conditions. To address this issue, two popular robust optimization approaches, namely the Taguchi technique and the Design for Six Sigma (DFSS) method, have been widely employed [13], [153]. These approaches, rooted in quality engineering principles, utilize probabilistic analysis and/or optimization techniques to enhance product quality and minimize defects.

The primary objective of the robust design optimization method is to develop products with exceptionally low defect rates. This process involves three key variations. First, at the system-level criteria stage, the defects per million opportunities and sigma levels were defined. These metrics provide a quantitative measure of the desired product quality. Second, during the production design phase, the design parameters and manufacturing technology are carefully considered. This stage focuses on identifying the design features and manufacturing processes that contribute to the robustness and minimize the occurrence of defects. Finally, in the third stage, the cost and feasibility of the manufacturing process were evaluated to ensure that the optimized design could be implemented effectively.

By integrating robust optimization techniques into the design and manufacturing processes, electromagnetic devices, including FSMs, can be engineered to exhibit improved performance and reliability, even in the presence of manufacturing variations. The Taguchi and DFSS methods provide systematic frameworks for considering both the design and manufacturing factors, enabling the development of high-quality products with reduced defect rates and enhanced overall performance.

The multi-objective optimization model for the DFSS robust design approach is given by [154]:

$$\begin{aligned} \text{min}: \quad & \{F_i[\mu_f(x), \sigma_f(x)], i = 1, 2, , p\} \\ \text{subject to} \quad & g_j[\mu_f(x), \sigma_f(x)] \leq 0, \quad j = 1, 2, , m \\ & x_l + n\sigma_x \leq \mu_x \leq x_u - n\sigma_x \\ & LSL \leq \mu_f \pm n\sigma_f \leq USL. \end{aligned} \tag{18}$$

The upper and lower specification limits are represented as USL and LSL, while the sigma level, n, is defined as 6 in many applications. The standard deviation (σ) and mean (μ) are typically determined using the Monte Carlo analysis method. The value of n in the context of robust optimization can be associated with the probability of a normal distribution. For instance, a value of "6σ" corresponds to a probability of 0.002, which is equivalent to a pass rate of 99.9999998% or 3.4 defects per million opportunities (DPMO) in terms of short-term and long-term quality control, respectively [153].

In practical terms, when a process or product is optimized to achieve a "6σ" level, it means that the process has been fine-tuned to such an extent that the probability of defects or errors occurring is extremely low, with only 3.4 defects per million opportunities on a long-term basis. This level of optimization ensures an exceptionally high level of quality and reliability in the final product or process. By targeting a high "n" value, companies can strive to achieve near-perfect performance and minimize defects, thereby contributing to greater customer satisfaction and operational excellence. More details on the DFSS method can be found in [32], [83], and [155].

In [156], robust design optimization was performed on an outer rotor surface-mounted permanent magnet motor for hybrid vehicles by utilizing the design for a six-sigma methodology. To address the computational time constraints associated with robust optimization, a high-dimensional surrogate model of the system was developed using Box-Behnken RSM. This surrogate model was then integrated with the PSO algorithm to significantly enhance the overall effectiveness and efficiency of the optimization process. The accuracy of the RSM results was verified through rigorous FEM simulations.

Subsequently, the deterministic and robust optimized motors underwent mass production simulations employing Monte Carlo analysis to evaluate their adherence to six-sigma quality standards. The results of these simulations demonstrated the compliance of the motors with stringent quality standards, affirming the success of the robust design optimization approach. This study demonstrates the benefits of combining the RSM and PSO methods, enabling a comprehensive and reliable optimization of the motor while ensuring its robustness for real-world applications in hybrid vehicles.

In [120], the Taguchi method was employed to determine the most effective parameters for a novel linear transverse flux-switching permanent-magnet generator used in direct-drive wave energy conversion. Similarly, in [121], the design of experiments with Taguchi optimization was applied to achieve optimum performance for double-sided flux-switching permanent-magnet generators utilizing ferrite magnets. The authors in [157] investigated different topology

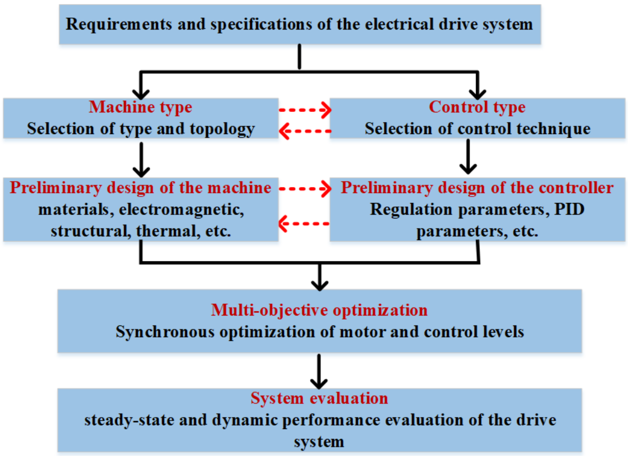

FIGURE 17. Framework for optimizing system-level design of electrical drive systems. The process comprises five stages: system requirement determination, motor/controller selection, motor/controller design, system optimization model construction, and system performance evaluation.

structures, shape parameters, and manufacturing tolerances of 12/14- and 12/10-pole permanent magnet flux switching machines using the design for the six-sigma technique to enhance the manufacturing quality for industrial applications.

Overall, the robust optimization method provides a valuable approach to ensure the reliability and stability of electrical machine designs in the presence of uncertainties. By considering worst-case scenarios and minimizing the effects of parameter variations, robust optimization enhances the robustness of electrical machines and increases their suitability for real-world applications. However, to the best of our knowledge, there is currently no reported application of the design for the six-sigma methodology for robust optimization in the context of the WFFSM and HEFSM.

E. SYSTEM-LEVEL DESIGN OPTIMIZATION METHOD

System-level design optimization methods aim to optimize the overall performance of an electrical drive system by considering the interactions and dependencies between its components. These methods consider various system-level objectives and constraints to determine the optimal design configuration [155]. In traditional design optimization approaches, the focus is mainly on the magnetic behavior of FSMs, neglecting other important aspects such as temperature, stress, and magnetic forces. However, these factors play a crucial role in determining the performance and reliability of machines. Temperature rise affects the lifespan of windings and lamination materials, whereas high stress can lead to deformation. In addition, the magnetic forces contribute to the different vibration modes of the machine. To achieve an optimal design, it is essential to consider the interplay between the electromagnetic, thermal, and mechanical fields and ensure that the design meets all the relevant constraints [64].

Moreover, in practical applications, the integration of machines and control systems into a unified unit is crucial. Evaluating the overall drive system performance is more meaningful than examining individual components in isolation. The stable operation of electrical machines is limited by the temperature increase of the power converter, and exceeding reasonable operating limits can degrade the performance of the device [158]. Therefore, a comprehensive evaluation of the entire driving system is necessary.

Fig. 17 illustrates a deductive system-level design and optimization framework for electrical drive systems, highlighting the interconnected nature of the different design aspects.

The process consists of five stages: system requirement determination, motor/controller selection, detailed design of the motor/controller, system optimization model construction, and system performance evaluation. This systematic framework ensures that the design process aligns with the desired performance and functionality, resulting in efficient and reliable electrical drive systems that meet specified requirements.

In [159], a two-level methodology was proposed to optimize the HEFSM for a selected driving cycle in EV applications. The hybridization ratio between the PM and wound excitation (WE) sources, known as the hybridization ratio (HR), was determined. The optimized HEFSM design exhibited a significantly higher global efficiency compared to pure WE or PM excitation.

Angle position control of the SRM was investigated in [84]. The limiting coefficient of the current density, which did not consider the temperature rise and coupling influences, was also determined. A high-dimensional system-level optimization problem for SRM drives with ten parameters was explored in [160]. The motor and control parameters were divided into three subspaces based on sensitivity analysis. The proposed multi-objective system-level optimization approach achieves high efficiency and low torque ripple, offering alternative solutions for different power output requirements. However, incorporating more complex control methods, such as direct torque control, direct instantaneous control, and model predictive control, into the system-level optimization process is challenging owing to the limited availability of suitable tools. To address these challenges, an iterative process must be employed for coupled analysis between physical fields to converge on the final design solution [161]. This approach inevitably increases the computational costs. Therefore, there is a need to develop more accurate and computationally efficient models for electromagnetic, thermal, and mechanical performance and to create integrated software capable of handling such calculations effectively.

IX. FUTURE PROSPECTS

The design optimization of FSMs and their drive systems is a complex and interdisciplinary challenge. This requires collaboration among researchers and engineers from various fields, including electrical engineering, mechanical engineering, applied mathematics, quality management, control, and materials science. Efficient problem-solving approaches are required to address this challenge by integrating knowledge from diverse disciplines. By leveraging expertise and perspectives from different fields, researchers and engineers can address the complexity of the problem and explore innovative solutions.

In this section, we provide an overview of the current trends in FSM technology research, highlighting seven key topics that offer promise and pose significant challenges for future exploration. These topics serve as focal points to advance the field and drive innovation.

A. MULTI-PHYSICS SIMULATION AND ANALYSIS

Advancements in multiphysics simulation tools are crucial for accurately modeling the complex interactions between the electromagnetic, thermal, and mechanical fields in FSMs. The development of efficient and accurate simulation techniques will enable more comprehensive design optimization. FEA is a widely used computational technique for analyzing coupled fields in FSMs [52]. It enables the examination of electromagnetic-thermal interactions, such as the impact of the heat generated during operation on the electromagnetic performance, and vice versa. Additionally, FEA allows for the investigation of electromagnetic-structural interactions and thermal-structural interactions, providing insights into how the mechanical properties and structural integrity of the machine are affected by electromagnetic and thermal loads [114].

In the pursuit of optimal machine design and performance, it is crucial to consider parasitic effects in large systems. Parasitic effects refer to unintended and undesirable interactions or interferences that arise because of factors such as electromagnetic coupling, stray losses, eddy currents, and magnetic saturation [162], [163]. Understanding and mitigating these parasitic effects are essential for achieving accurate and reliable simulations and ensuring the overall performance of an electrical machine. Therefore, in the multiphysics design of FSMs, it is important to incorporate comprehensive analysis techniques, such as FEA, to study the electromagnetic, thermal, structural, and coupled effects. By considering the interplay between these physical phenomena and accounting for parasitic effects, engineers and researchers can gain valuable insights and optimize the design and performance of FSMs for various applications.

B. NOVEL FSMs WITH NEW MATERIALS AND TOPOLOGIES

One promising and challenging topic in the research field of FSMs is the development of novel FSMs with new materials and topologies. This area of research focuses on exploring alternative materials and innovative machine structures to enhance the performance, efficiency, and reliability of the FSMs.

The choice of material used in FSMs plays a critical role in determining their electromagnetic, thermal, and mechanical properties. Researchers are actively investigating advanced magnetic materials, such as high-performance permanent magnets and soft magnetic materials, with improved energy densities, higher coercivities, and reduced losses [83], [84]. Additionally, the exploration of new insulation materials for windings and improved thermally conductive materials for effective heat dissipation is crucial for enhancing the overall efficiency and reliability of FSMs.

Traditional FSM topologies have been extensively studied, and research is ongoing to develop new machine topologies that offer improved performance and flexibility. Novel topologies may involve variations in the arrangement and configuration of the magnets, windings, and cores. For example, axial flux topologies, spoke-type topologies, and segmented core structures have been explored to achieve a higher power density, reduced cogging torque, and enhanced control capabilities [164]. These innovative topologies often require advanced manufacturing techniques to realize their full potential.

The development of novel FSMs with new materials and topologies offers opportunities for improving machine performance, efficiency, and reliability. However, it also poses challenges in terms of material characterization, manufacturing feasibility, and control-system adaptation [165], [166]. Future research in this area will involve a multidisciplinary approach combining expertise in materials science, electromagnetic design, manufacturing techniques, and control strategies to explore and exploit the full potential of these innovative FSM designs.

C. NEW DESIGN OPTIMIZATION METHODS

Another important and challenging topic in the research field of FSMs is the development of new design-optimization methods. Design optimization aims to determine the best configuration and parameters of an FSM that optimizes specific performance criteria, such as efficiency, power density, torque ripple, and thermal characteristics. Although traditional optimization methods have been widely used, there is a growing need for more advanced and efficient techniques to tackle the complex and multidisciplinary nature of FSM design. New design optimization methods for FSMs can encompass various approaches, including

- Surrogate modeling and metaheuristic algorithms: Surrogate modeling techniques, such as RSM and Kriging models, can be used to create computationally efficient approximations of the FSM behavior. These models can then be coupled with metaheuristic algorithms, such as GA, PSO, or Simulated Annealing (SA), to efficiently explore the design space and find optimal solutions [148].
- Robust optimization: Robust optimization methods aim to design FSMs that are resilient to uncertainties and variations in manufacturing processes, material properties, and operating conditions. By considering these uncertainties during the optimization process, robust designs that exhibit improved performance and

reliability under real-world conditions can be achieved [153], [154].

- Multi-level optimization: In complex FSM design problems, multi-level optimization methods divide the problem into subspaces and optimize them sequentially. This approach can improve computational efficiency and convergence to optimal solutions by considering different levels of design variables and objectives [152].
- System-level optimization: Instead of optimizing the FSM in isolation, system-level optimization considers the integration of the FSM within the entire drive system, including the power electronics, control algorithms, and mechanical components. This holistic approach ensures that the overall performance and efficiency of the drive system are maximized [155], [159].

New design optimization methods for FSMs will require advancements in mathematical modeling, optimization algorithms, and computational tools. They also require close collaboration between researchers in different disciplines, such as electrical engineering, mechanical engineering, optimization, and control theory, to develop comprehensive and efficient optimization frameworks tailored specifically for FSM design.

D. RELIABILITY AND ROBUSTNESS ANALYSIS

Reliability and robustness analyses are crucial aspects of the FSMs design and operation. It focuses on evaluating a machine's ability to perform consistently and withstand variations, uncertainties, and harsh operating conditions while maintaining its desired performance [166], [167]. Enhancing the reliability and robustness of FSMs is essential for ensuring their long-term functionality, reducing maintenance requirements, and minimizing unexpected failures or downtimes. To address reliability and robustness, several analysis techniques can be employed:

- Failure mode and effects analysis (FMEA): FMEA is a systematic approach to identify potential failure modes, their causes, and their effects on the FSM's performance. By assessing failure risks and their impacts, designers can prioritize improvements to enhance the machine's reliability [167].
- Probabilistic analysis: Probabilistic methods, such as probabilistic modeling, reliability block diagrams, and Monte Carlo simulations, can be used to quantify the reliability and predict the failure probabilities of FSMs under various operating conditions and uncertainties. These analyses provide insights into the weak points of the design and guide improvements to enhance robustness [168].
- Sensitivity analysis: Sensitivity analysis evaluates the impact of variations or uncertainties in design parameters, material properties, or operating conditions on the performance and reliability of FSMs. It helps identify critical factors and design parameters that significantly influence reliability and guides design modifications to enhance robustnes [169].
- Thermal analysis: Thermal analysis is crucial to assess the temperature distribution and heat dissipation in FSMs. High temperatures can degrade the insulation materials, reduce efficiency, and accelerate wear and tear, leading to reliability issues. By analyzing thermal behavior, designers can optimize cooling mechanisms, insulation materials, and thermal management strategies to improve reliability [158].
- Vibration and stress analysis: Vibration and stress analysis techniques, such as FEA, can be employed to evaluate the structural integrity and mechanical robustness of FSMs. Excessive vibrations and stress levels can lead to component fatigue, mechanical failures, and reduced overall reliability [170]. By analyzing and optimizing the structural design, material selection, and damping techniques, robustness can be improved.
- Environmental and operational testing: Real-world testing under different environmental and operational conditions is essential to validate the reliability and robustness of FSMs. Accelerated life testing, durability testing, and performance testing can help identify potential weaknesses and areas for improvement.

By incorporating reliability and robustness analysis throughout the design process, designers can identify critical design parameters, assess failure risks, and implement appropriate design modifications. This leads to FSMs that are more resilient, dependable, and capable of withstanding the challenges posed by real-world applications and operating conditions.

E. EFFICIENT CONTROL CIRCUITS AND ALGORITHMS

Efficient control circuits and algorithms are essential for achieving optimal performance and operation of FSMs. These circuits and algorithms govern the behavior of the machine, control the switching of currents, and ensure smooth and efficient operation. Here are some key aspects related to efficient control circuits and algorithms for FSMs:

- Pulse Width Modulation (PWM) Techniques: PWM is commonly used in the control of FSMs to regulate the voltage or current applied to the machine. By modulating the width of the switching pulses, PWM techniques enable precise control of the output variables, such as torque and speed [171]. Various PWM strategies, including carrier-based PWM, space vector modulation, and discontinuous PWM [172], can be employed based on the specific requirements of the FSM.
- Current Control Algorithms: Accurate control of the current flowing through the windings is crucial for optimal performance of FSMs. Current control algorithms, such as proportional-integral (PI) control, hysteresis control, and model predictive control, are employed to regulate the current to desired levels, ensuring efficient and smooth operation of the machine [173].
- Sensorless Control Techniques: Traditional FSM control often relies on position sensors to determine the rotor position. However, sensorless control techniques aim

to eliminate the need for position sensors, reducing complexity and cost. Sensorless control algorithms, such as back-EMF estimation, observer-based control, and adaptive algorithms, utilize the machine's electrical and magnetic properties to estimate the rotor position and achieve accurate control [174].
- Optimization-Based Control: Optimization-based control approaches use optimization algorithms to find the optimal control inputs for FSMs, considering various performance objectives and constraints. These algorithms can optimize control parameters in real-time based on the current operating conditions, leading to improved efficiency, torque ripple reduction, and enhanced overall performance [175].
- Advanced Control Strategies: Advanced control strategies, such as predictive control, sliding mode control, and fuzzy logic control, can be applied to FSMs for enhanced performance and robustness. These strategies utilize advanced mathematical models and algorithms to predict and control the machine's behavior, adapt to varying operating conditions, and achieve desired performance objectives [176].
- Fault Detection and Tolerant Control: Efficient control circuits and algorithms should also incorporate fault detection and tolerant control techniques to ensure robust operation of FSMs. These techniques involve monitoring various machine parameters, detecting faults or anomalies, and implementing appropriate control actions to mitigate the effects of faults, ensuring the reliability and longevity of the machine [177].

Efficient control circuits and algorithms are crucial for optimizing the performance, efficiency, and reliability of FSMs. By employing advanced control techniques, sensorless control methods, and optimization-based approaches, designers and researchers can enhance the control of FSMs, achieve smoother operation, reduce losses, and improve the overall system efficiency.

F. MACHINE LEARNING AND DATA MINING TECHNIQUES

Machine learning and data mining techniques have emerged as powerful tools in various domains, and their application to electrical machines holds significant potential for advancements in design, control, and performance optimization. Here are some key areas where machine learning and data mining techniques can be employed in relation to FSMs:
- Design Optimization: Machine learning algorithms can be used to optimize the design of FSMs by automatically exploring and analyzing a large design space. These algorithms can learn from existing designs, simulation data, and performance criteria to identify optimal design configurations, leading to improved efficiency, reduced losses, and enhanced performance [178].
- Fault Diagnosis and Prognostics: Machine learning techniques can be utilized for fault diagnosis and prognostics of FSMs. By analyzing sensor data and historical performance data, these techniques can detect abnormal behavior, identify potential faults, and predict the remaining useful life of the machine components [155]. This enables proactive maintenance and minimizes downtime.
- Control and Energy Management: Machine learning algorithms can be employed to develop intelligent control strategies for FSMs. These algorithms can learn from operational data and optimize control parameters in real-time to achieve desired performance objectives, such as energy efficiency, torque ripple reduction, and improved dynamic response [178], [179].
- Condition Monitoring: Machine learning techniques can be used for real-time condition monitoring of FSMs. By analyzing sensor data, these techniques can detect anomalies, monitor temperature rise, assess vibration patterns, and identify potential issues before they escalate [180]. This enables predictive maintenance, minimizes failures, and extends the machine's lifespan.
- Performance Prediction and Optimization: Data mining techniques can be applied to historical performance data to identify patterns, correlations, and relationships between operating conditions, design parameters, and performance metrics [181]. This information can then be used to predict the performance of FSMs under different conditions and optimize their operation for maximum efficiency and desired output.
- Virtual Prototyping and Simulation: Machine learning algorithms can be utilized to build accurate and efficient models of FSMs based on limited data or incomplete information. These models can be employed for virtual prototyping and simulation, reducing the need for extensive physical testing and accelerating the design and optimization process [181].
- Anomaly Detection and Quality Control: Machine learning techniques can be employed for anomaly detection in manufacturing processes and quality control of FSM components. By analyzing sensor data and process parameters, these techniques can identify deviations from expected behavior, detect defects, and ensure consistent quality in the manufacturing process [179], [180].

By harnessing the power of machine learning and data mining techniques, researchers and engineers can gain valuable insights, optimize performance, and enhance the overall design, control, and operation of FSMs. However, it is important to ensure that these techniques are applied with appropriate data quality, model interpretability, and consideration of the unique characteristics and requirements of FSMs.

G. EXPERIMENTAL VALIDATION AND INDUSTRIAL APPLICATION

Experimental validation and industrial application play a crucial role in the development and implementation of FSMs.

Here are some key aspects related to experimental validation and industrial application of FSMs:

- Prototype Development: Experimental validation begins with the development of physical prototypes of FSMs. This involves the fabrication and assembly of the machine according to the design specifications [54]. Prototypes can vary in size and complexity depending on the specific application requirements.
- Performance Testing: Once the prototypes are ready, performance testing is conducted to evaluate the electromagnetic, thermal, and mechanical characteristics of FSMs. Various tests are performed to measure parameters such as torque, power output, efficiency, temperature rise, vibration, and noise. These tests help assess the performance and validate the design calculations and simulation models.
- Efficiency and Loss Analysis: Experimental validation allows for accurate measurement and analysis of the efficiency and losses in FSMs. This helps identify areas for improvement and optimization, such as reducing copper losses, iron losses, and stray losses. The experimental results can be compared with theoretical models and simulations to validate their accuracy.
- Thermal Management: Thermal management is critical for the reliable and efficient operation of FSMs. Experimental validation helps assess the thermal behavior of the machine under different operating conditions. Temperature measurements are taken at various points to validate thermal models and ensure that the machine operates within safe temperature limits. Heat dissipation techniques, such as cooling systems or thermal coatings, can be evaluated and optimized based on experimental results.
- Reliability and Durability Testing: Experimental validation includes reliability and durability testing to assess the long-term performance and robustness of FSMs. These tests simulate harsh operating conditions, such as high temperature, high humidity, vibration, and mechanical stress. The aim is to identify potential failure modes, weak points, and design improvements to enhance the reliability and durability of the machine.
- Industrial Application and Field Testing: Once the performance and reliability of FSMs are validated through experiments, they can be deployed in real-world industrial applications. Field testing involves installing FSMs in their intended operating environments, such as electric vehicles [78], renewable energy systems [120], or industrial machinery [132]. Data is collected during real-world operation to evaluate performance, identify any operational challenges, and gather feedback for further optimization.
- Optimization and Iterative Design: The experimental validation results provide valuable feedback for iterative design improvements. Based on the insights gained from experiments and field testing, the design can be refined to enhance performance, efficiency, and reliability. This iterative process ensures that FSMs are continuously optimized for specific industrial applications.

The experimental validation and industrial application of FSMs help bridge the gap between theoretical models, simulations, and real-world performance. They provide critical insights into the machine's behavior, validate design choices, and facilitate the adoption of FSM technology in various industries. Continuous experimentation, testing, and optimization contribute to the advancement and successful implementation of FSMs in practical applications.

In summary, by focusing on these areas, we encourage collaboration between academia and industry, inspiring researchers and engineers to dedicate their efforts to advancing FSM technology. Through interdisciplinary research, shared knowledge, and collective endeavors, we can pave the way for advancements in FSM design optimization and drive system technology.

X. CONCLUSION

This study provides a detailed review of optimization strategies aimed at improving the performance metrics of flux switching machines (FSMs). It begins by introducing the design principles of various FSM variants, and then summarizes existing methods focused on reducing radial force/vibration, torque ripple, and enhancing torque density and efficiency. The objective functions used in the literature for permanent magnet-FSM (PMFSM), wound-field-FSMs (WFFSM), and hybrid excited-FSMs (HEFSM) are thoroughly examined and compared.

However, this review identifies some gaps in current research. Specifically, insufficient attention has been paid to integrating control schemes in the optimization process for PMFSM and WFFSM. Additionally, there has been a relative lack of attention given to incorporating acoustic noise, thermal effects, and structural profiles into the multicriteria design and optimization of FSMs.

To address these gaps, this study proposes the development of sophisticated strategies for robust optimization efficiency in FSMs. It explores state-of-the-art optimization methods, including robust and multilevel optimization, sequential optimization methods, surrogate models, and system-level design optimization.

Based on these research findings, several research directions for future work on FSM technology are recommended. These include integrating state-of-the-art control systems and developing control algorithms that exhibit superior performance and resilience to faults, exploring new materials, adopting advanced winding technology, and incorporating electromagnetic characteristics, thermal effects, and structural profiles in the multiphysics design process. Additionally, the study suggests leveraging machine learning and data mining techniques to further advance FSM technology. Addressing these research interests will undoubtedly contribute to the progress of the FSM technology and its successful application in new and emerging fields.

REFERENCES

[1] J. O. Merlyn and N. C. Lenin, "Review of control topologies for flux switching motor," *IEEE Access*, vol. 11, pp. 51241–51259, 2023, doi: 10.1109/ACCESS.2023.3278371

[2] S. Simizu, P. R. Ohodnicki, and M. E. McHenry, "Metal amorphous nanocomposite soft magnetic material-enabled high power density, rare earth free rotational machines," *IEEE Trans. Magn.*, vol. 54, no. 5, pp. 1–5, May 2018, doi: 10.1109/TMAG.2018.2794390.

[3] U. B. Akuru and M. J. Kamper, "Performance comparison of optimum wound-field and ferrite PM flux switching machines for wind energy applications," in *Proc. 22nd Int. Conf. Electr. Mach. (ICEM)*, Lausanne, Switzerland, Sep. 2016, pp. 2478–2485, doi: 10.1109/ICELMACH.2016.7732869.

[4] H. C. Idoko, U. B. Akuru, R.-J. Wang, and O. Popoola, "Potentials of brushless stator-mounted machines in electric vehicle drives—A literature review," *World Electr. Vehicle J.*, vol. 13, no. 5, p. 93, May 2022, doi: 10.3390/wevj13050093.

[5] P. Wang, W. Hua, G. Zhang, B. Wang, and M. Cheng, "Principle of flux-switching permanent magnet machine by magnetic field modulation theory—Part I: Back-electromotive-force generation," *IEEE Trans. Ind. Electron.*, vol. 69, no. 3, pp. 2370–2379, Mar. 2022, doi: 10.1109/TIE.2021.3070504.

[6] H. Wang, H. Zhu, S. Ding, Y. Dai, C. He, and X. Wang, "A new partitioned stator field modulation machine with H-shape permanent magnet excitation," *IEEE Trans. Magn.*, vol. 58, no. 8, pp. 1–6, Aug. 2022, doi: 10.1109/TMAG.2022.3165663.

[7] B. Ullah, F. Khan, S. Hussain, and B. Khan, "Modeling, optimization, and analysis of segmented stator flux switching linear hybrid excited machine for electric power train," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 3, pp. 3546–3553, Sep. 2022, doi: 10.1109/TTE.2022.3147263.

[8] W. Ullah, F. Khan, and M. Umair, "Design and optimization of segmented PM consequent pole hybrid excited flux switching machine for EV/HEV application," *CES Trans. Electr. Mach. Syst.*, vol. 4, no. 3, pp. 206–214, Sep. 2020, doi: 10.30941/CESTEMS.2020.00026.

[9] F. Khan, E. Sulaiman, and M. Z. Ahmad, "A novel wound field flux switching machine with salient pole rotor and nonoverlapping windings," *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 25, pp. 950–964, 2017, doi: 10.3906/elk-1507-80.

[10] V. Dmitrievskii, V. Prakht, and V. Kazakbaev, "Design optimization of a permanent-magnet flux-switching generator for direct-drive wind turbines," *Energies*, vol. 12, no. 19, p. 3636, Sep. 2019, doi: 10.3390/en12193636.

[11] N. Fernando, I. U. Nutkani, S. Saha, and M. Niakinezhad, "Flux switching machines: A review on design and applications," in *Proc. 20th Int. Conf. Electr. Mach. Syst. (ICEMS)*, Sydney, NSW, Australia, Aug. 2017, pp. 1–6, doi: 10.1109/ICEMS.2017.8056444.

[12] L. Wu, J. Zhu, and Y. Fang, "A novel doubly-fed flux-switching permanent magnet machine with armature windings wound on both stator poles and rotor teeth," *IEEE Trans. Ind. Electron.*, vol. 67, no. 12, pp. 10223–10232, Dec. 2020, doi: 10.1109/TIE.2019.2959504.

[13] O. I. Okoro, C. E. Abunike, U. B. Akuru, C. C. Awah, E. E. Okpo, I. E. Nkan, P. I. Udenze, U. O. Innocent, and M. J. Mbunwe, "A review on the state-of-the-art optimization strategies and future trends of wound-field flux switching motors," in *Proc. IEEE PES/IAS Power Africa*, Kigali, Rwanda, Aug. 2022, pp. 1–5, doi: 10.1109/PowerAfrica53997.2022.9905252.

[14] N. Ahmad, F. Khan, H. Ali, S. Ishaq, and E. Sulaiman, "Outer rotor wound field flux switching machine for in-wheel direct drive application," *IET Electr. Power Appl.*, vol. 13, no. 6, pp. 757–765, Jun. 2019, doi: 10.1049/iet-epa.2018.5355.

[15] U. B. Akuru and M. J. Kamper, "Formulation and multiobjective design optimization of wound-field flux switching machines for wind energy drives," *IEEE Trans. Ind. Electron.*, vol. 65, no. 2, pp. 1828–1836, Feb. 2018, doi: 10.1109/TIE.2017.2721928.

[16] U. B. Akuru, W. Ullah, H. C. Idoko, and F. Khan, "Comparative performance evaluation and prototyping of double-stator wound-field flux modulation machines," in *Proc. Int. Conf. Electr. Mach. (ICEM)*, Valencia, Spain, Sep. 2022, pp. 1893–1898, doi: 10.1109/ICEM51905.2022.9910929.

[17] S. Saeidabadi, L. Parsa, K. Corzine, C. Kovacs, and T. J. Haugan, "A double rotor flux switching machine with HTS field coils for all electric aircraft applications," *IEEE Trans. Appl. Supercond.*, vol. 33, no. 5, pp. 1–7, Aug. 2023, doi: 10.1109/TASC.2023.3269386.

[18] C. Yu, S. Niu, S. L. Ho, and W. N. Fu, "Design and analysis of a magnetless double-rotor flux switching motor for low cost application," *IEEE Trans. Magn.*, vol. 50, no. 11, pp. 1–4, Nov. 2014, doi: 10.1109/TMAG.2014.2329764.

[19] W. Fei, P. C. K. Luk, and J. Shen, "Torque analysis of permanent-magnet flux switching machines with rotor step skewing," *IEEE Trans. Magn.*, vol. 48, no. 10, pp. 2664–2673, Oct. 2012, doi: 10.1109/TMAG.2012.2198223.

[20] G. Zhao, W. Hua, and J. Qi, "Comparative study of wound-field flux-switching machines and switched reluctance machines," *IEEE Trans. Ind. Appl.*, vol. 55, no. 3, pp. 2581–2591, May 2019, doi: 10.1109/TIA.2019.2892362.

[21] H. Feng, W. Zhang, C. Xiao, X. Xu, and S. Zhang, "Performance comparison and optimization of permanent magnet flux switching linear motor for ropless elevator system," in *Proc. 13th Int. Symp. Linear Drives Ind. Appl. (LDIA)*, Wuhan, China, Jul. 2021, pp. 1–5, doi: 10.1109/LDIA49489.2021.9505742.

[22] M. Qasim, F. Khan, B. Ullah, H. U. Jan, S. Hussain, and Z. Ul Islam, "A novel double-sided linear flux switching machine with yokeless secondary for long stroke applications," in *Proc. Int. Conf. Emerg. Power Technol. (ICEPT)*, Topi, Pakistan, Apr. 2021, pp. 1–6, doi: 10.1109/ICEPT51706.2021.9435566.

[23] L. Xu, H. Liu, X. Zhu, W. Fan, C. Zhang, L. Zhang, and L. Quan, "Multiple-mode current control for a hybrid-excitation axial flux switching permanent magnet motor considering driving cycles," *IEEE Trans. Ind. Electron.*, vol. 71, no. 1, pp. 204–214, Jan. 2024, doi: 10.1109/TIE.2023.3243278.

[24] J. Zhao, M. Lin, D. Xu, L. Hao, and W. Zhang, "Vector control of a hybrid axial field flux-switching permanent magnet machine based on particle swarm optimization," *IEEE Trans. Magn.*, vol. 51, no. 11, pp. 1–4, Nov. 2015, doi: 10.1109/TMAG.2015.2435156.

[25] L. Mo, T. Zhang, and Q. Lu, "Design and analysis of an outer-rotor-permanent-magnet flux-switching machine for electric vehicle applications," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 2, pp. 1–5, Mar. 2019, doi: 10.1109/TASC.2018.2890816.

[26] S. M. Saghin, A. Ghaheri, M. Abolghasemi, and E. Afjei, "Performance optimization of excited outer rotor segmented-FSPM motor based on Taguchi method," in *Proc. 14th Power Electron., Drive Syst., Technol. Conf. (PEDSTC)*, Babol, Iran, Jan. 2023, pp. 1–5, doi: 10.1109/PEDSTC57673.2023.10087174.

[27] W. Hua, M. Cheng, Z. Q. Zhu, and D. Howe, "Analysis and optimization of back EMF waveform of a flux-switching permanent magnet motor," *IEEE Trans. Energy Convers.*, vol. 23, no. 3, pp. 727–733, Sep. 2008, doi: 10.1109/tec.2008.918612.

[28] J. Yan, H. Lin, Y. Feng, Z. Q. Zhu, P. Jin, and Y. Guo, "Cogging torque optimization of flux-switching transverse flux permanent magnet machine," *IEEE Trans. Magn.*, vol. 49, no. 5, pp. 2169–2172, May 2013, doi: 10.1109/TMAG.2013.2244855.

[29] Y. Mao, Y. Du, F. Xiao, X. Zhu, L. Quan, and D. Zhou, "Design and optimization of a pole changing flux switching permanent magnet motor," *IEEE Trans. Ind. Electron.*, vol. 70, no. 12, pp. 1–11, Dec. 2023, doi: 10.1109/TIE.2023.3237886.

[30] E. Sulaiman, T. Kosaka, and N. Matsui, "Design optimization of 12Slot-10Pole hybrid excitation flux switching synchronous machine with 0.4 kg permanent magnet for hybrid electric vehicles," in *Proc. 8th Int. Conf. Power Electron. (ECCE Asia)*, Jeju, South Korea, May 2011, pp. 1913–1920, doi: 10.1109/ICPE.2011.5944423.

[31] J. M. Kim, J. Y. Jang, J. Chung, and Y. J. Hwang, "A new outer-rotor hybrid-excited flux-switching machine employing the HTS homopolar topology," *Energies*, vol. 12, no. 14, p. 2654, Jul. 2019, doi: 10.3390/en12142654.

[32] Z. Xiang, X. Zhu, L. Quan, and D. Fan, "Optimization design and analysis of a hybrid permanent magnet flux-switching motor with compound rotor configuration," *CES Trans. Electr. Mach. Syst.*, vol. 2, no. 2, pp. 200–206, Jun. 2018, doi: 10.30941/CESTEMS.2018.00024.

[33] G. Bramerdorfer and A.-C. Zavoianu, "Surrogate-based multi-objective optimization of electrical machine designs facilitating tolerance analysis," *IEEE Trans. Magn.*, vol. 53, no. 8, pp. 1–11, Aug. 2017, doi: 10.1109/TMAG.2017.2694802.

[34] M. Degano, E. Carraro, and N. Bianchi, "Selection criteria and robust optimization of a traction PM-assisted synchronous reluctance motor," *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 4383–4391, Nov. 2015, doi: 10.1109/TIA.2015.2443091.

[35] Y. Wang and Z. Deng, "Comparison of hybrid excitation topologies for flux-switching machines," *IEEE Trans. Magn.*, vol. 48, no. 9, pp. 2518–2527, Sep. 2012, doi: 10.1109/TMAG.2012.2196801.

[36] M. Jenal, E. Sulaiman, F. Khan, and M. Z. Ahmad, "2D-FEA based design study of salient rotor three-phase permanent magnet flux switching machine with concentrated winding," *Appl. Mech. Mater.*, vol. 785, pp. 274–279, Aug. 2015, doi: 10.4028/www.scientific.net/amm.785.274.

[37] H. Chen, Y. Zuo, K. T. Chau, W. Zhao, and C. H. T. Lee, "Modern electric machines and drives for wind power generation: A review of opportunities and challenges," *IET Renew. Power Gener.*, vol. 15, no. 9, pp. 1864–1887, Jul. 2021, doi: 10.1049/rpg2.12114.

[38] J. K. Nøland, S. Nuzzo, A. Tessarolo, and E. F. Alves, "Excitation system technologies for wound-field synchronous machines: Survey of solutions and evolving trends," *IEEE Access*, vol. 7, pp. 109699–109718, 2019, doi: 10.1109/ACCESS.2019.2933493.

[39] C. H. T. Lee, K. T. Chau, C. Liu, and C. C. Chan, "Overview of magnetless brushless machines," *IET Electr. Power Appl.*, vol. 12, no. 8, pp. 1117–1125, Sep. 2018, doi: 10.1049/iet-epa.2017.0284.

[40] W. Hua, M. Cheng, and G. Zhang, "A novel hybrid excitation flux-switching motor for hybrid vehicles," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4728–4731, Oct. 2009, doi: 10.1109/tmag.2009.2022497.

[41] J. Krenn, R. Krall, and F. Aschenbrenner, "Comparison of flux switching permanent magnet machines with hybrid excitation," in *Proc. Int. Conf. Optim. Electr. Electron. Equip. (OPTIM)*, Cheile Gradistei, Romania, May 2014, pp. 338–341, doi: 10.1109/OPTIM.2014.6850902.

[42] M. Z. Ahmad, E. Sulaiman, and T. Kosaka, "Optimization of outer-rotor hybrid excitation FSM for in-wheel direct drive electric vehicle," in *Proc. IEEE Int. Conf. Mechatronics (ICM)*, Beijing, China, Mar. 2015, pp. 691–696, doi: 10.1109/ICMECH.2015.7084061.

[43] S. Akbar, F. Khan, W. Ullah, B. Ullah, A. H. Milyani, and A. A. Azhari, "Performance analysis and optimization of a novel outer rotor field-excited flux-switching machine with combined semi-closed and open slots stator," *Energies*, vol. 15, no. 20, p. 7531, Oct. 2022, doi: 10.3390/en15207531.

[44] M. Galea, C. Gerada, and T. Hamiti, "Design considerations for an outer rotor, field wound, flux switching machine," in *Proc. 20th Int. Conf. Electr. Mach.*, Marseille, France, Sep. 2012, pp. 171–176, doi: 10.1109/ICElMach.2012.6349859.

[45] W. Ullah and F. Khan, "Design and performance analysis of a novel outer-rotor consequent pole permanent magnet machine with H-type modular stator," *IEEE Access*, vol. 9, pp. 125331–125341, 2021, doi: 10.1109/ACCESS.2021.3111042.

[46] U. B. Akuru and M. J. Kamper, "A modest attempt on the electromagnetic design and performance prediction of turbo wound-field flux switching synchronous condensers," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Baltimore, MD, USA, Sep./Oct. 2019, pp. 1782–1789, doi: 10.1109/ECCE.2019.8913292.

[47] A. Nasr, S. Hlioui, M. Gabsi, M. Mairie, and D. Lalevee, "Design optimization of a hybrid-excited flux-switching machine for aircraft-safe DC power generation using a diode bridge rectifier," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9896–9904, Dec. 2017, doi: 10.1109/TIE.2017.2726974.

[48] S. Sharouni, P. Naderi, M. Hedayati, and P. Hajihosseini, "Performance analysis of a novel outer rotor flux-switching permanent magnet machine as motor/generator for vehicular and aircraft applications," *IET Electr. Power Appl.*, vol. 15, no. 2, pp. 243–254, Feb. 2021, doi: 10.1049/elp2.12019.

[49] C. Nissayan, P. Seangwong, S. Chamchuen, N. Fernando, A. Siritaratiwat, and P. Khunkitti, "Modeling and optimal configuration design of flux-barrier for torque improvement of rotor flux switching permanent magnet machine," *Energies*, vol. 15, no. 22, p. 8429, Nov. 2022, doi: 10.3390/en15228429.

[50] S. M. Saghin, A. Ghaheri, H. Shirzad, and E. Afjei, "Performance optimisation of a segmented outer rotor flux switching permanent magnet motor for direct drive washing machine application," *IET Electric Power Appl.*, vol. 15, no. 12, pp. 1574–1587, Dec. 2021, doi: 10.1049/elp2.12124.

[51] R. Cao, C. Mi, and M. Cheng, "Quantitative comparison of flux-switching permanent-magnet motors with interior permanent magnet motor for EV, HEV, and PHEV applications," *IEEE Trans. Magn.*, vol. 48, no. 8, pp. 2374–2384, Aug. 2012, doi: 10.1109/TMAG.2012.2190614.

[52] E. B. Sulaiman, F. Khan, and T. Kosaka, "Field-excited flux switching motor design, optimization and analysis for future hybrid electric vehicle using finite element analysis," *Prog. Electromagn. Res. B*, vol. 71, pp. 153–166, 2016, doi: 10.2528/PIERB16092502.

[53] E. Sulaiman, T. Kosaka, and N. Matsui, "A novel hybrid excitation flux switching synchronous machine for a high-speed hybrid electric vehicle applications," in *Proc. Int. Conf. Electr. Mach. Syst.*, Beijing, China, Aug. 2011, pp. 1–6, doi: 10.1109/ICEMS.2011.6073505.

[54] U. B. Akuru and M. J. Kamper, "Intriguing behavioral characteristics of rare-earth-free flux switching wind generators at small- and large-scale power levels," *IEEE Trans. Ind. Appl.*, vol. 54, no. 6, pp. 5772–5782, Nov. 2018, doi: 10.1109/TIA.2018.2848979.

[55] J. Falnes and M. Perlin, "Ocean waves and oscillating systems: Linear interactions including wave-energy extraction," *Appl. Mech. Rev.*, vol. 56, no. 1, p. B3, Jan. 2003, doi: 10.1115/1.1523355.

[56] A. R. Conn, N. Gould, and P. L. Toint, "A globally convergent Lagrangian barrier algorithm for optimization with general inequality constraints and simple bounds," *Math. Comput.*, vol. 66, no. 217, pp. 261–289, Jan. 1997.

[57] K. S. Garner, U. B. Akuru, and M. J. Kamper, "Optimization and performance evaluation of non-overlap wound-field converter-fed and direct-grid wind generators," *IEEE Access*, vol. 10, pp. 40587–40595, 2022, doi: 10.1109/ACCESS.2022.3167148.

[58] C. E. Abunike, O. I. Okoro, and S. S. Aphale, "Intelligent optimization of switched reluctance motor using genetic aggregation response surface and multi-objective genetic algorithm for improved performance," *Energies*, vol. 15, no. 16, p. 6086, Aug. 2022, doi: 10.3390/en15166086.

[59] P. Asef and A. Lapthorn, "Overview of sensitivity analysis methods capabilities for traction AC machines in electrified vehicles," *IEEE Access*, vol. 9, pp. 23454–23471, 2021, doi: 10.1109/ACCESS.2021.3056933.

[60] A. Vauquelin, J.-P. Vilain, S. Vivier, N. Labbe, and B. Dupeux, "A new modelling of DC machines taking into account commutation effects," in *Proc. 18th Int. Conf. Electr. Mach.*, Pattaya, Thailand, Sep. 2008, pp. 1–6, doi: 10.1109/ICELMACH.2008.4800014.

[61] E. Bostanci, M. Moallem, A. Parsapour, and B. Fahimi, "Opportunities and challenges of switched reluctance motor drives for electric propulsion: A comparative study," *IEEE Trans. Transport. Electrific.*, vol. 3, no. 1, pp. 58–75, Mar. 2017, doi: 10.1109/TTE.2017.2649883.

[62] M. Muteba, "Comparison of dynamic behaviors between a synchronous reluctance motor with brass rotor bars and a squirrel cage induction motor," in *Proc. IEEE PES/IAS PowerAfrica*, Abuja, Nigeria, Aug. 2019, pp. 374–378, doi: 10.1109/PowerAfrica.2019.8928746.

[63] X. Li, J. Deng, W. Chen, L. Yu, and X. Jin, "Commutation torque reduction strategy of brushless DC motor based on single-input dual-output Cuk converter," *Machines*, vol. 10, no. 2, p. 117, Feb. 2022, doi: 10.3390/machines10020117.

[64] K. Diao, X. Sun, G. Lei, G. Bramerdorfer, Y. Guo, and J. Zhu, "System-level robust design optimization of a switched reluctance motor drive system considering multiple driving cycles," *IEEE Trans. Energy Convers.*, vol. 36, no. 1, pp. 348–357, Mar. 2021, doi: 10.1109/tec.2020.3009408.

[65] A. Soomro, M. E. Amiryar, K. R. Pullen, and D. Nankoo, "Comparison of performance and controlling schemes of synchronous and induction machines used in flywheel energy storage systems," *Energy Proc.*, vol. 151, pp. 100–110, Oct. 2018, doi: 10.1016/j.egypro.2018.09.034.

[66] C. Liu, K. T. Chau, C. H. T. Lee, and Z. Song, "A critical review of advanced electric machines and control strategies for electric vehicles," *Proc. IEEE*, vol. 109, no. 6, pp. 1004–1028, Jun. 2021, doi: 10.1109/JPROC.2020.3041417.

[67] K. Diao, X. Sun, G. Bramerdorfer, Y. Cai, G. Lei, and L. Chen, "Design optimization of switched reluctance machines for performance and reliability enhancements: A review," *Renew. Sustain. Energy Rev.*, vol. 168, Oct. 2022, Art. no. 112785, doi: 10.1016/j.rser.2022.112785.

[68] L. Tom, M. R. Khowja, R. Ramanathan, G. Vakil, C. Gerada, P. Anpalahan, K. Wejrzanowski, and N. Brown, "Comparative analysis of synchronous reluctance machine against conventional induction machine for railway traction," in *Proc. Int. Conf. Electr. Mach. (ICEM)*, Valencia, Spain, Sep. 2022, pp. 69–75, doi: 10.1109/ICEM51905.2022.9910767.

[69] Y. Yang, B. Bilgin, M. Kasprzak, S. Nalakath, H. Sadek, M. Preindl, J. Cotton, N. Schofield, and A. Emadi, "Thermal management of electric machines," *IET Elect. Syst. Transp.*, vol. 7, no. 2, pp. 104–116, 2017, doi: 10.1049/iet-est.2015.0050.

[70] F. Mahmouditabar, A. Vahedi, and N. Takorabet, "Robust design of BLDC motor considering driving cycle," *IEEE Trans. Transport. Electrific.*, early access, Jun. 21, 2023, doi: 10.1109/TTE.2023.3285650.

[71] A. Boglietti, A. Cavagnino, D. Staton, M. Shanel, M. Mueller, and C. Mejuto, "Evolution and modern approaches for thermal analysis of electrical machines," *IEEE Trans. Ind. Electron.*, vol. 56, no. 3, pp. 871–882, Mar. 2009, doi: 10.1109/tie.2008.2011622.

[72] M. Murataliyev, M. Degano, M. Di Nardo, N. Bianchi, and C. Gerada, "Synchronous reluctance machines: A comprehensive review and technology comparison," *Proc. IEEE*, vol. 110, no. 3, pp. 382–399, Mar. 2022, doi: 10.1109/JPROC.2022.3145662.

[73] F. Barrero and M. J. Duran, "Recent advances in the design, modeling, and control of multiphase machines—Part I," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 449–458, Jan. 2016, doi: 10.1109/TIE.2015.2447733.

[74] A. Nobahari, M. Aliahmadi, and J. Faiz, "Performance modifications and design aspects of rotating flux switching permanent magnet machines: A review," *IET Electr. Power Appl.*, vol. 14, no. 1, pp. 1–15, Jan. 2020, doi: 10.1049/iet-epa.2019.0339.

[75] C. Chen, X. Ren, D. Li, R. Qu, K. Liu, and T. Zou, "Torque performance enhancement of flux-switching permanent magnet machines with dual sets of magnet arrangements," *IEEE Trans. Transport. Electrific.*, vol. 7, no. 4, pp. 2623–2634, Dec. 2021, doi: 10.1109/TTE.2021.3063426.

[76] W. Hua, M. Cheng, Z. Zhu, and D. Howe, "Design of flux-switching permanent magnet machine considering the limitation of inverter and flux-weakening capability," in *Proc. Conf. Rec. IEEE Ind. Appl. Conf., 41st IAS Annu. Meeting*, Tampa, FL, USA, Oct. 2006, pp. 2403–2410.

[77] Y. Du, Y. Mao, F. Xiao, X. Zhu, L. Quan, and F. Li, "Partitioned stator hybrid excited machine with DC-biased sinusoidal current," *IEEE Trans. Ind. Electron.*, vol. 69, no. 1, pp. 236–248, Jan. 2022, doi: 10.1109/TIE.2021.3053901.

[78] E. Sulaiman, T. Kosaka, and N. Matsui, "Parameter optimization study and performance analysis of 6S-8P permanent magnet flux switching machine with field excitation for high speed hybrid electric vehicles," in *Proc. 14th Eur. Conf. Power Electron. Appl.*, Birmingham, United Kingdom, Aug. 2011, pp. 1–9.

[79] Y. Du, F. Xiao, W. Hua, X. Zhu, M. Cheng, L. Quan, and K. T. Chau, "Comparison of flux-switching PM motors with different winding configurations using magnetic gearing principle," *IEEE Trans. Magn.*, vol. 52, no. 5, pp. 1–8, May 2016, doi: 10.1109/TMAG.2015.2513742.

[80] A. Ahmed and I. Husain, "Power factor improvement of a transverse flux machine with high torque density," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 4297–4305, Sep. 2018, doi: 10.1109/TIA.2018.2840487.

[81] Z. Wu, Z. Q. Zhu, W. Hua, S. Akehurst, X. Zhu, W. Zhang, J. Hu, H. Li, and J. Zhu, "Analysis and suppression of induced voltage pulsation in DC winding of five-phase wound-field switched flux machines," *IEEE Trans. Energy Convers.*, vol. 34, no. 4, pp. 1890–1905, Dec. 2019, doi: 10.1109/TEC.2019.2938161.

[82] Y. J. Zhou and Z. Q. Zhu, "Comparison of wound-field switched-flux machines," *IEEE Trans. Ind. Appl.*, vol. 50, no. 5, pp. 3314–3324, Sep. 2014, doi: 10.1109/TIA.2014.2309726.

[83] G. Lei, J. Zhu, Y. Guo, C. Liu, and B. Ma, "A review of design optimization methods for electrical machines," *Energies*, vol. 10, no. 12, p. 1962, Nov. 2017, doi: 10.3390/en10121962.

[84] A. Krings, A. Boglietti, A. Cavagnino, and S. Sprague, "Soft magnetic material status and trends in electric machines," *IEEE Trans. Ind. Electron.*, vol. 64, no. 3, pp. 2405–2414, Mar. 2017, doi: 10.1109/TIE.2016.2613844.

[85] O. D. Aladetola, M. Ouari, Y. Saadi, T. Mesbahi, M. Boukhnifer, and K. H. Adjallah, "Advanced torque ripple minimization of synchronous reluctance machine for electric vehicle application," *Energies*, vol. 16, no. 6, p. 2701, Mar. 2023, doi: 10.3390/en16062701.

[86] M. Yousuf, F. Khan, A. Muhammad, H. U. Jan, and M. Qasim, "Design and optimization of five phase nonoverlapping stator wound field flux switching machine for torque performance enhancement," in *Proc. Int. Conf. Emerg. Power Technol. (ICEPT)*, Topi, Pakistan, Apr. 2021, pp. 1–7, doi: 10.1109/ICEPT51706.2021.9435482.

[87] J. Yu and C. Liu, "Multi-objective optimization of a double-stator hybrid-excited flux-switching permanent-magnet machine," *IEEE Trans. Energy Convers.*, vol. 35, no. 1, pp. 312–323, Mar. 2020, doi: 10.1109/TEC.2019.2932953.

[88] T. Orosz, A. Rassõlkin, A. Kallaste, P. Arsénio, D. Pánek, J. Kaska, and P. Karban, "Robust design optimization and emerging technologies for electrical machines: Challenges and open problems," *Appl. Sci.*, vol. 10, no. 19, p. 6653, Sep. 2020, doi: 10.3390/app10196653.

[89] S. Kukkonen and J. Lampinen, "GDE3: The third evolution step of generalized differential evolution," in *Proc. IEEE Congr. Evol. Comput.*, vol. 1. Vancouver, BC, Canada, Sep. 2005, pp. 443–450, doi: 10.1109/cec.2005.1554717.

[90] M. Marek and P. Kadlec, "Another evolution of generalized differential evolution: Variable number of dimensions," *Eng. Optim.*, vol. 54, no. 1, pp. 61–80, Jan. 2022, doi: 10.1080/0305215x.2020.1853714.

[91] M. F. B. Omar, E. B. Sulaiman, I. A. Soomro, M. Z. B. Ahmad, and R. Aziz, "Design optimization methods for electrical machines: A review," *J. Electr. Eng. Technol.*, vol. 18, no. 4, pp. 2783–2800, Jul. 2023, doi: 10.1007/s42835-022-01358-y.

[92] M. Colombino, E. Dall'Anese, and A. Bernstein, "Online optimization as a feedback controller: Stability and tracking," *IEEE Trans. Control Netw. Syst.*, vol. 7, no. 1, pp. 422–432, Mar. 2020, doi: 10.1109/TCNS.2019.2906916.

[93] M. G. Abdolrasol, S. S. Hussain, T. S. Ustun, M. R. Sarker, M. A. Hannan, R. Mohamed, J. A. Ali, S. Mekhilef, and A. Milad, "Artificial neural networks based optimization techniques: A review," *Electronics*, vol. 10, no. 21, p. 2689, Oct. 2021, doi: 10.3390/electronics10212689.

[94] A. Sorgdrager, R.-J. Wang, and A. Grobler, "Taguchi method in electrical machine design," *SAIEE Afr. Res. J.*, vol. 108, no. 4, pp. 150–164, Dec. 2017, doi: 10.23919/SAIEE.2017.8531928.

[95] M. Yousuf, F. Khan, W. Ullah, S. Hussain, and A. Muhammad, "Optimization and reduction of DC winding induced voltage in 5Slot/7Pole five phase non-overlapped stator wound field flux switching machine," in *Proc. Int. Conf. Technol. Policy Energy Electr. Power (ICT-PEP)*, Jakarta, Indonesia, Sep. 2021, pp. 406–411, doi: 10.1109/ICT-PEP53949.2021.9600957.

[96] R. T. Ogulata and S. M. Mezarcioz, "Optimization of air permeability of knitted fabrics with the Taguchi approach," *J. Textile Inst.*, vol. 102, no. 5, pp. 395–404, May 2011, doi: 10.1080/00405000.2010.482347.

[97] L. Xu, X. Zhu, W. Fan, C. Zhang, L. Zhang, and L. Quan, "Comparative analysis and design of partitioned stator hybrid excitation axial flux switching PM motors for in-wheel traction applications," *IEEE Trans. Energy Convers.*, vol. 37, no. 2, pp. 1416–1427, Jun. 2022, doi: 10.1109/TEC.2021.3130475.

[98] M. Jiang, X. Zhu, Z. Xiang, L. Quan, H. Que, and B. Yu, "Suppression of torque ripple of a flux-switching permanent magnet motor in perspective of flux-modulation principle," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 1, pp. 1116–1127, Mar. 2022, doi: 10.1109/TTE.2021.3105460.

[99] S. Zhu, W. Zhao, J. Ji, G. Liu, and C. H. T. Lee, "Design to reduce modulated vibration in fractional-slot concentrated-windings PM machines considering slot-pole combination," *IEEE Trans. Transport. Electrific.*, vol. 9, no. 1, pp. 575–585, Mar. 2023, doi: 10.1109/TTE.2022.3192639.

[100] S.-H. Lee, I.-J. Yang, W.-H. Kim, and I.-S. Jang, "Electromagnetic vibration-prediction process in interior permanent magnet synchronous motors using an air gap relative permeance formula," *IEEE Access*, vol. 9, pp. 29270–29278, 2021, doi: 10.1109/ACCESS.2021.3055864.

[101] D. Wang, C. Peng, J. Li, and C. Wang, "Comparison and experimental verification of different approaches to suppress torque ripple and vibrations of interior permanent magnet synchronous motor for EV," *IEEE Trans. Ind. Electron.*, vol. 70, no. 3, pp. 2209–2220, Mar. 2023, doi: 10.1109/TIE.2022.3156034.

[102] Z. Sadeghi, S. M. S. Nejad, A. Rashidi, and M. Shahparasti, "Fast demagnetization and vibration reduction in switched reluctance motor drive system," *IEEE Access*, vol. 9, pp. 110904–110915, 2021, doi: 10.1109/ACCESS.2021.3103335.

[103] A. K. Sahu, A. Emadi, and B. Bilgin, "Noise and vibration in switched reluctance motors: A review on structural materials, vibration dampers, acoustic impedance, and noise masking methods," *IEEE Access*, vol. 11, pp. 27702–27718, 2023, doi: 10.1109/ACCESS.2023.3257124.

[104] Y. Zhu, C. Zhao, J. Zhang, and Z. Gong, "Vibration control for electric vehicles with in-wheel switched reluctance motor drive system," *IEEE Access*, vol. 8, pp. 7205–7216, 2020, doi: 10.1109/ACCESS.2020.2964582.

[105] Y.-G. Lee, T.-K. Bang, J.-I. Lee, J.-H. Woo, S.-T. Jo, and J.-Y. Choi, "Characteristic analysis and experimental verification of electromagnetic and vibration/noise aspects of fractional-slot concentrated winding IPMSMs of e-Bike," *Energies*, vol. 15, no. 1, p. 238, Dec. 2021, doi: 10.3390/en15010238.

[106] H. Lan, J. Zou, Y. Xu, and M. Liu, "Effect of local tangential force on vibration performance in fractional-slot concentrated winding permanent magnet synchronous machines," *IEEE Trans. Energy Convers.*, vol. 34, no. 2, pp. 1082–1093, Jun. 2019, doi: 10.1109/TEC.2018.2881043.

[107] M. Z. Ali, M. N. S. K. Shabbir, X. Liang, Y. Zhang, and T. Hu, "Machine learning-based fault diagnosis for single- and multi-faults in induction motors using measured stator currents and vibration signals," *IEEE Trans. Ind. Appl.*, vol. 55, no. 3, pp. 2378–2391, May 2019, doi: 10.1109/TIA.2019.2895797.

[108] H. Zhu, Z. Yang, X. Sun, D. Wang, and X. Chen, "Rotor vibration control of a bearingless induction motor based on unbalanced force feed-forward compensation and current compensation," *IEEE Access*, vol. 8, pp. 12988–12998, 2020, doi: 10.1109/ACCESS.2020.2964106.

[109] D. Grauvogl, P. Stauder, B. Hopfensperger, and D. Gerling, "Multiphysics design of a wound field synchronous machine with magnetic asymmetry," in *Proc. IEEE Int. Electr. Mach. Drives Conf. (IEMDC)*, Hartford, CT, USA, May 2021, pp. 1–8, doi: 10.1109/IEMDC47953.2021.9449564.

[110] M. G. Pasquinelli, P. Bolognesi, A. Guiducci, S. Nuzzo, and M. Galea, "Design of a high-speed wound-field synchronous generator for the more electric aircraft," in *Proc. IEEE Workshop Electr. Mach. Design, Control Diagnosis (WEMDCD)*, Modena, Italy, Apr. 2021, pp. 64–69, doi: 10.1109/WEMDCD51469.2021.9425625.

[111] J. Guo, H. Fang, D. Li, R. Qu, Y. Xu, T. Pei, and Yuzhao, "Vibration analysis of internal permanent magnet synchronous machines under asymmetric three-phase current condition," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Baltimore, MD, USA, Sep. 2019, pp. 3872–3877, doi: 10.1109/ECCE.2019.8913037.

[112] J. Ma and Z. Q. Zhu, "Mitigation of unbalanced magnetic force in a PM machine with asymmetric winding by inserting auxiliary slots," *IEEE Trans. Ind. Appl.*, vol. 54, no. 5, pp. 4133–4146, Sep. 2018, doi: 10.1109/TIA.2018.2829879.

[113] W. Deng and S. Zuo, "Electromagnetic vibration and noise of the permanent-magnet synchronous motors for electric vehicles: An overview," *IEEE Trans. Transport. Electrific.*, vol. 5, no. 1, pp. 59–70, Mar. 2019, doi: 10.1109/TTE.2018.2875481.

[114] G. Lei, J. Zhu, and Y. Guo, *Multidisciplinary Design Optimization Methods for Electrical Machines and Drive Systems*, vol. 691. Berlin, Germany: Springer, 2016, doi: 10.1007/978-3-662-49271-0.

[115] F. Mahmouditabar, A. Vahedi, M. R. Mosavi, and M. H. Bafghi, "Sensitivity analysis and multiobjective design optimization of flux switching permanent magnet motor using MLP-ANN modeling and NSGA-II algorithm," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 9, Sep. 2020, Art. no. e12511, doi: 10.1002/2050-7038.12511.

[116] X. Zhu, D. Fan, L. Mo, Y. Chen, and L. Quan, "Multiobjective optimization design of a double-rotor flux-switching permanent magnet machine considering multimode operation," *IEEE Trans. Ind. Electron.*, vol. 66, no. 1, pp. 641–653, Jan. 2019, doi: 10.1109/TIE.2018.2818643.

[117] S. Meo, A. Zohoori, and A. Vahedi, "Optimal design of permanent magnet flux switching generator for wind applications via artificial neural network and multi-objective particle swarm optimization hybrid approach," *Energy Convers. Manage.*, vol. 110, pp. 230–239, Feb. 2016, doi: 10.1016/j.enconman.2015.11.062.

[118] Z. Xiang, X. Zhu, L. Quan, Y. Du, C. Zhang, and D. Fan, "Multilevel design optimization and operation of a brushless double mechanical port flux-switching permanent-magnet motor," *IEEE Trans. Ind. Electron.*, vol. 63, no. 10, pp. 6042–6054, Oct. 2016, doi: 10.1109/TIE.2016.2571268.

[119] S. Eduku, Q. Chen, G. Xu, G. Liu, J. Liao, and X. Zhang, "A new fault-tolerant rotor permanent magnet flux-switching motor," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 3, pp. 3606–3617, Sep. 2022, doi: 10.1109/TTE.2022.3143097.

[120] A. Ghaheri, E. Afjei, and H. Torkaman, "Design optimization of a novel linear transverse flux switching permanent magnet generator for direct drive wave energy conversion," *Renew. Energy*, vol. 198, pp. 851–860, Oct. 2022, doi: 10.1016/j.renene.2022.08.058.

[121] S. A. Mirnikjoo, K. Abbaszadeh, and S. E. Abdollahi, "Multiobjective design optimization of a double-sided flux switching permanent magnet generator for counter-rotating wind turbine applications," *IEEE Trans. Ind. Electron.*, vol. 68, no. 8, pp. 6640–6649, Aug. 2021, doi: 10.1109/TIE.2020.3005106.

[122] V. Prakht, V. Dmitrievskii, V. Kazakbaev, and M. N. Ibrahim, "Comparison between rare-earth and ferrite permanent magnet flux-switching generators for gearless wind turbines," *Energy Rep.*, vol. 6, pp. 1365–1369, Dec. 2020, doi: 10.1016/j.egyr.2020.11.020.

[123] W. Gu, X. Zhu, L. Quan, and Y. Du, "Design and optimization of permanent magnet brushless machines for electric vehicle applications," *Energies*, vol. 8, no. 12, pp. 13996–14008, Dec. 2015, doi: 10.3390/en81212410.

[124] E. Sulaiman, F. Khan, M. F. Omar, G. M. Romalan, and M. Jenal, "Optimal design of wound-field flux switching machines for an all-electric boat," in *Proc. 22nd Int. Conf. Electr. Mach. (ICEM)*, Lausanne, Switzerland, Sep. 2016, pp. 2464–2470, doi: 10.1109/ICELMACH.2016.7732867.

[125] U. B. Akuru, M. Mabhula, and M. J. Kamper, "On the electromagnetic performance prediction of turbo synchronous condensers based on wound-field flux switching machine design," *IEEE Trans. Ind. Appl.*, vol. 57, no. 4, pp. 3687–3698, Jul. 2021, doi: 10.1109/TIA.2021.3080668.

[126] N. Ahmad, F. Khan, N. Ullah, and M. Ahmad, "Performance analysis of outer rotor wound field flux switching machine for direct drive application," *The Appl. Comput. Electromagn. Soc. J. (ACES)*, pp. 913–922, 2018.

[127] W. Jiang, W. Huang, X. Lin, Y. Zhao, X. Wu, Y. Zhao, D. Dong, and X. Jiang, "A novel stator wound field flux switching machine with the combination of overlapping armature winding and asymmetric stator poles," *IEEE Trans. Ind. Electron.*, vol. 69, no. 3, pp. 2737–2748, Mar. 2022, doi: 10.1109/tie.2021.3063955.

[128] N. Ullah, A. Basit, F. Khan, Y. A. Shah, A. Khan, O. Waheed, and A. Usman, "Design and optimization of complementary field excited linear flux switching machine with unequal primary tooth width and segmented secondary," *IEEE Access*, vol. 7, pp. 106359–106371, 2019, doi: 10.1109/ACCESS.2019.2932791.

[129] U. B. Akuru, K. S. Garner, and M. J. Kamper, "Design optimisation and comparison of large-scale non-overlap wound-field machines," in *Proc. XIII Int. Conf. Electr. Mach. (ICEM)*, Alexandroupoli, Greece, Sep. 2018, pp. 2117–2122, doi: 10.1109/ICELMACH.2018.8507045.

[130] W. Ullah, F. Khan, U. B. Akuru, S. Hussain, M. Yousaf, and L. L. Amuhaya, "Design and parametric analysis of dual mechanical port field excited flux switching generator for wind turbine applications," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Detroit, MI, USA, Oct. 2022, pp. 1–5, doi: 10.1109/ECCE50734.2022.9948099.

[131] Z. Zeng, Y. Shen, Q. Lu, B. Wu, D. Gerada, and C. Gerada, "Investigation of a partitioned-primary hybrid-excited flux-switching linear machine with dual-PM," *IEEE Trans. Ind. Appl.*, vol. 55, no. 4, pp. 3649–3659, Jul. 2019, doi: 10.1109/TIA.2019.2912553.

[132] M. Cheng, Z. Xu, M. Tong, G. Zhao, and P. Han, "Analysis and optimization of a five-phase hybrid excitation flux switching machine based on the consistency and complementarity principle," *Chin. J. Electr. Eng.*, vol. 7, no. 3, pp. 52–64, Sep. 2021, doi: 10.23919/CJEE.2021.000025.

[133] B. Ullah, F. Khan, and A. H. Milyani, "Analysis of a discrete stator hybrid excited flux switching linear machine," *IEEE Access*, vol. 10, pp. 8140–8150, 2022, doi: 10.1109/ACCESS.2022.3143794.

[134] H. Geng, X. Zhang, L. Tong, Q. Ma, M. Xu, Y. Zhang, and L. Wang, "Performance optimization analysis of hybrid excitation generator with the electromagnetic rotor and embedded permanent magnet rotor for vehicle," *IEEE Access*, vol. 9, pp. 163640–163653, 2021, doi: 10.1109/ACCESS.2021.3133960.

[135] X. Wang, Y. Fan, C. Yang, Z. Wu, and C. H. T. Lee, "Multi-objective optimization framework of a radial-axial hybrid excitation machine for electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 72, no. 2, pp. 1638–1648, Feb. 2023, doi: 10.1109/TVT.2022.3207231.

[136] B. Praslicka, C. Ma, and N. Taran, "A computationally efficient high-fidelity multi-physics design optimization of traction motors for drive cycle loss minimization," *IEEE Trans. Ind. Appl.*, vol. 59, no. 2, pp. 1351–1360, Mar. 2023, doi: 10.1109/TIA.2022.3220554.

[137] M. Salameh, S. Singh, S. Li, and M. Krishnamurthy, "Surrogate vibration modeling approach for design optimization of electric machines," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 3, pp. 1126–1133, Sep. 2020, doi: 10.1109/TTE.2020.3017232.

[138] F. Nishanth, G. Bohach, M. M. Nahin, J. Van de Ven, and E. L. Severson, "Development of an integrated electro-hydraulic machine to electrify off-highway vehicles," *IEEE Trans. Ind. Appl.*, vol. 58, no. 5, pp. 6163–6174, Sep. 2022, doi: 10.1109/TIA.2022.3189609.

[139] M. Palmieri, G. Gallicchio, and F. Cupertino, "An automated design procedure for the power density optimization of IPM machines," in *Proc. IEEE Int. Conf. Power Electron., Drives Energy Syst. (PEDES)*, Jaipur, India, Dec. 2020, pp. 1–6, doi: 10.1109/pedes49360.2020.9379355.

[140] B.-K. Song, J.-H. Kim, K.-Y. Hwang, and M.-S. Lim, "Electromechanical characteristics of dual-winding motor according to winding arrangement for brake systems in highly automated driving vehicles," *IEEE Trans. Veh. Technol.*, early access, May 3, 2023, doi: 10.1109/TVT.2023.3272729.

[141] C. Gong and F. Deng, "Design and optimization of a high-torque-density low-torque-ripple Vernier machine using ferrite magnets for direct-drive applications," *IEEE Trans. Ind. Electron.*, vol. 69, no. 6, pp. 5421–5431, Jun. 2022, doi: 10.1109/TIE.2021.3090714.

[142] D. Talebi, M. C. Gardner, S. V. Sankarraman, A. Daniar, and H. A. Toliyat, "Electromagnetic design characterization of a dual rotor axial flux motor for electric aircraft," *IEEE Trans. Ind. Appl.*, vol. 58, no. 6, pp. 7088–7098, Nov. 2022, doi: 10.1109/TIA.2022.3191300.

[143] O. Gundogmus, M. Elamin, Y. Yasa, T. Husain, Y. Sozer, J. Kutz, J. Tylenda, and R. L. Wright, "Acoustic noise mitigation of switched reluctance machines with windows on stator and rotor poles," *IEEE Trans. Ind. Appl.*, vol. 56, no. 4, pp. 3719–3730, Jul./Aug. 2020, doi: 10.1109/TIA.2020.2992664.

[144] G. Lei, G. Bramerdorfer, B. Ma, Y. Guo, and J. Zhu, "Robust design optimization of electrical machines: Multi-objective approach," *IEEE Trans. Energy Convers.*, vol. 36, no. 1, pp. 390–401, Mar. 2021, doi: 10.1109/TEC.2020.3003050.

[145] Z. Shi, X. Sun, Y. Cai, and Z. Yang, "Robust design optimization of a five-phase PM hub motor for fault-tolerant operation based on Taguchi method," *IEEE Trans. Energy Convers.*, vol. 35, no. 4, pp. 2036–2044, Dec. 2020, doi: 10.1109/TEC.2020.2989438.

[146] J. Zhu, L. Wu, and H. Wen, "Optimization and comparison of dual-armature flux-switching permanent magnet machines with different stator core shapes," *IEEE Trans. Ind. Appl.*, vol. 58, no. 1, pp. 314–324, Jan. 2022, doi: 10.1109/TIA.2021.3131300.

[147] G. C. Enss, M. Kohler, A. Krzyzak, and R. Platz, "Nonparametric quantile estimation based on surrogate models," *IEEE Trans. Inf. Theory*, vol. 62, no. 10, pp. 5727–5739, Oct. 2016, doi: 10.1109/TIT.2016.2586080.

[148] N. Taran, D. M. Ionel, and D. G. Dorrell, "Two-level surrogate-assisted differential evolution multi-objective optimization of electric machines using 3-D FEA," *IEEE Trans. Magn.*, vol. 54, no. 11, pp. 1–5, Nov. 2018, doi: 10.1109/TMAG.2018.2856858.

[149] K. Diao, X. Sun, G. Lei, Y. Guo, and J. Zhu, "Multimode optimization of switched reluctance machines in hybrid electric vehicles," *IEEE Trans. Energy Convers.*, vol. 36, no. 3, pp. 2217–2226, Sep. 2021, doi: 10.1109/TEC.2020.3046721.

[150] J. Gu, W. Hua, W. Yu, Z. Zhang, and H. Zhang, "Surrogate model-based multiobjective optimization of high-speed PM synchronous machine: Construction and comparison," *IEEE Trans. Transport. Electrific.*, vol. 9, no. 1, pp. 678–688, Mar. 2023, doi: 10.1109/TTE.2022.3173940.

[151] X. Sun, Z. Shi, G. Lei, Y. Guo, and J. Zhu, "Multi-objective design optimization of an IPMSM based on multilevel strategy," *IEEE Trans. Ind. Electron.*, vol. 68, no. 1, pp. 139–148, Jan. 2021, doi: 10.1109/TIE.2020.2965463.

[152] X. Zhu, D. Fan, Z. Xiang, L. Quan, W. Hua, and M. Cheng, "Systematic multi-level optimization design and dynamic control of less-rare-earth hybrid permanent magnet motor for all-climatic electric vehicles," *Appl. Energy*, vol. 253, Nov. 2019, Art. no. 113549, doi: 10.1016/j.apenergy.2019.113549.

[153] G. Lei, G. Bramerdorfer, C. Liu, Y. Guo, and J. Zhu, "Robust design optimization of electrical machines: A comparative study and space reduction strategy," *IEEE Trans. Energy Convers.*, vol. 36, no. 1, pp. 300–313, Mar. 2021, doi: 10.1109/TEC.2020.2999482.

[154] P. N. Koch, R.-J. Yang, and L. Gu, "Design for six sigma through robust optimization," *Struct. Multidisciplinary Optim.*, vol. 26, nos. 3–4, pp. 235–248, Feb. 2004, doi: 10.1007/s00158-003-0337-0.

[155] B. Ma, "Advanced design and optimization techniques for electrical machines," Ph.D. dissertation, Faculty Eng Inf. Technol., Univ. Technol. Sydney, Sydney, NSW, Australia, 2020.

[156] V. Rafiee and J. Faiz, "Robust design of an outer rotor permanent magnet motor through six-sigma methodology using response surface surrogate model," *IEEE Trans. Magn.*, vol. 55, no. 10, pp. 1–10, Oct. 2019, doi: 10.1109/TMAG.2019.2923160.

[157] G. Lei, Y. G. Guo, J. G. Zhu, and W. Xu, "Six-sigma robust topology and shape optimization for flux switching permanent magnet machines," in *Proc. IEEE Int. Conf. Appl. Supercond. Electromagn. Devices (ASEMD)*, Shanghai, China, Nov. 2015, pp. 122–123, doi: 10.1109/ASEMD.2015.7453496.

[158] E. C. Abunike, O. I. Okoro, and I. E. Davidson, "Thermal analysis of an optimized switched reluctance motor for enhanced performance," in *Proc. IEEE PES/IAS Power Africa*, Nairobi, Kenya, Aug. 2021, pp. 1–5, doi: 10.1109/PowerAfrica52236.2021.9543275.

[159] A. S. Mohammadi and J. P. F. Trovão, "System-level optimization of hybrid excitation synchronous machines for a three-wheel electric vehicle," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 2, pp. 690–702, Jun. 2020, doi: 10.1109/TTE.2020.2992008.

[160] K. Diao, X. Sun, G. Lei, Y. Guo, and J. Zhu, "Application-oriented system level optimization method for switched reluctance motor drive systems," in *Proc. IEEE 9th Int. Power Electron. Motion Control Conf. (IPEMC-ECCE Asia)*, Nanjing, China, Nov. 2020, pp. 472–477, doi: 10.1109/IPEMC-ECCEAsia48364.2020.9367987.

[161] W. Jiang and T. M. Jahns, "Coupled electromagnetic–thermal analysis of electric machines including transient operation based on finite-element techniques," *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1880–1889, Mar. 2015, doi: 10.1109/TIA.2014.2345955.

[162] F. Magnussen and H. Lendenmann, "Parasitic effects in PM machines with concentrated windings," *IEEE Trans. Ind. Appl.*, vol. 43, no. 5, pp. 1223–1232, Sep./Oct. 2007, doi: 10.1109/tia.2007.904400.

[163] D. Li, R. Qu, X. Ren, and Y. Gao, "Brushless dual-electrical-port, dual mechanical port machines based on the flux modulation principle," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Milwaukee, WI, USA, Sep. 2016, pp. 1–8, doi: 10.1109/ECCE.2016.7854902.

[164] M. F. Omar, E. Sulaiman, and H. A. Soomro, "New topology of single-phase segmented rotor field excitation flux switching machine for high density air-condition," *Appl. Mech. Mater.*, vol. 695, pp. 783–786, Nov. 2014, doi: 10.4028/www.scientific.net/amm.695.783.

[165] W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. B. Williams, C. C. L. Wang, Y. C. Shin, S. Zhang, and P. D. Zavattieri, "The status, challenges, and future of additive manufacturing in engineering," *Comput.-Aided Design*, vol. 69, pp. 65–89, Dec. 2015, doi: 10.1016/j.cad.2015.04.001.

[166] G. Bramerdorfer, G. Lei, A. Cavagnino, Y. Zhang, J. Sykulski, and D. A. Lowther, "More robust and reliable optimized energy conversion facilitated through electric machines, power electronics and drives, and their control: State-of-the-art and trends," *IEEE Trans. Energy Convers.*, vol. 35, no. 4, pp. 1997–2012, Dec. 2020, doi: 10.1109/TEC.2020.3013190.

[167] F. Ismagilov, R. Valiev, V. Vavilov, and R. Urazbakhtin, "The main aspects of the FMEA usage in the design of modern and advanced electrical machines," in *Proc. Int. Conf. Electrotech. Complexes Syst. (ICOECS)*, Ufa, Russia, Oct. 2020, pp. 1–4, doi: 10.1109/ICOECS50468.2020.9278407.

[168] T. Wang, Z. Liu, M. Liao, N. Mrad, and G. Lu, "Probabilistic analysis for remaining useful life prediction and reliability assessment," *IEEE Trans. Rel.*, vol. 71, no. 3, pp. 1207–1218, Sep. 2022, doi: 10.1109/TR.2020.3032157.

[169] P. Offermann, H. Mac, T. T. Nguyen, S. Clenet, H. De Gersem, and K. Hameyer, "Uncertainty quantification and sensitivity analysis in electrical machines with stochastically varying machine parameters," *IEEE Trans. Magn.*, vol. 51, no. 3, pp. 1–4, Mar. 2015, doi: 10.1109/tmag.2014.2354511.

[170] G. Verez, G. Barakat, and Y. Amara, "Influence of slots and rotor poles combinations on noise and vibrations of magnetic origins in 'U'-core flux-switching permanent magnet machines," *Prog. Electromagn. Res. B*, vol. 61, pp. 149–168, 2014, doi: 10.2528/PIERB14100902.

[171] H. Jia, M. Cheng, W. Hua, W. Lu, and X. Fu, "Investigation and implementation of control strategies for flux-switching permanent magnet motor drives," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Edmonton, AB, Canada, Oct. 2008, pp. 1–6, doi: 10.1109/08ias.2008.216.

[172] M. Tong, W. Hua, P. Su, M. Cheng, and J. Meng, "Investigation of a vector-controlled five-phase flux-switching permanent-magnet machine drive system," *IEEE Trans. Magn.*, vol. 52, no. 7, pp. 1–5, Jul. 2016, doi: 10.1109/TMAG.2016.2524503.

[173] H. Jia, M. Cheng, W. Hua, W. Zhao, and W. Li, "Torque ripple suppression in flux-switching PM motor by harmonic current injection based on voltage space-vector modulation," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 1527–1530, Jun. 2010, doi: 10.1109/TMAG.2010.2040250.
[174] H. Q. Nguyen and S.-M. Yang, "Rotor position sensorless control of wound-field flux-switching machine based on high frequency square-wave voltage injection," *IEEE Access*, vol. 6, pp. 48776–48784, 2018, doi: 10.1109/ACCESS.2018.2867899.
[175] Z. Song, Y. Cui, Y. Wang, and T. Liu, "Flux-trajectory-optimization-based predictive flux control of permanent magnet synchronous machines," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 4, pp. 4364–4375, Aug. 2021, doi: 10.1109/JESTPE.2021.3058630.
[176] B. Shweta and D. V. Sadhana, "Model predictive control and higher order sliding mode control for optimized and robust control of PMSM," *IFAC-PapersOnLine*, vol. 55, no. 22, pp. 195–200, 2022.
[177] W. Zhao, M. Cheng, W. Hua, H. Jia, and R. Cao, "Back-EMF harmonic analysis and fault-tolerant control of flux-switching permanent-magnet machine with redundancy," *IEEE Trans. Ind. Electron.*, vol. 58, no. 5, pp. 1926–1935, May 2011, doi: 10.1109/TIE.2010.2050758.
[178] Y. Meng, S. Fang, Z. Pan, W. Liu, and L. Qin, "Machine learning technique based multi-level optimization design of a dual-stator flux modulated machine with dual-PM excitation," *IEEE Trans. Transport. Electrific.*, vol. 9, no. 2, pp. 2606–2617, Jun. 2023, doi: 10.1109/TTE.2022.3213083.
[179] S. Barmada, N. Fontana, L. Sani, D. Thomopulos, and M. Tucci, "Deep learning and reduced models for fast optimization in electromagnetics," *IEEE Trans. Magn.*, vol. 56, no. 3, pp. 1–4, Mar. 2020, doi: 10.1109/TMAG.2019.2957197.
[180] T. Sato and M. Fujita, "A data-driven automatic design method for electric machines based on reinforcement learning and evolutionary optimization," *IEEE Access*, vol. 9, pp. 71284–71294, 2021, doi: 10.1109/ACCESS.2021.3078668.
[181] P.-H. Arnoux, P. Caillard, and F. Gillon, "Modeling finite-element constraint to run an electrical machine design optimization using machine learning," *IEEE Trans. Magn.*, vol. 51, no. 3, pp. 1–4, Mar. 2015, doi: 10.1109/TMAG.2014.2364031.

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