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Research Article

Evolution of Multi-Phase Synchronous Reluctance Motors: A Comprehensive Review

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ABSTRACT

Synchronous reluctance motors (SynRMs) are electric motors that operate based on reluctance torque, where the rotor aligns with magnetic field produced by stator to minimize reluctance. Unlike conventional motors, SynRMs do not require permanent magnets or rotor windings, making them cost-effective and reliable. Recently, there has been increasing interest in multi-phase SynRMs, due to their enhanced performance characteristics, such as improved fault tolerance, efficiency, and torque control. This review paper provides a comprehensive analysis of multi-phase SynRMs, examining their evolution from three-phase to multi-phase designs and their applications in industries requiring high reliability and performance. The review highlights the advantages of multi-phase configurations in reducing torque ripple, enhancing fault resilience, and improving efficiency, making them well-suited for critical systems with demanding operational conditions. The paper discusses the evolution of three-phase SynRMs, followed by an exploration of five-phase and six-phase systems that offer further improvements in torque control and fault tolerance. Additionally, the review identifies current challenges and proposes future research directions for optimizing these motor designs for broader industrial applications.

Keywords: Three-phase SynRMs, Five-phase SynRMs, Six-phase SynRMs, Fault tolerance, Efficiency, Torque ripple, Motor control strategies, Synchronous reluctance motors.

1. INTRODUCTION

Synchronous reluctance technology, initially introduced in the 1920s, has not gained mainstream acceptance due to the prevailing success of induction motor and, later, the 1980s observed the advent of materials for permanent magnets with significant energy densities. These advancements in permanent magnets led to the widespread adoption of permanent magnet machines, especially in specialized and high-performance applications. But by 2016, as reported in the media, research was focused on creating electrical devices that need less rare earth permanent magnetic elements [1]. This shift also included a focus on creating super-premium efficiency electrical machines targeted at industrial applications. These emerging research directions are driven by different motivations. The push for reduced rare earth magnet usage stems from supply-related issues, including concerns about material availability, price volatility, and environmental impacts associated with magnet production. Meanwhile, SynRM (a typical profile is shown in Figure 1) presents itself as a compelling alternative, aligning well with both research streams: it operates without magnets and has the potential to achieve high efficiency.

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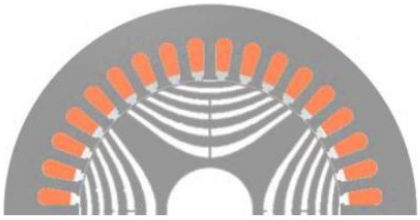

Figure 1: Typical SynRM lamination profile [2]

The SynRM has garnered a lot of attention over the last decade due to its inherent advantages, which include a straightforward and solid rotor design, no need for permanent magnets, minimal cogging torque, no rotor copper loss, cheap cost, dependability, and high efficiency. Because of these qualities, it is a good contender to take the role of induction motors in a variety of speed-driving applications, including electric vehicles (EVs) [3]. SynRMs achieve energy conversion efficiencies up to the IE4 class, surpassing induction motors (IMs) and approaching the levels of permanent magnet synchronous motors (PMSMs). However, SynRMs also face notable challenges, such as minor power factor, higher core loss, increased torque ripple, and challenges in setting precise pulse-width modulation (PWM) commutation timings.

Recent research has focused on the development of energy-efficient motors that strike a balance between size, cost, torque density, and reliability. SynRMs have attracted attention in this context owing to their cost-effectiveness and the absence of rare earth magnets [4, 5]. Several studies have aimed to enhance SynRM performance by refining magneto-motive force components and optimizing winding designs. For instance, research indicates that reducing torque ripple can be achieved through careful rotor and flux barrier design relative to stator slots [6, 7]. Novel rotor configurations such as shifted asymmetrical poles [8], "R and J" motor designs, and Machaon rotor structures have shown effectiveness in mitigating torque ripple. Additionally, advancements in winding configurations have contributed to performance improvements. A combined star-delta winding configuration, for example, increased average torque by 6.67% compared to conventional star windings, while a dual n-phase winding with a 30° phase shift demonstrated a 9.5% increase in average torque [9]. Similarly, a single-tooth winding developed for a six-slot, four-pole double-layer SynRM achieved a high slot fill factor, though with increased torque ripple and reduced power factor [10].

Research into multiphase SynRMs is still evolving, yet several studies have made notable strides. For example, some research has explored optimal flux barrier arrangements and mixed stator windings as methods to reduce torque ripple [11]. Additionally, torque ripple minimization techniques for permanent magnet-assisted SynRMs have been proposed [12]. In multiphase SynRMs, space vector PWM techniques were utilized to reduce switching losses in five-phase configurations [13].

SynRMs are a specialized type of electric motor that generate torque through principle of magnetic reluctance. These motors are recognized for their high efficiency and robustness, making them advantageous over other motor types. However, the operation of a SynRM requires a dedicated controller to provide precise control of the rotor's position and speed [14, 15, and 16]. SynRM controllers are designed to ensure accurate and responsive performance, often employing sensor less control methods includes field-oriented control (FOC) to attain significant precision and dynamic responsiveness. In addition to FOC, various controllers use innovative control processes like space vector modulation (SVM) and direct torque control (DTC) to further enhance motor performance [17]. These advanced techniques enable SynRMs to achieve better dynamic control and improved efficiency, making them suitable for a wide range of demanding applications. By optimizing torque and minimizing losses, SVM and DTC contribute to SynRM's overall performance and energy efficiency, reinforcing its competitive edge in applications requiring both reliability and efficiency.

1.1. Need for SynRM

SynRMs provide a number of benefits that make them ideal for businesses and factories:

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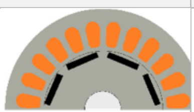
- High efficiency: The simple rotor design and absence of rotor windings minimize power losses, resulting in exceptional efficiency.
- Cost-effectiveness: The straightforward rotor structure and elimination of rotor windings make SynRMs more affordable.
- High Power density: Their intrinsic rotor design enables the production of significant torque at high speeds.
- Low Noise levels: The lack of rotor windings and simplified rotor design contribute to quieter operation, making then ideal for noise-sensitive applications.
- Durability: SynRMs are highly robust, capable of withstanding variations in motor characteristics and external disturbances, which makes them reliable for industrial use.
- High Torque at low speeds: These motors are particularly effective for applications requiring substantial torque at lower speeds.
- Versatile applications: SynRMs are well-suited for various uses, including pumps, fans, compressors, conveyors and other industrial and commercial systems.
- Enhanced control flexibility: Direct torque control (DTC) and field-oriented control (FOC) are examples of advanced control procedures that may be used to maximize energy economy and performance.

The SynRM shares a similar stator structure with the IM but lacks rotor field windings, which simplifies its construction and eliminates the need for magnets, making it more cost-effective than permanent magnet motors [20]. Compared to squirrel cage motors, SynRM has a simpler, more robust design, requires less maintenance, has a tiny moment of inertia, is inexpensive to manufacture, and has a high torque per unit volume. Its control systems are simple, and because there are no rotor windings, losses are reduced, increasing efficiency.

When compared to brushless (BL) motors, SynRM is more robust and has a lower-cost rotor structure. Structurally, SynRM features a salient rotor, in contrast to doubly salient structure of switched reluctance motor (SRM), which also gives SynRM an advantage in terms of reduced torque ripple [21]. However, SynRM does have various disadvantages, includes a lower power factor and reduced torque density, which, though somewhat manageable, able to be improved through control strategies and careful attention to design parameters. Increasing the number of phases in a SynRM has also proven to be an effective method for reducing torque ripple [22].

Table 1: Performance analysis of various motors

Motor Type	Stator and Rotor structure sample	Various kinds	Applications	Pros	Cons
IM [22]		Copper Rotor Aluminium Rotor	Industrial Applications.	High inertia High efficiency and torque capability Line-start capability	Low power factory Moderate torque ripple
PMSM [23]		Interior PM Line-start PMSM	Robotics, high-performance and automation.	High performance in wide speed range operation Low-speed ripple Low-torque ripple	Higher cost compared to other motors

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SynRM [24, 25]		Line-start SynRM Skewed rotor	Industrial applications includes fans, traction etc.	Reliable High dynamic High speed control	High torque ripple Low power factor
PMSynRMs		Rotor skewing Different barrier structure	Traction applications.	High performance without rare earth PMs	Instalment and manufacturing process is difficult

Table 1 provides a summary of key features distinguishing the dominant motors from SynRMs. In order to determine if SynRM technology can eventually replace current motor technologies, this comparison attempts to highlight the advantages and disadvantages of every motor type. In applications like pumps, fans, and conveyors, IMs currently dominate but could eventually be substituted by SynRMs. To facilitate this transition, SynRMs need to match or exceed the cost-effectiveness and efficiency of IMs to make them appealing to industry. Similarly, while PMSynRMs incorporate ferrite magnets, their performance must remain competitive with that of PMSMs to capture the interest of manufacturers.

The modelling of a SynRM rotor in d-q reference frame is very important for motors. The rotor angular velocity is ω_r with d-axis signified in phasor diagram [26] in figure 2. The d-q model of a SynRM is a mathematical model that simplifies the analysis and control of motor by transforming motor's stator currents and voltages into a two-axis reference frame: the direct-axis (d-axis) and quadrature-axis (q-axis). This model is based on the concept of vector control, where the motor's operation is analyzed in terms of two orthogonal components of the magnetic field. The equations are given by:

d-axis voltage: $$v_d = R_s i_d + \frac{d}{dt}(\lambda_d) - \omega_r \lambda_q \quad (1)$$

q-axis voltage: $$v_q = R_s i_q + \frac{d}{dt}(\lambda_q) - \omega_r \lambda_d \quad (2)$$

where, v_d, v_q are d- and q-axis stator voltages. R_s is stator resistance. i_d, i_q are d and q-axis stator currents. λ_d, λ_q are d and q-axis flux linkages. The flux linkage in stator windings in dq is explained by (3) and (4).

d-axis flux linkage: $$\lambda_d = L_d i_d + \lambda_m \quad (3)$$

q-axis flux linkage: $$\lambda_q = L_q i_q \quad (4)$$

where L_d and L_q are direct and quadrature axis inductance. λ_m is permanent magnet flux linkage. The d-q model is crucial for understanding and controlling the performance of SynRM, particularly in high-performance applications requiring precise torque control and fault tolerance.

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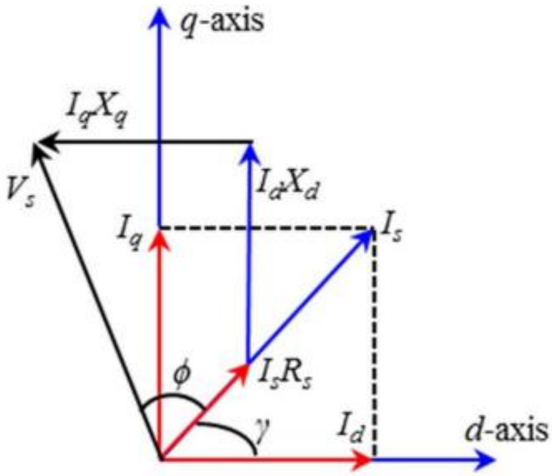

Figure 2: Phasor diagram of SynRMs

1.2. Control methodologies for SynRMs

Control methodologies in SynRMs primarily focus on efficient torque control, speed regulation, and minimizing torque ripple. These methods are generally classified into Scalar Control and Vector Control approaches. Figure 3 shows the hierarchical structure of different control techniques for SynRMs.

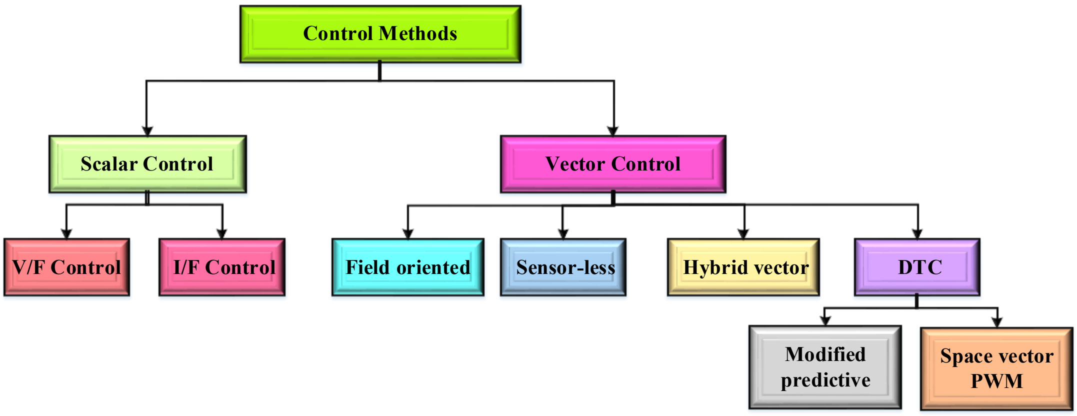

Figure 3: Frequently employed control strategies for SynRM

Scalar Control: Scalar Control, also identified as "voltage and frequency" or "V/F" control, adjusts scalar quantities like voltage, current, or frequency, rather than focusing on motor flux and torque direction. This method is simpler and less computationally intensive than vector control. It includes:

- *V/F Control (Voltage/Frequency Control):* This technique maintains a constant voltage-to-frequency ratio, providing a basic form of speed control for the motor. It is simple to implement but lacks precise control over dynamic performance, making it suitable for applications that do not require high torque accuracy.

- *I/F Control (Current/Frequency Control):* in this approach, the current-to-frequency ratio is adjusted. It is less common than V/F control but can be useful for specific applications where maintaining a certain current level is essential for efficient operation.

Vector Control: A more sophisticated method is Vector Control, sometimes referred to as Field-Oriented Control (FOC) that controls the motor's magnetic flux and torque by decomposing current into components aligned with the motor's magnetic field. This allows for precise and responsive control of motor dynamics, making it suitable for high-performance applications. Vector control techniques such as:

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- *Field-Oriented Control:* FOC methods involve aligning the stator current with the rotor's magnetic field to precisely control torque and speed. It is divided into:

Direct FOC: In this approach, direct measurements of the motor's magnetic field and torque are used for control.

Indirect FOC: Instead of directly measuring the field, this method estimates rotor position and magnetic flux using mathematical models, which can simplify implementation.

- *Sensor-less Control:* This techniques do not rely on external sensors to detect rotor position or speed, instead estimating these values from electrical measurements. This reduces system complexity and cost, and enhances robustness by eliminating mechanical sensors.
- *Hybrid Vector Control:* This control combines aspects of various vector control methods to enhance performance, particularly under varying load or operational conditions. It aims to leverage the strengths of multiple control techniques to optimize motor performance.
- *Direct Torque control (DTC):* DTC focuses on directly controlling motor torque and magnetic flux, resulting in a faster dynamic response than FOC. Within DTC, specific approaches include:

Modified Predictive Control: Uses predictive algorithms to anticipate motor behaviour and adjust control parameters proactively, enhancing precision and stability.

Space Vector PWM: this technique optimizes the switching of motor drive components to minimize losses and improve efficiency, particularly in applications where energy savings are critical.

In conclusion, this offers a comprehensive and organized perspective on various control methods for motor systems, particularly focusing on scalar and vector control strategies. By breaking down each method into specific subcategories, it facilitates a deeper understanding of how each approach meets distinct operational requirements and enhances motor performance. This structured classification allows for a clearer comparison of each control method's strengths and limitations, providing valuable insights into their applicability for different motor control applications. SynRMs have gained renewed interest due to their efficiency, cost-effectiveness, and absence of rare earth magnets, making them a promising alternative to traditional motor technologies. Initially induction and permanent magnet motors, SynRMs have emerged as a viable solution for high-efficiency industrial applications. Their simple, robust structure, combined with advanced control methods, positions SynRMs as a strong candidate to replace induction motors in various sectors. Despite some limitations, such as lower power factors and torque ripple, recent advancements in rotor design and control strategies have significantly improved SynRM performance. This paper explores the potential of SynRMs to become a leading technology, examining their advantages and addressing key challenges compared to established motor types. The contribution of this work is as follows:

- This review presents an in-depth analysis of multi-phase SynRMs, exploring their evolution from conventional three-phase to advanced five-phase and six-phase designs.
- The paper systematically compares the performance metrics of three-phase, five-phase, and six-phase SynRMs. This comparative analysis helps identify the advantages and limitations of each configuration in various applications.
- By reviewing existing literature, the paper identifies and discusses the industrial applications where multi-phase SynRMs are most beneficial, emphasizing the role of these configurations in systems that require high reliability, efficiency, and resilience against faults.

This review paper is organized as follows: Section 2 defines materials and methods used in review process. Section 3 provides a comprehensive survey of multi-phase synchronous reluctance motors, covering three-phase, five-phase, and six-phase configurations, along with their advantages, objectives, and the results obtained in various studies. Section 4 details the performance metrics used by different authors to evaluate the effectiveness of multi-phase SynRMs. Section 5 presents a summary and discussion of review findings. The review article is finally concluded and references are included in Section 6.

2. MATERIALS AND METHODS

For this systematic investigation, numerous papers were sourced from reputable databases, including Google Scholar, IEEEXplore, Science Direct, Web of Science, and Scopus. A PRISMA diagram outlining the entire screening and article identification process is displayed in Figure 3. The preliminary step involved a screening process to

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eliminate duplicate papers from the extracted records. To establish eligibility, only research articles highly relevant to the central focus of the current study were selected. Articles that utilized the same methods in unrelated contexts or lacked crucial details were excluded. The final collection of publications was then organized into three categories: three-phase SynRMs, five-phase SynRMs, and six-phase SynRMs. Figure 4 shows the PRISMA diagram of this review paper.

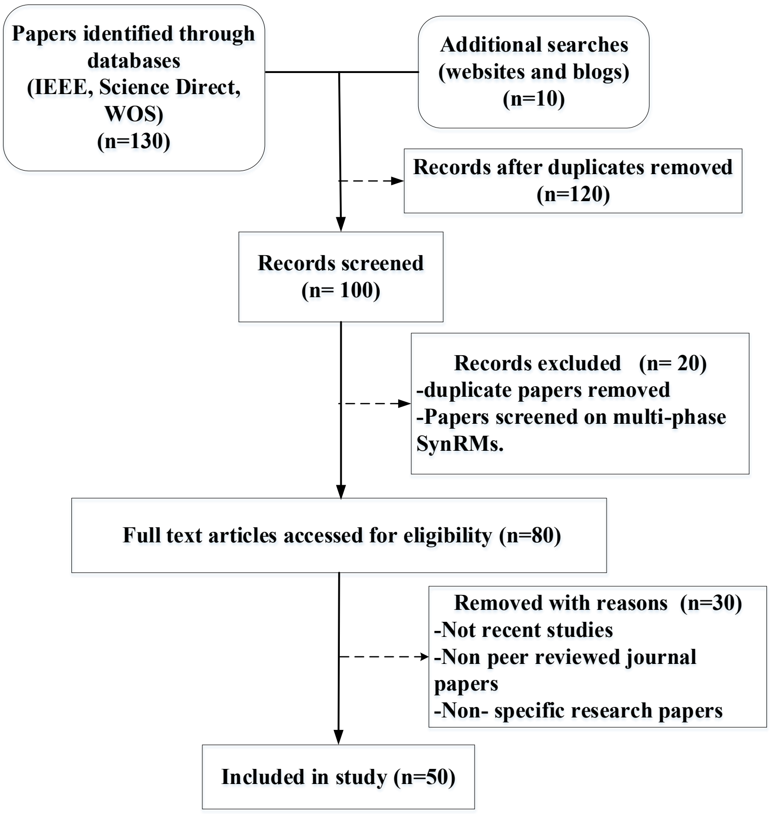

Figure 4: PRISMA diagram

3. SURVEY BASED ON MULTI-PHASE SYNCHRONOUS RELUCTANCE MOTORS

This section provides a detailed overview of multi-phase synchronous reluctance motors proposed by various authors, highlighting their techniques, methods, and results. It discusses the different phases explored in existing research, showcasing the advancements and performance improvements achieved by each approach.

3.1. Survey based on three-phase SynRMs

This section provides a detailed explanation of the three-phase SynRMs discussed in existing papers, highlighting the techniques, methods, and objectives proposed in the studies.

Tawfiq et al. [27] explored enhancements in efficiency, torque density, and reliability by modifying stator of conventional three-phase SynRMs, transforming them into multiphase machines. In their approach, they retained the original stator housing, shaft, bearings, and rotor to minimize refurbishment costs. This required maintaining constraints on inner and outer stator diameters, air gap length, and axial length, as well as keeping the copper volume in the windings identical to the original configuration. The study integrated an optimization technique with a two-dimensional finite element method (2D FEM) to identify optimal slot dimensions, resulting in a five-phase SynRM that demonstrated significant performance improvements. The redesigned multiphase SynRM exhibited increases in average torque, efficiency, and power factor when compared to original three-phase configuration, particularly under rated and high-speed conditions. Additionally, they examined a fault scenario where one phase was open, revealing that the five-phase SynRM maintained a considerably higher torque level than the three-phase machine under similar fault conditions.

A research suggested by Yusheng et al. [28], the rotor structure of a three-phase line-start SynRM (LS-SynRM) was designed and optimized, focusing on improving its starting and steady-state performance. The LS-SynRM utilizes asynchronous torque produced by rotor conductor bars for startup and switches to synchronous operation via reluctance torque created by inductance difference. The authors conducted a simulation to assess the impact of number and ratio of rotor flux barriers on dq-axis inductance, determining an optimal rotor flux barrier structure. The study also applied transient theory to develop a method for isolating each torque during the LS-SynRM's startup phase, which helped identify the primary reason behind the motor's initial weak starting performance. Additionally, influence of rotor conductor bars' area and distribution on starting ability was analysed, especially for cases involving heavy-load startup conditions. By optimizing the rotor flux barrier structure and conductor bar arrangement, the authors enhanced the LS-SynRMs performance. A prototype test confirmed that the rated efficiency of optimized LS-SynRM was 2.8% greater than that of a standard three-phase squirrel cage induction motor (SCIM), validating the accuracy of simulated outcomes.

In a study by Wang et al. [29], fault operation characteristics of a triple redundant three-phase permanent magnet-assisted SynRM (PMA-SynRM) were thoroughly investigated. The analysis focused on understanding the mutual coupling mechanism across different three-phase modules by examining the distribution of magneto motive force (MMF). It was observed that each three-phase module influences the others through an MMF offset component, resulting in second harmonic components in dq axis currents, voltages, and torque. The research examined the behaviours of machine under both open circuit and short circuit fault circumstances, validating the analysis through FE simulations and experimental tests across various fault scenarios. The findings suggested that advanced control techniques are necessary to improve current tracking capabilities under post-fault conditions. This improvement is essential for maintaining operational stability and performance in fault scenarios, making it particularly relevant for high-reliability applications requiring enhanced fault tolerance.

In the study conducted by Jun-Kyu Park et al. [30], performance and characteristics of a dual three-phase SynM were examined under various operating conditions, including strong, half-control, and post-fault states. The research focused on analysing inductances to understand the interactions between the two three-phase systems and measuring induced voltages in every phase to confirm these interactions. For post-fault conditions, different fault scenarios were analysed, such as open-circuit faults and short-circuit faults. Experimental tests were conducted to validate the predicted results. Additionally, the study explored the half-control mode as an efficient and fault-tolerant operational strategy, demonstrating its effectiveness in maintaining motor performance in fault scenarios.

In the study by Huang et al. [31], a novel approach was introduced to address the limitations of traditional Direct Torque Control (DTC) methods, particularly their inability to effectively suppress inherent 5th and 7th current harmonics in SynRMs. The authors proposed a low-harmonic vector approach to replace the large vector used in conventional DTC. This approach achieves harmonic suppression by synthesizing a low-harmonic vector through precise adjustments in action time and sequence of three adjacent large vectors within a single control period. This method, referred to as three-vector synthesis, optimizes the utilization of available space voltage vectors. Two distinct synthesis schemes were introduced to adapt to different operating conditions: a switching frequency reduction type for enhanced efficiency and a torque response unchanged type for stable torque performance. Additionally, Huang et al. optimized the DTC switching table using this new vector synthesis technique to improve harmonic suppression while maintaining the simplicity of the DTC structure. The study demonstrated that this low-harmonic DTC method effectively suppresses current harmonics in the x–y subspace, with significantly reduced harmonic content compared to traditional DTC. Moreover, the low-harmonic DTC method was shown to be computationally efficient, easy to implement, and effective in harmonic suppression, making it appropriate for high-speed and high-performance applications, such as flywheel batteries.

In a study by Jeong et al. [32], output characteristics of a dual three-phase SynRM (DT-SynRM) were examined under various winding configurations and control modes, specifically normal and half-control (HC) modes. The researchers aimed to understand how different winding arrangements and rotor barrier designs impact the performance of DT-SynRM. To achieve this, this study applied conventional Winding Function Theory (WFT), which allows the prediction of output characteristics based on inductance behavior influenced by winding function, turn function, and inverse air gap function. The DT-SynRM's performance was analysed using two winding configurations, designated

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as W1122 and W1212 models, under both normal and HC conditions. Additionally, rotor barrier shape was assessed as a design factor affecting the motor's performance. The analysis was conducted through a combination of analytical methods, simulations, and experimental verification. The results highlighted that, under normal conditions, performance differences between the two models were negligible; however, in HC mode, rotor design significantly impacted performance. The findings verified that when designing a DT-SynRM, rotor shape and winding configuration are crucial for achieving optimal performance, especially in half-control mode.

In the study by Kotb B. Tawfiq et al. [33], the authors conducted a comparative analysis of three drive systems for SynRM, focusing on their cost, performance, and reliability under various operational conditions. The three drive systems include a three-phase SynRM (Drive-1), a five-phase star-connected SynRM (Drive-2), and a combined star-pentagon SynRM with an indirect matrix converter (Drive-3). The analysis evaluated the average torque, torque ripple, efficiency, power factor, cost, and fault tolerance of each drive. The findings showed that Drive-2 and Drive-3 achieved 6.56% and 13.35% higher average torque than Drive-1, correspondingly, with corresponding torque ripples of 6.58% and 5.52%, compared to 7.94% for Drive-1. Drive-2 and Drive-3 were slightly more efficient (0.32% and 0.58% higher) than Drive-1 at rated conditions. Although Drive-2 and Drive-3 had higher initial costs (2.44% and 2.19% more, respectively), Drive-3 proved to be the most reliable, while Drive-1 was the least reliable. Additionally, under single-phase open-fault conditions, Drive-2 and Drive-3 delivered significantly higher torque and lower torque ripple compared to Drive-1.

Zhou et al. [34] investigated fault-tolerant control strategies for dual three-phase PMSM (DT-PMSM). The primary focus was on open-phase faults, a significant concern for multiphase motors due to their high fault tolerance. When an open-phase fault occurs, currents in a–c and z1–z2 subspaces of the motor are no longer decoupled, making it necessary to set up a new mathematical model. The study utilized the vector space decomposition modeling method to develop mathematical model of DT-PMSM with one open phase. Two optimal current control modes were implemented: one to minimize stator loss and another to maximize torque output. The vector control strategy was used to achieve these control modes. The experimental outcomes validated the effectiveness and feasibility of suggested fault-tolerant control strategy. The results showed that the strategy successfully suppressed torque ripple and enhanced the reliability of drive system, demonstrating a robust fault-tolerant performance in open-phase conditions.

Jun-Kyu Park et al. [35] conducted a study on DT-SynRM to analyse post-fault characteristics under open-circuit and short-circuit faults in motor windings and inverter switches. The research examined various winding configurations and proposed half-supply (HS) mode as a strategy to maintain efficient operation in fault-tolerant mode. The study included different winding arrangements and analysed the performance of DT-SynRM under normal, HS-mode, and post-fault conditions for both open-circuited and short-circuited scenarios. For open-circuit faults, single open-phase (single-OSF) and double open-phase (double-OSF) faults were considered, while single short-circuit (single-SSF) and triple short-circuit (triple-SSF) faults were examined. Results indicated that single-OSF was most severe condition owing to its high torque ripple and low average torque. As a fault mitigation strategy, HS-mode operation was explored, achieving around 50% of the normal average torque. Under HS-mode, Model 1 demonstrated about 16% higher average torque than Model 2 due to its higher self-inductance, while Model 2 showed a higher average torque under normal mode and across fault conditions owing to its greater mutual inductance. Simulations were conducted using hysteresis current control, without considering saturation effects.

Hisham M. Eldeeb et al. [36] presented an approach for pre- and post-fault stator current control structures for symmetrical dual three-phase reluctance synchronous machines (SDT-RSMs) with varied neutral-point configurations. The study analyzed the influence of winding chording and rotor saliency on harmonic mapping across different subspaces, providing insights for simplifying control structures in fault-free scenarios. Additionally, the study identified machine non-linearities, leading to the calculation of maximum-torque-per-ampere (MTPA) loci, which were applied for both pre- and post-fault operation. The proposed approach differed from traditional methods by utilizing a double-layer stator winding with an optimal chording angle, which eliminated need for harmonic controllers in the healthy (2N) case. If optimal angle was not implemented, harmonics such as the 5th and 7th appeared in the $\alpha\beta$ and XY subspaces, requiring the $\alpha\beta$ controller to mitigate these harmonics. The approach incorporated torque mapping based on identified non-linear flux linkages in the $\alpha\beta$ subspace, accounting for effects like cross-coupling and saturation. This estimation allowed the creation of MTPA loci, enhancing control for both fault-free and post-fault operations. FE simulations validated the proposed harmonic mapping, and the theoretical framework was experimentally confirmed using a 3 kW SDT-RSM prototype, ensuring reliable stator current performance in both pre- and post-fault conditions.

Cristian Babetto et al. [37] conducted a study on fault-tolerant operation of a dual three-phase winding SynRM. This motor design aimed to improve fault tolerance by utilizing two three-phase windings powered by separate inverters. In the event of a fault in a winding phase or inverter, faulty winding would be disconnected, allowing motor to continue operating with remaining healthy winding. This approach required analysing different winding configurations to optimize performance under faulty conditions, specifically focusing on average torque, radial force, and magnetic coupling between windings. Three distinct winding configurations—W-11-22, W-12-12, and W-6phase—were examined using FEA to identify the best design for reducing torque ripple and unbalanced radial force. The findings indicated that under faulty conditions, the average torque achieved by each winding configuration ranged between 35% and 44% of the normal, healthy motor torque. However, torque ripple increased significantly in all faulty scenarios, ranging between 37% and 61% of the nominal ripple. This analysis underscores the importance of designing synchronous reluctance motors with minimized torque ripple to improve reliability during fault-tolerant operations. Table 2 shows the comparison of each papers along with their techniques.

Table 2: Comparison of Three-Phase Synchronous Reluctance Motor

Author name	**Technique/ Methodology**	**Objective**	**Performance**	**Pros**	**Cons**
Tawfiq et al.[27]	Optimization + 2D FEM	Improve efficiency, torque density, and reliability in SynRMs	11.78% avg. torque, 0.72% efficiency at rated, 33.67% torque at 3x speed	Higher torque density, improved fault tolerance, minimal structural changes	Requires specific stator design modifications
Yusheng et al.[28]	Rotor Design Optimization + Simulation	Improve efficiency and starting capability of LS-SynRM	Rated Efficiency, Starting Capability	Enhanced synchronous performance, improved starting with heavy loads	Complexity in rotor design
Wang et al [29]	Fault Analysis with FE Simulations and Experimental Testing	To analyse fault behavior in PMA-SynRM and understand inter-module interactions	dq-axis current and voltage harmonics, torque performance	High fault tolerance, improved understanding of module interaction	Requires advanced control for current tracking in fault conditions
Jun-Kyu Park et al. [30]	Inductance & Voltage Analysis, Experimental Validation	Analyze performance under healthy, half-control, and fault conditions for fault tolerance	Fault tolerance, Efficiency	Fault-tolerant operation with half-control mode, enhanced efficiency in fault mode	Additional complexity in control logic

Huang et al [31]	Low-Harmonic Direct Torque Control (DTC) based on Three Vector Synthesis	To suppress 5th and 7th current harmonics in motors, improving traditional DTC	Reduces current harmonic content in x–y subspace	- Simple DTC structure - Effective harmonic suppression - Low dependency on motor parameters - Small calculation effort - Suitable for high-speed control	May require optimization for specific applications
Jeong et al [32]	Analytical method, simulation, and experimental validation using W1122 and W1212 winding configurations under normal and HC modes	Winding Function Theory (WFT)	Torque characteristics	Comprehensive analysis of torque under different configurations	Limited to DT-SynRM applications with dual-phase windings
Kotb B. Tawfiq et al. [33]	Comparative Analysis of Three SynRM Drive Systems	To evaluate and compare the cost, performance, and reliability of three SynRM-based drive systems	Average torque, torque ripple, efficiency, power factor, fault tolerance	Improved torque and fault tolerance for Drive-2 and Drive-3; Drive-3 is the most reliable	Higher initial cost for Drive-2 and Drive-3
Zhou et al. [34]	Vector space decomposition modeling method, vector control strategy	To develop a fault-tolerant control strategy for DT-PMSM with one	- Effective suppression of torque ripple - Improved reliability of the drive system	Fault-tolerant under open-phase conditions - Increased reliability of the motor system	May not be applicable for other types of faults or motor configurations

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	Objective	open-phase fault			
Jun-Kyu Park et al. [35]	Hysteresis current control, fault analysis under open and short-circuit conditions, half-supply mode (HS)	To analyse the post-fault characteristics of DT-SynRM under open-circuit and short-circuit faults, and assess the HS-mode as a fault mitigation strategy	- HS-mode achieved ~50% of normal average torque. - Model 1 exhibited 16% higher torque in HS-mode due to high self-inductance.	- Fault-tolerant operational mode (HS) maintains efficiency - Allows for analysis of different winding configurations under various fault conditions	- Neglects saturation effect, potentially limiting real-world accuracy - Single-OSF fault condition has high torque ripple and low average torque
Hisham M. Eldeeb et al.[36]	Harmonic mapping, MTPA loci identification, torque map estimation, finite element (FE) simulations	To develop a stator current control structure for SDT-RSM that ensures high performance during pre- and post-fault conditions	High-quality stator current control in pre- and post-fault modes - Elimination of harmonic controllers in fault-free cases with optimal chording angle	Simplifies control in healthy operation with optimal chording - Robust fault performance due to harmonic compensation	Additional harmonics in $\alpha\beta$ and XY subspaces if optimal chording angle is not applied - Complexity of non-linear flux linkage analysis and torque map estimation
Cristian Babetto et al.[37]	Fault-tolerant motor design, finite element analysis (FEA) for performance evaluation under fault conditions	To investigate and optimize fault tolerance in dual three-phase winding synchronous reluctance motors	-Faulty winding operation achieved 35%-44% of healthy torque -Torque ripple under fault conditions increased by 37%-61%	-Allows continued motor operation under fault conditions -Separate winding and inverter design enhances fault isolation	-Significant increase in torque ripple under fault conditions -Higher radial force imbalance and magnetic coupling effects during faulty operations

3.1.1. Summary

This study focuses on the development and analysis of three-phase SynRM design. The objective is to enhance the motor's efficiency, torque density, and reliability, particularly during faulty operations. Various methodologies, including optimization techniques, FEA, rotor design simulations, and harmonic mapping, are employed to evaluate the performance of different winding configurations and fault mitigation strategies. Key performance indicators such as torque, torque ripple, efficiency, fault tolerance, and radial force are analysed under healthy and fault conditions. The results show that most of the fault-tolerant systems maintain a fraction of the normal torque under fault conditions, typically between 35% and 44% of the healthy motor's output. However, the faulted operations often result in significant increases in torque ripple and imbalances in radial forces, ranging from 37% to 61% higher than normal conditions. In terms of advantages, these systems allow continued motor operation even in the event of a winding or inverter fault, enhancing overall reliability and reducing downtime. However, they also introduce complexity in terms of control strategies, with certain configurations requiring sophisticated control mechanisms to mitigate increased torque ripple and balance the system's operation.

3.2. Survey based on five-phase SynRMs

This section provides an explanation of five-phase SynRMs as proposed in existing papers, along with the objectives, methods, advantages, and disadvantages outlined by the authors.

Arafat et al. [38] proposed a fault-tolerant control (FTC) strategy for a five-phase Permanent Magnet Assisted SynRM (PMa-SynRM), focusing on optimizing phase advances under various fault conditions. The study addresses critical applications, mostly in the automotive and aerospace businesses, where consistency and safety are paramount. The multi-phase motor design, which includes redundant phases, is considered promising for fault tolerance, but advanced control techniques for maximizing reluctance torque in PMa-SynRMs are relatively underexplored. In traditional approaches, maintaining a constant magneto-motive force under fault conditions requires a significant rise in phase currents, leading to saturation of the motor and a drastic reduction in reluctance torque. To overcome this limitation, authors suggested a phase current control technique that maximizes reluctance torque while minimizing phase current. The methodology involves mathematical analysis of fault conditions, and the effectiveness of suggested technique was verified through both theoretical analysis and experimental tests using a 5-hp dynamo system controlled by a TI DSP F28335. In the presence of open-phase defects, the study shows that an optimal phase advance approach can provide maximum sustained torque control.

Zakirul Islam et al. [39] presented a study on designing a robust five-phase ferrite (Fe) Permanent Magnet Assisted Synchronous Reluctance Motor (PMaSynRM) to address the challenges of irreversible demagnetization and mechanical deformation. The study highlights increasing interest in multi-phase PMaSynRMs for vehicular applications owing to their high fault tolerance, torque density, and low torque ripple, offering advantages over three-phase counterparts. Though, Fe-based magnets bring specific design challenges, particularly around demagnetization and rotor stability. To overcome these, the authors introduced additional geometrical parameters to the rotor structure and incorporated weight reduction notches and an optimal center post, aimed at enhancing structural stability and reducing demagnetization risks. The study utilized both lumped parameter and FEM for design optimization and performance analysis, followed by the fabrication of a 3 kW prototype for experimental testing. Comparative testing with a rare-earth magnet-based PMaSynRM validated the suggested design and simulation results, demonstrating the feasibility and reliability of Fe-based PMaSynRMs as an alternative to rare-earth magnets in automotive applications.

Sinan Oğuzhan et al. [40] conducted a study comparing three-phase and five-phase SynRMs, focusing specifically on the impact of modifying only stator winding distribution while maintaining identical stator and rotor geometries. The objective was to evaluate performance improvements, particularly in torque output, harmonic reduction, and overall efficiency, resulting from the conversion to a five-phase configuration. Findings indicated that the five-phase motor achieved significantly higher output torque and a 15.4% decrease in torque ripple compared to three-phase motor. Additionally, substantial reductions were observed in critical harmonics that influence motor performance, including the 3rd, 5th, and 7th harmonics, alongside THD. The study employed an analysis method in which the initial three-phase motor design was first developed and evaluated under defined constraints and initial ratings. The motor was then rewound to form a five-phase configuration, and both versions were compared in terms of copper and iron losses, efficiency, power factor, torque capability, and harmonic characteristics. Authors concluded that the five-phase SynRM offers advantages in output torque, harmonic suppression, and flux density reduction, suggesting its suitability for applications requiring low torque ripple and efficient power distribution.

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Namariq Abdul Ameer et al. [41] proposed a five-phase SynRM design using a Direct Torque Control (DTC) strategy aimed at reducing torque ripple and improving motor speed control during acceleration and deceleration phases. The design uses a five-phase voltage source inverter, with pulses generated through a specialized DTC Space Vector Modulation (DTC-SVM) method. To control the motor effectively, two look-up tables were created to manage stator flux linkage and electromagnetic torque by employing optimized voltage space vectors. According to authors, the suggested method is efficient, offering fast and straightforward torque control. The study provides a schematic of the control block and demonstrates the system's performance under numerous load conditions and reference speeds. The authors implemented the five-phase SynRM DTC with two hysteresis controllers—one for torque and one for stator flux linkage—to achieve desired control. The simulation results affirmed that the developed model performs reliably across multiple operating scenarios.

Umoh et al. [42] presented a model of a five-phase SynRM designed to study the machine's performance under multi-phase fault conditions. The model, with an ACEBD winding configuration, considers both fundamental component and the third harmonic of air-gap magneto-motive force (MMF). To analyse the impact of multi-phase faults, two distinct approaches were explored: one that includes the third harmonic MMF and one that neglects it. The investigation examined the motor's speed performance during faults involving phase losses of $2\pi/5$ and $4\pi/5$ radians, along with their subsequent restoration. The study noted the synchronous speed drops to a negative value when up to four phases are lost, demonstrating the influence of reluctance torque on electromagnetic torque under fault conditions. The study provides a comparative analysis of models with and without the third harmonic MMF, focusing on how reluctance torque contributes to the motor's electromagnetic torque, especially during fault events. The findings underscore the SynRM's capability to maintain performance by leveraging reluctance torque, even when multiple phases are lost.

Kotb B. et al. [43] presented a rewinding approach for constructing a five-phase motor using star-connected or combined star-pentagon winding configurations with prevailing three-phase stator frames. The study aimed to repurpose off-the-shelf three-phase stators for five-phase machine applications, thereby saving on drive costs and enhancing performance without entirely redesigning motor frames. The research analyzed two approaches for power adjustment—constant current with reduced voltage, and increased voltage with reduced current—and investigated their impact on operational speed and output power. The authors explored optimal slot/pole configurations for balanced five-phase connections. Using harmonic mapping through vector-space-decomposition, they compared rewound machine configurations with conventional five-phase machines, focusing on harmonic distribution and leakage inductance. The final comparison involved transient simulations using 2D Ansys Maxwell to evaluate performance between rewound combined star-pentagon winding and an optimally designed symmetrical five-phase machine with a 60-slot/4-pole configuration.

Namariq Abdulameer et al. [44] explored the expanding use of five-phase SynRMs as alternatives to permanent magnet and induction motors in electric drive systems, particularly within the automotive industry. The motivation for this shift includes the fluctuating costs of permanent magnets and SynRM's reliance on high reluctance torque without the need for rotor field excitation windings. This design allows for significant cost and material savings by avoiding magnetic materials in the rotor. The study focuses on a dynamic simulation of a five-phase SynRM powered by a five-phase voltage source inverter. The simulation is grounded in mathematical modeling, and pulses for inverter are generated by means of sinusoidal pulse width modulation (SPWM) technique. By employing the theory of reference frames, the authors simplified the five-phase SynRM voltage equations, effectively removing the angular dependency of inductances. Employing magnetic co-energy approach, they computed the torque and saw typical torque results, confirming the correctness of concept.

Tawfiq et al. [45] examined how rewinding a three-phase stator to incorporate a higher number of phases could enhance the performance of SynRMs. This modification led to better air gap flux distribution, improved winding factors, and an increase in the fundamental magneto-motive force while reducing harmonic distortions. By maintaining a fixed copper volume, they calculated the number of turns required for multiphase winding, resulting in an increase in torque density and efficiency of the SynRM. Finite element simulations verified these improvements, demonstrating that the torque density for rewound five-phase and seven-phase SynRMs was increased by 6.56% and 3.37%, respectively, compared to original three-phase machine under rated conditions. Additionally, torque ripple

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was decreased by 17.13% and 15.87% for the five-phase and seven-phase SynRMs, respectively. The study also found a significant increase in torque gain and efficiency at higher speeds. At 9000 rpm, the torque gain for the rewound machines rose by 23.48%, and the efficiency increased by 3%. Under open-circuit fault conditions, the rewound machine demonstrated a substantial advantage: with one phase open, it maintained 78% of the rated torque compared to only 43% in the three-phase machine, which also experienced a severe torque ripple of about 228%. Table 3 presents a comparison of various five-phase SynRMs, highlighting the techniques employed and their respective objectives.

Table 3: Comparison of Five-Phase Synchronous Reluctance Motor

Author's name	Technique/ Methodology	Objective	Performance	Pros	Cons
Arafat et al. [38]	Optimal Phase Advances, Fault-Tolerant Control (FTC), Phase Current Control	Maximize reluctance torque under fault conditions, optimize phase current control	-Maximal torque during faults -Maintains torque in open-phase fault -Reduced phase current	Redundant phases for fault tolerance, minimizes phase current, effective under fault conditions	Saturation effects considered in the algorithm, real-world applicability might need further optimization
Zakirul Islam et al. [39]	Fe-based Permanent Magnet, Optimized Rotor Geometry, Structural Stability Enhancements	Avoid rare-earth magnets while mitigating demagnetization and deformation risks in PMaSynRMs	-Comparable to rare-earth PMaSynRMs -Fault Tolerance is high - Improved with optimized rotor design	Cost-effective Fe-based design, avoids rare-earth dependencies, reliable in automotive applications	Potentially higher magnetic losses, further optimization may be needed for extreme applications
Sinan Oğuzhan et al. [40]	Stator Rewinding for Phase Change, Harmonic Analysis	Compare torque and harmonic characteristics of three-phase vs. five-phase SynRMs	- Achieved higher torque with five-phase -Torque Ripple Reduction is 15.4% lower - Reduced 3rd, 5th, and 7th harmonics	Higher output torque, reduced torque ripple, lower THD, efficient five-phase configuration	Increased complexity in stator winding, potential increase in manufacturing cost
Namariq Abdulameer et al. [41]	Five-Phase SynRM DTC with DTC-SVM	Achieve torque ripple reduction and precise speed control	- Torque Ripple is reduced to ±5 - Speed Control is high accuracy with reference speed tracking	Efficient and straightforward control method; smooth control in transient states	Limited experimental validation; no direct physical testing

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Umoh et al. [42]	Five-Phase SynRM with ACEBD Winding	Investigate fault tolerance in SynRM under multi-phase fault conditions	- Fault Tolerance is maintained performance under phase loss - Speed Drop is significant at four-phase loss	Effective analysis of reluctance torque contribution to electromagnetic torque	Complexity in fault restoration mechanisms
Kotb B. et al. [43]	Rewound Five-Phase Motor Design	Repurpose three-phase stators for five-phase machines	- Power Adjustment: Reduced voltage impact - Harmonic Balance: Maintained with optimal slot/pole	Cost-effective use of existing frames; Balanced performance	Potential performance limits due to lower inductance in some configurations
Namariq Abdulameer et al. [44]	SPWM for inverter control; Reference frame theory	Develop dynamic simulation for five-phase SynRM	Achieved typical torque results confirming model validity	Cost-effective due to no rotor magnetic materials	Complexity in control design for five-phase systems
Tawfiq et al. [45]	Rewinding technique for phase conversion; FEA	Evaluate the impact of rewinding a three-phase SynRM to five and seven phases	Increased torque density (5-phase: 6.56%, 7-phase: 3.37%); decreased torque ripple (5-phase: 17.13%, 7-phase: 15.87%); efficiency gain (5-phase: 0.3%)	Enhanced torque density and efficiency; fault-tolerant operation	Complexity of rewinding process

3.2.1. Summary

The survey on five-phase SynRMs explores various advancements, fault tolerance strategies, and design optimizations aimed at enhancing performance, reliability, and fault resilience. Research into five-phase SynRMs is driven by their potential applications in automotive and aerospace sectors, where high fault tolerance and efficient power management are critical. Studies demonstrate that five-phase configurations offer significant benefits over traditional three-phase systems, including higher torque output, reduced torque ripple, and better harmonic suppression. Researchers have developed methods to address fault tolerance in five-phase SynRMs under single-phase and multi-phase fault conditions. Techniques like optimized phase advance control for maximum torque retention, deadbeat current prediction algorithms, and DTC with specialized Space Vector Modulation have shown promising results in maintaining stability and operational performance during faults. Additionally, the use of alternative magnet materials, like ferrite (Fe), has been investigated to reduce dependence on rare-earth elements while managing challenges like demagnetization and structural integrity. Overall, this survey underscores the

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potential of five-phase SynRMs as robust and efficient alternatives to traditional motors, especially where fault tolerance, high efficiency, and material cost savings are prioritized. The findings support the continued development of five-phase SynRMs for high-demand applications, as they provide sustainable solutions in terms of performance, cost-effectiveness, and resilience to operational faults.

3.3. Survey based on Six-phase SynRMs

This section provides a six-phase SynRMs based on existing papers along with their techniques, objectives and the methodology mentioned.

Danilo Herrera et al. [46] designed a six-phase SynRM aimed at powertrain applications in electric vehicles (EVs). This SynRM was also configured to operate in "charger mode," providing high instantaneous power, power density, and efficiency. The motor's specifications are 60 kW, 9000 rpm, and 400 Nm torque. The SynRM powertrain's dual-mode charging capability was validated through electrical, thermal, and fault-tolerance testing on a dedicated test bench. Performance testing revealed that when connected to a three-phase grid, rotating the rotor provided optimal performance. For single-phase charging, a locked rotor position was found to be most efficient, eliminating the need for decoupling from the main EV axis. Additionally, the SynRM was tested with an Optimal Rotor Speed (ORS) algorithm, maintaining power quality with torque near zero. The design showed potential for additional features, such as grid stabilization or STATCOM functionality, as rotor inertia could compensate for voltage and frequency drops in the grid. This opens the possibility for active and reactive power control, as well as position and speed regulation.

Cezary et al, [47] developed a fault-tolerant six-phase SynRM by adapting stator from a general-purpose three-phase induction motor. This motor design included an extended Clarke transformation specifically tailored for a six-phase asymmetrical system, allowing for more accurate performance analysis. The study verified the design method using a field–circuit method to simulate electromagnetic behavior and assess motor performance. Comparative analysis with a classical three-phase SynRM showed an increase in torque output and reduced torque ripple in six-phase SynRM, proving it advantageous under normal and fault conditions. A significant focus of the study was on the motor's fault tolerance under inverter-fault conditions. Simulations revealed that only six-phase SynRM maintained operational stability and efficiency when an inverter fault occurred, demonstrating superior fault tolerance compared to its three-phase counterpart. Additionally, winding design calculations and preliminary prototype tests were performed, confirming the enhanced performance characteristics of the six-phase motor design.

Gelver et al [48], the control mechanisms of high-speed and low-speed six-phase SynRMs were analyzed. The research focused on two primary control configurations: (1) two galvanically isolated three-phase windings and (2) a single six-phase winding connected in a wye configuration. For both configurations, the authors presented a mathematical framework, mathematical models, and control system synthesis results. The study aimed to identify and resolve control challenges specific to each configuration, and practical experiments were performed to validate the proposed control approaches. The control algorithms proposed in this study were designed to ensure desired static and dynamic behavior of six-phase SynRMs. For the setup with two isolated three-phase windings, four control loops were necessary, focusing on the sum and difference of magnetizing and loading currents. In contrast, only two control loops were required when a common zero-point was shared between windings. The research revealed that the configuration with two isolated three-phase windings offers higher reliability, as a fault in one frequency converter does not result in a complete drive failure.

Chih-Hong et al. [49], a multi-objective optimization design was developed for a six-phase SynRM used in centrifugal compressors. This study introduced an innovative approach combining altered Bee Colony Optimization (BCO) method with Taguchi method, along with FEA. This two-step optimization aimed to maximize efficiency, power factor, and output torque while minimizing manufacturing costs and material weight, specifically focusing on stator and rotor regions. The methodology entailed a two-phase optimization process. In first phase, design goals focused on maximizing efficiency, power factor, and torque output, while second phase concentrated on minimizing the manufacturing costs by reducing stator iron and winding weights. The experimental results demonstrated the success of this optimization approach, resulting in higher efficiency, reduced torque ripple, and improved performance with lower magnetic saturation.

Gao et al. [50], an advanced fault-tolerant control (FTC) strategy for a six-phase permanent SynRMs is suggested, specifically addressing a double-Y phase-shifted (30°) configuration. The study introduces a dimension-reduction approach to model the six-phase motor under single-phase fault conditions, leveraging vector decoupling transformations. This allows for effective decoupling control and improved FTC performance. A deadbeat current prediction algorithm replaces the traditional PI regulator to enhance dynamic response, using motor current feedback and reference values for expected voltage prediction. To mitigate instability due to inductance parameter variations, the voltage prediction algorithm incorporates weighted coefficients to optimize direct-quadrature axis current equations, thereby stabilizing current oscillations and broadening stable operation under fault conditions. The paper concludes that this approach, validated by both simulation and experimentation, significantly reduces current oscillations and enhances system stability in fault scenarios. Table 4 presents a comparison of six-phase SynRMs proposed by various authors, along with their respective techniques and objectives.

Table 4: Comparison of six-phase Synchronous Reluctance Motors

Author's name	Technique/ methodology	Objective	Performance	Pros	Cons
Danilo Herrera et al. [46]	Six-phase SynRM with ORS algorithm; back-to-back full converter	Design and test six-phase SynRM for EV powertrain and charging	High performance in three-phase rotating rotor mode; efficient single-phase charging with locked rotor; potential for grid stabilization via STATCOM	High fault tolerance, dual-mode charging, high reliability and safety	Complexity in charger design
Cezary et al. [47]	Six-phase SynRM with extended Clarke transformation	Design and analyse a fault-tolerant six-phase SynRM	Increased torque, reduced torque ripple; maintained functionality in inverter-fault scenarios	High fault tolerance, reduced torque ripple, enhanced performance under faults	Increased complexity in design
Fyodor Gelver et al. [48]	Control of six-phase SynRM with isolated windings vs. wye configuration	To compare control configurations for SynRM operation	Ensured dynamic and static behavior across configurations; four control loops for isolated setup, two for wye setup	High reliability with isolated windings	Complexity in control requirements

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Chih-Hong et al. [49]	BCO and Taguchi methods, FEA	Optimize SynRM for centrifugal compressors with multi-objective design	Enhanced efficiency, power factor, and torque with minimized manufacturing cost and material weight	Effective cost and performance optimization	Complexity of combined methods
Gao et al.[50]	Improved DPC-FTC with Deadbeat Control	Fault-tolerant control in six-phase PMSM	Improved stability, reduced current oscillation	Enhanced fault tolerance, broad stable operation	High computational requirements

3.3.1. Summary

The development of six-phase SynRMs has advanced significantly, with a variety of designs tailored to specific applications and performance requirements. In electric vehicle powertrains, six-phase SynRMs were developed to operate in dual modes, providing efficient charging capabilities and the ability to support grid stabilization functions. Testing showed high power density and fault tolerance, allowing for effective operation under different charging configurations without additional decoupling mechanisms. Control mechanisms were further refined to manage both high-speed and low-speed SynRMs through two main configurations: galvanically isolated three-phase windings and single six-phase windings in a wye configuration. Each setup addressed unique control challenges, with isolated windings providing higher reliability as they could maintain operation despite individual converter faults. For centrifugal compressors, a multi-objective optimization strategy improved SynRM efficiency, power factor, and torque output while minimizing costs and material weight. This was achieved using an optimization approach that reduced stator iron and winding weights, leading to improved motor performance and reduced magnetic saturation. Finally, advanced fault-tolerant control strategies were proposed for six-phase SynRMs in double-Y phase-shifted configurations. A dimension-reduction technique enabled effective decoupling control, while a deadbeat current prediction algorithm stabilized current oscillations during fault conditions, enhancing system stability and fault resilience. Overall, these developments underscore the potential of six-phase SynRMs for various high-performance, fault-tolerant applications.

4. PERFORMANCE METRICS

The performance metrics used in the existing papers are explained in this section. These metrics were employed to evaluate the performance of multi-phase SynRMs.

Average Torque: This metric indicates the motor's output torque under various operating conditions. Improvements in torque are typically a result of optimized rotor structures, improved control strategies, and better phase configurations.

Efficiency: Efficiency improvements generally translate into better energy utilization and reduced losses. The comparison with standard motors shows efficiency gains in multi-phase configurations.

Power Factor: Power factor improvements signify better power quality and reduced reactive power in the system. A higher power factor indicates more efficient power usage.

Fault Tolerance: This refers to the motor's ability to continue operating efficiently in the event of a fault, such as phase loss. The results show significant fault tolerance, where torque output remains functional even under fault conditions.

Harmonic Content: Reduced harmonic content indicates improved motor performance, lower mechanical stress, and smoother operation. The reduction in torque ripple and harmonic current content is particularly significant in improving overall motor performance.

Phase Current Reduction: This metric measures the reduction in current needed to produce the same torque output. A reduction in phase current typically leads to less energy loss and better overall efficiency.

Synchronous Speed Drop: This refers to a decrease in the motor's speed from its synchronous (design) speed. A small drop is manageable, but a severe drop may indicate operational faults affecting performance.

Inverter Control: Optimized inverter control ensures stable operation and efficient power conversion for the SynRM.

Torque expression: The general torque expression of a multi-phase SynRM can be derived based on the reluctance torque principle. For a multi-phase SynRM, electromagnetic torque T_e is typically described as:

$$T_e = \frac{1}{2}\left(L_d - L_q\right)I^2 \sin(2\theta) \tag{5}$$

Saliency Ratio: is the proportion of direct-axis inductance (L_d) to the quadrature-axis inductance (L_q). It is a key parameter in SynRMs, as it determines the ability of the motor to produce reluctance torque. The saliency ratio S is given by:

$$S = \frac{L_d}{L_q} \tag{6}$$

5. SUMMARY AND DISCUSSION

This review highlights the strong potential of multi-phase SynRMs as high-performance alternatives to traditional three-phase machines, offering significant advancements in fault tolerance, reliability, efficiency, and torque control. The exploration of configurations from five-phase to six-phase systems demonstrates that multi-phase SynRMs excel in torque output and fault resilience, with reduced torque ripple and smoother operation, particularly in six-phase configurations. These improvements lead to reduced mechanical wear and extended component lifespan, which is crucial for applications requiring stable performance under varying conditions. Multi-phase designs offer enhanced fault tolerance, with the ability to maintain operation despite phase loss or inverter faults, making them ideal for critical systems where downtime is costly. The addition of isolated windings further improves fault resilience but introduces greater control complexity. Additionally, these systems exhibit improved energy efficiency and power factor, reducing energy losses and optimizing the use of input power, which makes them suitable for energy-sensitive applications. The review lies in its comprehensive evaluation of multi-phase SynRM configurations, focusing on their torque, fault resilience, and efficiency improvements. The paper uniquely synthesizes findings from various configurations, shedding light on the benefits of multi-phase designs in reducing torque ripple and enhancing fault tolerance. It also highlights the practical advantages of these motors, particularly in minimizing maintenance needs while meeting high operational requirements. By combining advanced control techniques and multi-phase configurations, the review underscores the potential of these motors as robust, energy-efficient solutions capable of outperforming traditional three-phase systems in demanding applications.

6. CONCLUSION

In conclusion, this review emphasizes the important potential of multi-phase SynRMs as an advanced alternative to traditional motors, particularly for applications demanding high efficiency, fault tolerance, and reliability. Through the examination of various configurations, including five-phase and six-phase systems, the review demonstrates substantial improvements in key performance metrics such as torque output, fault resilience, and energy efficiency. The inherent advantages of multi-phase SynRMs, such as reduced torque ripple, enhanced operational stability, and the ability to maintain performance during faults, make them an attractive choice for critical applications. Furthermore, advancements in control strategies and optimization for power factor and efficiency further solidify their suitability for energy-sensitive and high-performance environments. Overall, multi-phase SynRMs offer a promising solution for enhancing the robustness, efficiency, and longevity of motor-driven systems, positioning them as a key technology in industries where reliable and efficient performance is paramount. While multi-phase SynRMs offer substantial performance benefits, their adoption is still limited by higher manufacturing costs compared to traditional motors. Future work will prioritize reducing high torque ripple and improving power factor. These efforts aim to enhance the overall performance and efficiency of synchronous reluctance motors, making them more viable for a broader range of industrial applications. By addressing torque ripple and power factor challenges, future research can contribute to smoother motor operation and more effective power utilization.

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