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Review Article

Comprehensive Overview of Modern Controllers for Synchronous Reluctance Motor

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Synchronous reluctance motor drives (SynRMs) are the best promising machines utilized in modern industries and electric vehicles, according to the current study. Research on new SynRMs drive systems has increased as a result. This review article disseminates the most recent developments in these technologies' design, modeling, and controlling. First, a simple comparison between the main motor technologies and SynRMs is made. To aid researchers in selecting the appropriate motor controller for their motor drive systems, the most common motor control approaches are examined and classed.

1. Introduction

Special electric motors known as synchronous reluctance motors (SynRM) use the principle of magnetic reluctance to produce torque. These motors are superior to other types of motors in a variety of ways, including high efficiency and robustness. However, using a specific controller is required to operate a SynRM. The purpose of synchronous reluctance motor controllers is to deliver accurate control over the rotor position and speed of a SynRM [1–3]. They frequently make use of sensorless control techniques such as field-oriented control (FOC) to achieve high accuracy and dynamic performance. Some controllers employ advanced control algorithms such as space vector modulation (SVM) and direct torque control (DTC) to increase performance [4–10].

For this study, we compiled the most significant research publications in the area of SynRM. An orderly qualitative assessment of the evidence about SynRM drive systems is provided as follows: the most promising motor technology as well as potential alternatives is examined in the second part. In addition, it investigates the applications and possibilities and contrasts the motors' performance in terms of price and eco-friendly considerations. The possibilities for SynRM modeling are examined in Section 3, along with each model's applications, advantages, and disadvantages. The control methodologies for various machines are discussed in Section 4. Future direction and conclusions are listed in Sections 5 and 6.

2. Need for Synchronous Reluctance Motor

For several reasons, SynRMs are suitable in industrial and commercial applications, [1, 11–14] including

(I) SynRMs are extremely efficient because of their simple rotor structure and lack of rotor windings, which reduces power losses in the motor.

(II) Low Cost: Because SynRMs have a simple rotor structure and do not require rotor windings, the motor is less expensive.

(III) SynRMs have a high-power density due to their fundamental rotor structure, allowing them to produce significant torque at high speeds.

(IV) Less Noise: Because of its simple rotor structure and absence of rotor windings, SynRMs produce less noise, making them excellent for low-noise applications.

(V) Robustness: SynRMs are suitable for industrial applications since they are robust to changes in motor properties as well as external disturbances.

(VI) SynRMs are perfect for applications that need significant torque at low speeds since they have a high torque.

(VII) Pumps, fans, compressors, conveyors, and other industrial and commercial applications, among others, can all use SynRMs.

(VIII) SynRMs provide a great degree of control flexibility, making it possible to boost performance and energy efficiency by employing current control algorithms such as FOC and (DTC) [9, 15].

Table 1 summarizes the types, advantages, disadvantages, and main applications of dominant motors, and in most of the industrial applications, induction motors are used, which can be effectively replaced using SynRM [1, 2, 15–25].

3. AC Motor Classifications

AC motor drives are often employed in a widespread range of industrial and consumer applications [26]. The motor type used is determined by the individual application requirements such as power output, efficiency, and dependability. Based on their design and working principles, AC motors are categorized into numerous categories. Here are some examples of popular AC motor classifications:

(I) Synchronous AC motors: The rotor of this motor rotates at the same speed as the stator's revolving magnetic field. High-power applications such as compressors, pumps, and generators require this sort of motor [27–30].

(II) Induction AC motors: These are the most popular form of AC motors, often known as asynchronous motors. They work based on electromagnetic induction, and the rotor speed is always somewhat variable [21, 31].

(III) Single-phase AC motors: These motors are employed in low-power appliances and machinery. They have only one winding (for starting purposes, auxiliary windings are used), and the magnetic field direction changes in time with the alternating current.

(IV) Three-phase AC motors: These motors, which have three windings in the stator, are employed in industrial applications. They are more powerful and efficient than single-phase motors [26].

(V) Brushless alternating current motors: These motors use a permanent magnet rotor and an electronic controller which controls the stator current of the stator windings [32, 33]. They are utilized in robots, electric cars, and HVAC systems, among other things.

(VI) Universal AC motors: Used in various applications such as power tools and general fans and these motors can run on either AC or DC power.

(VII) Stepper AC motors: These motors are mostly used in precision applications, such as robotics and 3D printers. They move in small steps, and the speed and direction of rotation can be controlled with precision.

3.1. Induction Motor Classification. Induction motors are one of the types of AC motor that operates based on the principle of electromagnetic induction. They can be classified into different types based on their construction, rotor type, and method of starting. Here are some common induction motor classifications:

(1) Squirrel cage induction motor (SCIM): This is the one of the commonly used induction motors. It possesses rotor with conductive bars that are permanently short-circuited at the ends, resembling a squirrel cage. When the stator windings are energized, it produces a rotating magnetic field that induces rotor currents in the bars, causing it to rotate [1–3, 34].

(2) Wound rotor induction motor (WRIM): This type of motor possesses windings in the rotor which are connected to slip rings. The slip rings are used to connect external resistors which can be added to the rotor circuit. This external resistance will can control the starting torque and speed of the motor [21, 35].

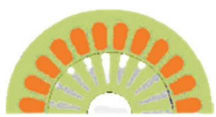
(3) Double cage induction motor: This type of motor will have two sets of rotor bars, one of them in the outer periphery and another in the inner core. This design provides higher starting torque and better efficiency compared to the single-cage motor [31, 36–38].

(4) Synchronous induction motor: This type of motor combines the features of both synchronous and induction motors. It has a rotor with salient poles, which align with the rotating magnetic field in the stator, resulting in synchronous operation. However, the rotor also has conductive bars to induce currents, allowing it to start as an induction motor [37, 38].

(5) Single-phase induction motor: These motors have a stator with single-phase winding, making them suitable for small appliances and machines. They use auxiliary windings or capacitors to create a revolving magnetic field that induces currents in the rotor.

(6) Variable frequency drive (VFD) induction motor: These motors can operate at different speeds and torque levels by varying the frequency of the power supplied to the motor. VFDs are used in applications such as HVAC systems, pumps, and conveyor belts to improve energy efficiency and control motor speed [37, 38].

Table 1: Performance analysis of different electrical motors.

Motor	Rotor types	Advantages	Disadvantages	Main applications
Induction motor [1, 16, 17] 	(i) Rugged squirrel cage rotor (ii) Wounded rotor	(i) High inertia (ii) Wide range of power ratings (iii) High torque capability (iv) Flux ripple due to magnetic saturation (v) Good speed regulation (vi) Robust and simple mechanical structure (vii) Cost-effectiveness (viii) High efficiency	(i) Moderate torque ripple (ii) Moderate speed ripple (iii) Moderate total harmonic distortion (THD) (iv) Moderate weight and volume/weight ratio	Industrial applications, pumps, fans, conveyors, etc.
Synchronous motors [2] 	(i) Wounded rotor	(i) Wide range of power ratings (ii) High torque capability (iii) Low-torque ripple (iv) Low-speed ripple (v) Low total harmonic distortion (THD) (vi) Excellent speed regulation	(i) Relatively higher cost compared to induction motors	Robotics, automation, and high-performance applications
SynRM [18–22] 	(i) Skewed rotor (ii) Rotor with asymmetric flux barrier	(i) Reliable (ii) High dynamic response (iii) High-speed control	(i) High torque ripple (ii) Low-power factor	Industrial applications such as pumps, fans, traction, etc.
PMSYNRM [15] 	(i) Skewed rotor (ii) Rotor with asymmetric flux barrier (iii) PM materials	(i) Reliable (ii) High dynamic response (iii) Very high performance	(i) The manufacturing process is very hard (ii) The installation process is quite difficult	Traction applications

3.2. About Synchronous Reluctance Motor. SynRM, as the name implies, generates reluctance torque by varying magnetic reluctance, also known as magnetic resistance. The magnetic flux flows into the magnetic resistance with the lowest value. As a result, the flux produced by the stator flows into the rotor with the lowest magnetic resistance. As a result, if the rotor is not aligned with the flux, the reluctance torque will cause the rotor to revolve in the direction with the least magnetic resistance [22, 36, 39–44]. In this sense, the magnetomotive force (MMF) is caused by the saliency ratio, and the reluctance torque spins the rotor. SynRM's rotor design, which lacks bars and magnets, results in chilly rotor operation. As a result, SynRM offers commendable loadability, especially at lower speeds. This motor may be loaded up to 2.5 times its nominal torque [18–20, 23, 35, 45].

Torque density was the main area of interest for SynRMs in the past. However, more recent research has shown that these motors are a highly effective option for the industrial sector [46]. The lack of bars in the rotor, which lowers iron loss and promotes proper motor performance, is one of the main elements enhancing their efficiency [45]. The SynRM drive's payback period is exceptionally short due to its efficiency advantage, making it a practical and sensible alternative to conventional induction motors (IM). For a 37 kW, 1500 rpm SynRM with 8000 yearly running hours, the projected payback time for an IE4 SynRM drive, as opposed to an IE2 drive, is expected to be merely 1.6 years [46]. International Energy-Efficiency (IE) standards included in IEC 60034-30 Parts 1, 2, and 3 determine the efficiency class of electric motors [47]. Better IE ratings imply better motor efficiency, and these codes represent the necessary degree of efficiency. The SynRM offers the even more efficient IE5 efficiency class (Super-Premium class), whereas the European Union nations have made the IE3 efficiency class (Premium class) required since 2015 [47].

3.3. Modeling SynRM. The process of modeling a SynRM involves simulating the motor's activity mathematically. For the model to accurately imitate a SynRM, it has to include high precision and linearity. The FEA-based model is frequently utilized for accurate and trustworthy motor simulations. For online applications like control systems, FEA is inconvenient and time-consuming due to its large computational weight. Therefore, FEA is more suited for design and optimization goals in different electrical devices.

Researchers frequently use analytical models instead of FEA for various objectives to overcome this constraint. As an illustration, the inductance values of the winding function model, a typical analytical model used for SynRM, are contrasted with those produced through FEA in References [48–50]. In addition, the SynRM d, q model is another analytical strategy that has been extensively researched in several research papers. In-depth analytical models for permanent magnet synchronous reluctance motors (PMSynRM) have also been created by researchers. In Reference [51, 52], Armando et al. constructed and verified a straightforward model that examines the influence of cross-saturation on rotor position estimation while ignoring cross-saturation effects. In Reference [53], a new method is used to get currents and flux connections in both SynRM and interior permanent magnet synchronous motors (IPM). This method uses radial basis function neural networks. It is said that the connection between these numbers can create magnetic models effectively.

3.4. Summary of Modeling SynRM. The d, q model of SynRM is examined in several research works, and it is determined to be the most appropriate modeling for practical purposes.

4. Control Methodologies

Figure 1 shows the control methodologies for SynRMs, and it is given as follows.

4.1. Conventional P, PI, and PID Controllers. To obtain accurate control of the motor's states, conventional P, PI, and PID controllers can be employed for synchronous reluctance motors [5]. These controllers employ feedback control to modify control inputs such as voltage and current depending on the error signals between the motor's actual and desired states. The P controller adjusts the control input based on the error signal using proportional gain. To reduce steady-state error and enhance overshoot time, the PI controller adds an integral term to the proportional gain. The PID controller augments the PI controller with a derivative term to increase stability and prevent overshoot and undershooting [58, 59].

Traditional controllers have several benefits, including simple design, robustness against disturbances, and ease of adjustment.

4.2. FOC for SynRM. The rotor position and speed of a SynRM are routinely managed using the sensorless control approach known as FOC [10, 53]. Using a mathematical model of the motor, it determines the stator current and voltage required to give the specified torque and speed [15, 54–57]. FOC is especially well liked in sectors such as steel and mining where efficiency and steady-state reaction are valued more highly than transient response. To provide practical control, this approach operates in the d, q reference frame and treats the motor as a DC motor.

Direct field-oriented control (DFOC) and indirect field-oriented control (IFOC) are the two basic strategies for controlling the decoupling currents in the synchronous reference frame. While in IFOC, the flux angle is generated from the detected rotor position utilizing a mounted shaft encoder, and in DFOC, the rotor flux angle is determined by estimated flux.

In conclusion, the benefits of FOC include

(i) High performance is there during the steady state
(ii) Precise control of the current is possible
(iii) Compatible with a variety of AC motors
(iv) Implementing a modulation system is simple
(v) Constant frequency of switching is possible

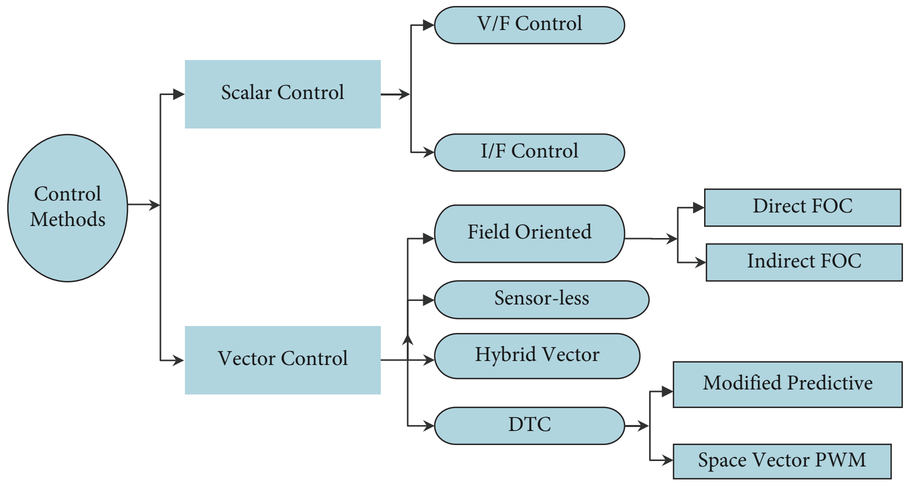


Figure 1: Various most commonly used control methodologies for SynRM [10, 15, 47, 53–57].

However, the FOC control approach is somewhat sophisticated, the controller design would need a full understanding of the motor dynamics, the system is relatively expensive, and the current control and modulation approach imposes a substantial computational burden on the CPU.

4.3. DTC for SynRM. Boldea et al. made the first attempt to implement DTC on SynRM in 1991, which has now piqued the market's attention as shown in Figure 2. This allure is due to its inherent characteristics, which are as follows:

(i) The absence of a PWM signal-generating module
(ii) The current control mode is simple
(iii) Direct torque control enables quick reactions and great dynamics
(iv) High robust control

Direct control of the motor's instantaneous torque and stator flux linkage is used in the DTC approach, which eliminates the requirement for coordinate transformation. Based on input signals, the switching table, a lookup table, picks predetermined combinations of switching sequences. These inputs include the indications of the stator flux and torque errors, as well as the stator flux sector. DTC enables fast and accurate torque control, which improves performance and boosts energy efficiency. It is extremely suitable for industrial applications due to its resistance to changes in motor characteristics and external disturbances. DTC has a very simple control structure, making it easy to use and understand.

However, the DTC control mechanism is somewhat intricate, the controller design may need a full understanding of motor dynamics, and the system is quite expensive. The lack of a current controller in the DTC block diagram results in large torque ripples. Researchers have investigated numerous solutions to this problem. When paired with DTC, one viable solution includes employing multiple inverters, as illustrated in Reference [9]. The overmodulation approach for SynRM DTC is another solution proposed in Reference [60]. This solution keeps DTC's simplicity while eliminating torque ripples and maintaining a steady switching frequency. Furthermore, a reference flux-vector calculator (RFVC) has been devised and used in Reference [61] for IPM to prevent high torque ripples in DTC. Through space vector modulation (SVM), RFVC substitutes the two hysteresis controllers and the torque PI controllers, achieving constant switching frequency. This effectively eliminates the disadvantage of the variable switching frequency.

4.4. Sensorless Vector Control (SVC) for SynRM. SynRM employs the reluctance torque generated by the stator and rotor to achieve great efficiency and power density. SVC is a technology for regulating SynRMs that does not require sensors on the rotor and results in a trustworthy and cost-effective control system as shown in Figure 3.

SVC is based on the idea that stator currents and voltages may be utilized to calculate rotor position and speed [62]. To estimate, either a model-based approach or an observer is utilized. The observer-based technique predicts rotor position and speed from stator currents and voltages using a mathematical model of the motor [63]. The model-based method estimates rotor position and speed from stator currents and voltages using a mathematical model of the motor and a parameter identification tool.

The primary advantage of SVC is the elimination of rotor position sensors, which decreases the cost and enhances the reliability of the control system [63]. Because of its excellent performance and robustness, SVC is well suited for high-speed and high-power applications.

The first step in creating SVC is deciding whether to use an observer or a model-based method [62]. The most common algorithms are the extended Kalman filter (EKF), the unscented Kalman filter (UKF), the Luenberger observer, and the sliding mode observer (SMO) [63]. The algorithm of choice is determined by the requirements of the specific application, as well as the benefits and drawbacks of each technique.

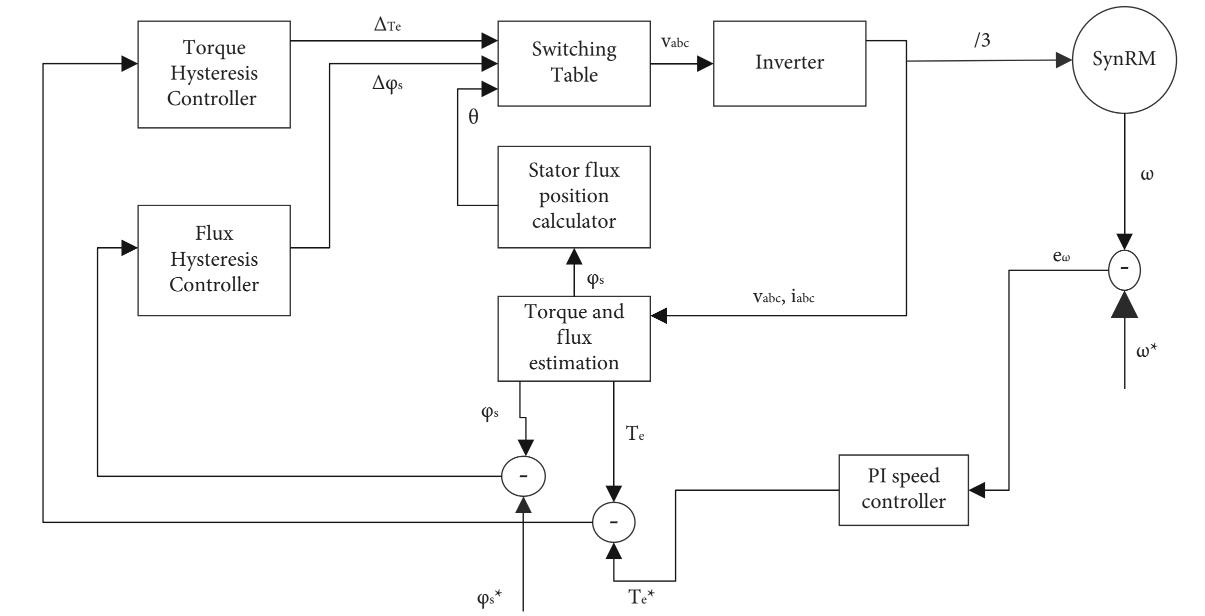


Figure 2: DTC for SynRM [9, 47, 60].

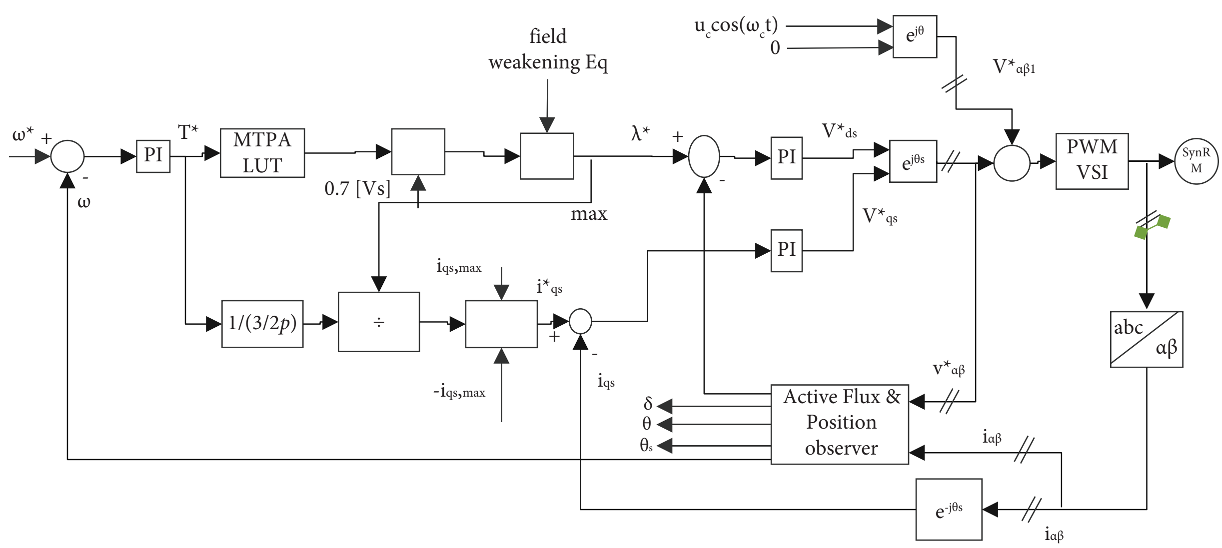


Figure 3: Block diagram for sensorless control for SynRM [47, 62].

After deciding on an observer or model-based method, the next step is to identify the motor parameters. The identification is performed using the stator voltages and currents, as well as the expected rotor position and speed. The least squares (LS), recursive least squares (RLS), and maximum likelihood (ML) identification methods are the most commonly used. Accurate initial estimates of the parameters, as well as a proper identification approach, are critical to the iterative identification process.

The final stage of SVC implementation is the control of stator currents and voltages. To carry out the control, either a model-based controller or a PI controller is employed [63]. The PI controller manages the stator currents and voltages based on the expected rotor position and speed. The model-based controller controls the stator currents and voltages by employing a mathematical model of the motor as well as the estimated rotor position and speed [62].

The SVC of SynRM, which has been fully explored in the literature, has been employed in several high-performance and high-power applications, including electric automobiles, wind turbines, and rapid industrial motors. The SVC has shown to be a successful, trustworthy, and cost-effective control mechanism for SynRMs, and it is expected to be used in more scenarios in the future.

The fundamental disadvantage of SVC is that it is dependent on the validity of the motor's mathematical model and the technique for detecting its characteristics, which can be influenced by temperature and aging changes in the motor parameters. Another disadvantage of SVC is its vulnerability to measurement noise and disturbances in

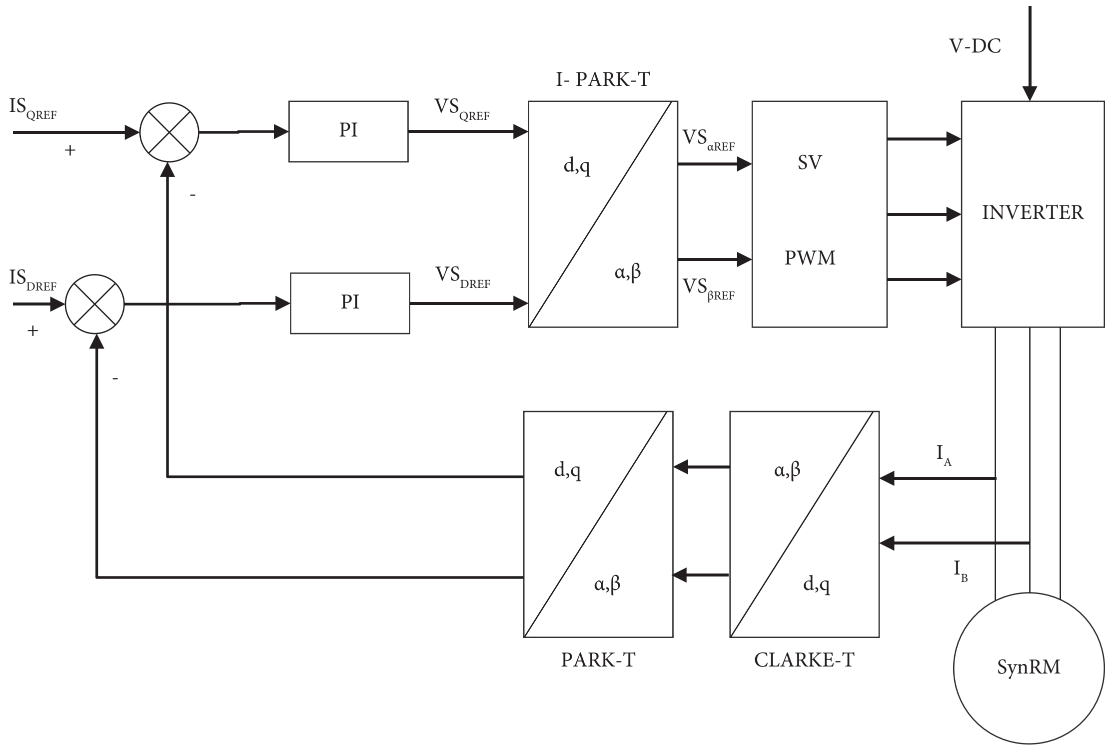


Figure 4: Block diagram for SVM for SynRM [31, 47].

stator currents and voltages. This sensitivity can lead to estimation errors and a reduction in control performance.

To summarise, sensorless vector control is an excellent approach for regulating synchronous reluctance motors. It eliminates the need for rotor position sensors, lowering costs and increasing the dependability of the control system. Its exceptional performance and robustness make it ideal for high-speed and high-power applications.

4.5. Space Vector Modulation (SVM) for SynRM. The stator current of a SynRM is regulated using the pulse width modulation (PWM) technique known as SVM as shown in Figure 4 [31]. A mathematical model of the motor is used to find the ideal PWM signal that will provide the necessary torque and speed [40].

The basic principle behind SVM is to manage the stator current to get the motor to produce the proper amount of torque. This requires determining the PWM signal that will provide the required torque and speed. SVM features a closed-loop control system composed of an inner current loop for stator current regulation and a feedback loop for torque measurement.

SVM reduces harmonic distortion in the stator current, improving power factor and decreasing motor losses. Control structure that is simple to understand and implement: SVM features a control structure that is simple to understand and implement [36]. However, the SVM control technique is somewhat sophisticated, the controller design may need a detailed understanding of motor dynamics, and the device is relatively expensive. It is also worth noting that SVM may not be adequate on its own to regulate the motor's speed and that other control algorithms may be required [36]. Overall, space vector modulation for SynRM provides an efficient and effective means of controlling the motor, delivering improved performance, reduced losses, and smoother operation for various industrial applications.

4.6. The Modified Predictive Direct Torque Control (MPDTC) for SynRM. The MPDTC control technology manages the operation of a SynRM as depicted in Figure 5. It is a complex control approach that combines the benefits of DTC with predictive control to improve the effectiveness and efficiency of the motor [64].

The basic idea of MPDTC is to use a predictive model to foresee the motor's future torque and speed and then use that knowledge to immediately modify the stator current. MPDTC is a closed-loop control system that uses an inner current loop to regulate stator current and a feedback loop to measure torque and speed [27, 64].

MPDTC has several advantages over prior SynRM control techniques, including

Enhancements to performance and energy efficiency: MPDTC's ability to adjust torque quickly and precisely contributes to improved performance and energy efficiency. MPDTC is suited for industrial applications due to its resistance to changes in motor settings and external disturbances. MPDTC's capacity to control nonlinearity makes it an excellent choice for systems with complex dynamics.

MPDTC is well suited for systems with uncertain or imprecise information because it can manage uncertainty and imprecise information. However, because MPDTC is so complex, a thorough understanding of predictive control, direct torque control, and motor dynamics may be required

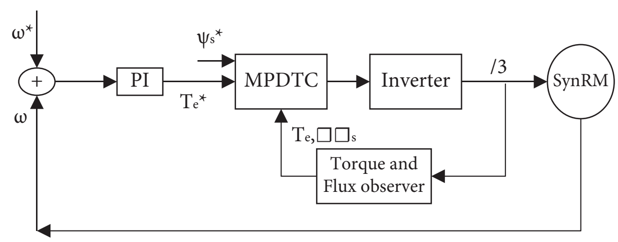


FIGURE 5: Block diagram for MPDTC for SynRM [47, 64].

for controller design. Furthermore, calibrating the MPDTC controller may be difficult and need a trial-and-error process [47, 65].

4.7. Model Predictive Control (MPC) for SynRM. MPC, a complex control system, is used to govern the performance of a SynRM as shown in Figure 6. It uses mathematics to predict the motor's future behavior and changes the control inputs to achieve the desired performance [63, 66–71].

In the case of a SynRM, the MPC controller anticipates future rotor position, speed, and torque and uses this information to change the stator current in real time. The controller constantly analyses the rotor position and speed and changes the stator current to eliminate errors and move the system closer to the optimal operating point [5].

MPC has a variety of advantages over traditional SynRM control approaches, including

MPC improves performance and energy economy by rapidly and precisely regulating the rotor's position, speed, and torque.

MPC can manage nonlinear systems, making it a strong fit for systems with complex dynamics.

Managing ambiguity: MPC is capable of managing uncertainty and imprecise information, making it an excellent fit for systems with these sorts of input.

MPC is well suited for systems with changing conditions since it is adaptive and can alter with the system's dynamics.

MPC can manage both control input and system state limits, making it an excellent choice for systems with operational constraints.

MPC is a rather challenging control approach; therefore, a thorough understanding of optimization, predictive control, and motor dynamics may be required for controller design. Furthermore, fine-tuning the MPC controller may be difficult and requires a trial-and-error approach.

4.8. Adaptive Recurrent Fuzzy Neural Network (ARFNN) for SynRM. An ARFNN combines the properties of adaptive control, recurrent neural networks, and fuzzy logic to govern the operation of a SynRM [57, 72].

The basic idea behind an ARFNN is to use a fuzzy logic system to mimic the nonlinear dynamics of the SynRM, followed by a recurrent neural network to continually modify the parameters of the fuzzy logic system. The ARFNN also has an inner current loop that regulates the stator current and a feedback loop that measures the rotor position, speed, and torque.

ARFNN has a variety of advantages over other SynRM control techniques, including

ARFNN's capacity to control nonlinearity makes it an excellent fit for systems with intricate dynamics. Because it can manage uncertainty and imprecise information, ARFNN is well suited for systems with uncertain or imprecise information.

Adaptability: Because it can respond to changes in system dynamics, ARFNN is well suited for systems with changing situations.

ARFNN is well suited for systems with operational constraints because it can manage control input and system state limits. Because of its resistance to changes in motor settings and outside disturbances, ARFNN is well suited for industrial applications.

However, because ARFNN is a very advanced control approach, the controller design may need a thorough understanding of adaptive control, recurrent neural networks, fuzzy logic, and motor dynamics. ARFNN controller tuning may likewise be difficult, necessitating a trial-and-error approach.

4.9. Fuzzy Controller for SynRM. A fuzzy controller is a type of control system that uses fuzzy logic to manage the operation of a SynRM [57, 73]. Fuzzy logic is a mathematical method that allows for the logical representation of ambiguous or erroneous information. In a fuzzy controller for a SynRM, fuzzy sets are generated from input variables such as rotor position, speed, and torque. These fuzzy sets are then used to select the appropriate stator current, the output variable.

The fuzzy controller finds the appropriate stator current for a given set of input variables by applying a set of rules based on the designer's knowledge or system data [57]. Because the rules are expressed in plain English, the control system is straightforward to understand and modify.

Fuzzy controllers provide several advantages over other SynRM control approaches, including

Fuzzy controllers are resistant to changes in motor properties as well as external disturbances, making them appropriate for industrial applications. Simple to understand and modify: fuzzy controllers convey control rules in plain language, making the control system simple to understand and modify. Fuzzy controllers' ability to handle ambiguity and imprecise logic-based information makes them appropriate for systems containing such information. However, because fuzzy controllers are rather complicated, creating and implementing them necessitate a strong understanding of fuzzy logic. Furthermore, tweaking the fuzzy controller may be difficult and need a trial-and-error process. Various types of membership functions based on fuzzy logic control for ac drive are reported [34].

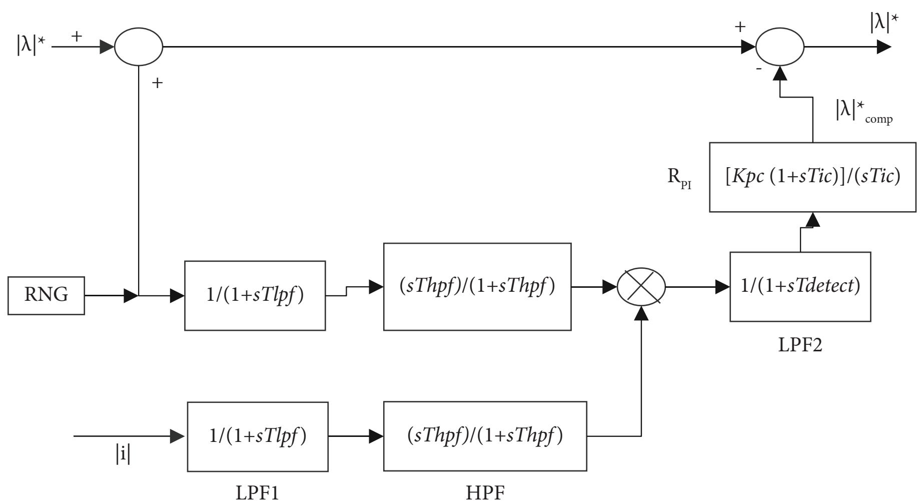


Figure 6: Block diagram of MTPA detector schematic for SynRM [47, 63, 66–70].

4.10. Sliding Mode Controller (SMC) for SynRM. A sliding mode algorithm in a sliding mode controller, or SMC, controls the functioning of a SynRM [74]. The primary idea underlying SMC is to force the system to work on the chosen sliding surface by using a set of nonlinear equations to describe it. The sliding surface represents the system's optimal working position, and the controller uses a switching mechanism to ensure that it stays there. In the case of a SynRM, the sliding surface is determined by the planned rotor position and speed and the controller uses the stator current as the control input. The controller constantly measures the rotor position and speed and changes the stator current to keep the system on the sliding surface [74].

SMC outperforms alternative SynRM control approaches in several areas, including the following:

SMC is appropriate for industrial applications because of its resistance to changes in motor properties and external disturbances. SMC ensures the system's overall stability, ensuring that it will always converge to the desired operating point. Unaffected by parameter variations: because SMC is unaffected by parameter variations, it is an excellent fit for systems that employ ambiguous or erroneous data. However, due to the intricacy of the sliding mode algorithm, creating and implementing SMC controllers necessitate a full understanding of it. Furthermore, tweaking the SMC controller can be difficult and may involve a trial-and-error approach [74]. The fuzzy logic control plus SMC for converters for motor application is well addressed [75].

4.11. Artificial Neural Network (ANN) Controller for SynRM. An ANN controller is a type of control system that uses a neural network algorithm to manage the operation of a synchronous reluctance motor (SynRM) and brushless DC BLDC motor [33, 73, 76]. ANNs, which are used to approximate complex nonlinear systems, simulate the structure and operation of biological brain networks.

In the case of a SynRM, an input-output dataset is utilized to train an ANN controller. The rotor position, speed, and torque are the inputs to this dataset, while the stator current is the output. Once trained, the network can predict the stator current for a given set of input variables. The ANN controller constantly adjusts the stator current in response to the neural network output, while the rotor position and speed are continuously monitored. ANN controllers provide a variety of advantages over other SynRM control techniques, including

Handling nonlinearity: ANNs can handle nonlinear systems, making them appropriate for systems with complex dynamics.

Handling ambiguity: Because ANNs can handle ambiguity and erroneous information, they are an excellent fit for systems with ambiguous or wrong data.

Adaptability: Because ANNs can respond to changes in the system's dynamics, they are well suited for systems with changing situations. However, because of the complexity of neural networks, building and implementing ANN controllers necessitate extensive knowledge of neural networks. Furthermore, a robust dataset is required to train the network since fine-tuning the ANN controller may be difficult and may necessitate a trial-and-error procedure.

4.11.1. Controller Summary

(i) FOC and DTC are popular control techniques for SynRM, each offering unique advantages in terms of efficiency and dynamic performance.

(ii) SVC utilizes advanced algorithms to estimate the rotor position and flux information, enabling precise control without the need for physical sensors, reducing system complexity and cost.

(iii) SVM optimizes the voltage applied to the motor's stator, achieving reduced switching losses and improved motor efficiency, making it suitable for various motor types, including SynRM.

Table 2: Comprehensive analysis of different motor controls.

	DTC [47]	FOC [53]	SVC [62, 77]	SVM [47]	MPDTC [64]	MPC [71, 78]
Coordinates reference frame	α,β reference frame	d-q reference frame	d-q reference frame	Space vector reference frame	α,β reference frame	d-q reference frame
Principle	Stationary voltage equations	Rotor reference frame equation	Rotor flux and position estimators	Space vector reference frame	Stationary voltage equations	Rotor reference frame equation
Controlled variables	Torque and stator flux	Stator currents (i_d, i_q) and stator voltage (v_d, v_q)	Switching states of the inverter	Rotor position and rotor flux	Torque and stator flux	Stator currents (i_d, i_q) and stator voltage (v_d, v_q)
Rotor position measurement	Not required	Required	Not required	Not required	Not required	Not required
Current control	Without	With	With	With	Without	With
Coordinate transformations	Not required	Required	Required	Required	Not required	Required
Modulator	Not required	Required	Required	Required	Not required	Not required
Switching frequency	Variable	Constant	Variable	Constant	Variable	Variable
Controllers	Hysteresis	Proportional integral controller	Model-based algorithms	Proportional integral controller	Cost function optimization	Cost function optimization
Implementation cost	Lower cost compared to FOC	Moderate	Moderate	Moderate	Costly	Costly
Applications	Electric traction systems	Robotics and automation systems	Electric motor drives in industries	Electric motor drives in renewable energy systems	High-performance robotics and automation systems	Electric vehicle (EV) and hybrid electric vehicle (HEV) applications

(iv) MPDTC is an enhanced version of DTC, incorporating predictive algorithms to achieve improved torque and flux control, lower torque ripples, and enhanced efficiency.

(v) MPC, ARFNN, SMC, and ANN controllers are advanced control techniques applied to SynRM, each utilizing unique methodologies to enhance motor performance and achieve precise control in various operating conditions.

An overview of the main vector control methods regarding the control method structure is presented in Table 2.

5. Future Scope

An evaluation of a high-performance controller for variable speed drive (VSD)-fed SynRMs considered several crucial factors. These factors include the controller's robustness against parameter variation and external disturbances, the level of torque ripples affecting average torque, and the drive's efficiency over a wide speed range. The SynRM's anisotropic rotor structure leads to electrical parameter variability and torque ripple, which can degrade drive system performance. Ignoring system mismatch contradicts efficiency, productivity, and environmental and energy concerns.

To address parameter variation issues, developing a robust control algorithm is essential as it directly impacts machine controllability. Investigating and modifying the controller's robustness against external disturbances, such as tough load torques, is vital. The study highlights that high torque ripples are a significant concern in SynRM drive systems, leading to pulsation, vibration, decreased efficiency, and increased noise in the environment. Optimizing control techniques and proposals to decrease torque ripples will improve the performance of SynRMs.

Designing a control method that covers the entire motor speed range with desired performance poses challenges due to theoretical and practical constraints. With the extensive potential applications of SynRMs with VSDs, the development of more intelligent control techniques is projected to preserve their efficiency over a wide speed range, encompassing transient and steady-state operation. Approaches from other motor technologies can be adapted for SynRM with modifications, suggesting potential directions for future research.

6. Conclusion

There is no doubt on the importance of motor-drive systems in commercial and residential applications. This review article demonstrated the market debut of the cutting-edge SynRM drive package, which is more efficient than the IM drive package and potentially less expensive. Furthermore, SynRMs' drive provides comparable performance to PMSM drive at a lower cost, with a more environmentally friendly and straightforward construction. This study looked briefly at SynRM's potential for improved modeling and design. The study demonstrates a significant improvement in motor function as well as an upward trend in research projects with perhaps.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

It was performed as a part of the Employment of Ramash Kumar K, Department of Electrical and Electronics Engineering, Dr. N.G.P. Institute of Technology, Coimbatore-48, Tamil Nadu, India.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] B. Asad, T. Vaimann, A. Rassõlkin, A. Kallaste, and A. Belahcen, "A survey of broken rotor bar fault diagnostic methods of induction motor," *Electrical, Control and Communication Engineering*, vol. 14, no. 2, pp. 117–124, Dec. 2018.

[2] B. Asad, T. Vaimann, A. Belahcen, A. Kallaste, A. Rassolkin, and M. Iqbal, "Broken rotor bar fault detection of the grid and inverter-fed induction motor by effective attenuation of the fundamental component," *IET Electric Power Applications*, vol. 13, no. 12, pp. 2005–2014, Dec. 2019.

[3] B. Asad, T. Vaimann, A. Belahcen, A. Kallaste, A. Rassõlkin, and H. Heidari, "The low voltage start-up test of induction motor for the detection of broken bars," in *Proceedings of the 2020 International Conference on Electrical Machines (ICEM)*, pp. 1481–1487, Gothenburg, Sweden, August 2020.

[4] K. Lee, H.-Y. Kim, and S. Lukic, "A rotating restart method for scalar (v/f) controlled synchronous reluctance machine drives using a single DC-link current sensor," *IEEE Access*, vol. 8, pp. 106629–106638, Jun. 2020.

[5] C. S. Lim, E. Levi, M. Jones, N. A. Rahim, and W. P. Hew, "FCS-MPC-Based current control of a five-phase induction motor and its comparison with PI-PWM control," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 1, pp. 149–163, Jan. 2014.

[6] C. Lin, J. Yu, H. Yu, and Y. Lo, "Simplified model-free predictive current control for synchronous reluctance motor drive systems," in *Proceedings of the 2015 IEEE International Magnetics Conference (INTERMAG)*, p. 1, Beijing, China, May 2015.

[7] T. A. Lipo, "Synchronous reluctance machines-A viable alternative for AC drives?" *Electric Machines and Power Systems*, vol. 19, no. 6, pp. 659–671, Nov. 1991.

[8] T. Matsuo, A. El-Antably, and T. A. Lipo, "A new control strategy for optimum-efficiency operation of a synchronous reluctance motor," *IEEE Transactions on Industry Applications*, vol. 33, no. 5, pp. 1146–1153, 1997.

[9] D. Mohan, X. Zhang, and G. H. Beng Foo, "Generalized DTC strategy for multilevel inverter fed IPMSMs with constant inverter switching frequency and reduced torque ripples," *IEEE Transactions on Energy Conversion*, vol. 32, no. 3, pp. 1031–1041, Mar. 2017.

[10] R. Morales-Caporal and M. Pacas, "A predictive torque control for the synchronous reluctance machine taking into

account the magnetic cross saturation," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 2, pp. 1161–1167, Mar. 2007.

[11] L. Aarniovuori, J. Kolehmainen, A. Kosonen et al., "Application of calorimetric method for loss measurement of a SynRM drive system," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 4, pp. 2005–2015, Apr. 2016.

[12] C. A. Agustin, J.-T. Yu, Y.-S. Cheng, C.-K. Lin, H.-Q. Huang, and Y.-S. Lai, "Model-Free predictive current control for SynRM drives based on optimized modulation of triple-voltage-vector," *IEEE Access*, vol. 9, pp. 130472–130483, Sep. 2021.

[13] R. Antonello, L. Ortombina, F. Tinazzi, and M. Zigliotto, "Enhanced low-speed operations for sensorless anisotropic PM synchronous motor drives by a modified back-EMF observer," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 4, pp. 3069–3076, Apr. 2018.

[14] N. Aros, V. Mora, and C. Alarcón, "Model predictive control for synchronous reluctance motor drive," in *Proceedings of the 2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)*, pp. 1–6, Pucon, Chile, September 2017.

[15] S. Sayeef, G. Foo, and M. F. Rahman, "Rotor position and speed estimation of a variable structure direct-torque-controlled IPM synchronous motor drive at very low speeds including standstill," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 11, pp. 3715–3723, Feb. 2010.

[16] B. Asad, T. Vaimann, A. Rassõlkin, A. Kallaste, and A. Belahcen, "Review of electrical machine diagnostic methods applicability in the perspective of industry 4.0," *Electrical, Control and Communication Engineering*, vol. 14, no. 2, pp. 108–116, Dec. 2018.

[17] F. Betin, G. A. Capolino, D. Casadei et al., "Trends in electrical machines control: samples for classical, sensorless, and fault-tolerant techniques," *IEEE Industrial Electronics Magazine*, vol. 8, no. 2, pp. 43–55, Jun. 2014.

[18] N. Bianchi, S. Bolognani, E. Carraro, M. Castiello, and E. Fornasiero, "Electric vehicle traction based on synchronous reluctance motors," *IEEE Transactions on Industry Applications*, vol. 52, no. 6, pp. 4762–4769, Aug. 2016.

[19] A. Boglietti, A. Cavagnino, M. Pastorelli, D. Staton, and A. Vagati, "Thermal analysis of induction and synchronous reluctance motors," *IEEE Transactions on Industry Applications*, vol. 42, no. 3, pp. 675–680, Jun. 2006.

[20] E. Daryabeigi, A. Mirzaei, H. Abootorabi Zarchi, and S. Vaez-Zadeh, "Deviation model-based control of synchronous reluctance motor drives with reduced parameter dependency," *IEEE Transactions on Power Electronics*, vol. 34, no. 7, pp. 6697–6705, Jul. 2019.

[21] H. Heidari, A. Rassõlkin, M. H. Holakooie et al., "A parallel estimation system of stator resistance and rotor speed for active disturbance rejection control of six-phase induction motor," *Energies*, vol. 13, no. 5, p. 1121, Mar. 2020.

[22] M. Hinkkanen, P. Pescetto, E. Molsa, S. E. Saarakkala, G. Pellegrino, and R. Bojoi, "Sensorless self-commissioning of synchronous reluctance motors at standstill without rotor locking," *IEEE Transactions on Industry Applications*, vol. 53, no. 3, pp. 2120–2129, May 2017.

[23] N. Bianchi, S. Bolognani, D. Bon, and M. Dai Pre, "Rotor flux-barrier design for torque ripple reduction in synchronous reluctance and PM-assisted synchronous reluctance motors," *IEEE Transactions on Industry Applications*, vol. 45, no. 3, pp. 921–928, May 2009.

[24] C. Morales-Perez, J. Rangel-Magdaleno, H. Peregrina-Barreto, J. P. Amezquita-Sanchez, and M. Valtierra-Rodriguez, "Incipient broken rotor bar detection in induction motors using vibration signals and the orthogonal matching pursuit algorithm," *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 9, pp. 2058–2068, Apr. 2018.

[25] J. Y. Park, C. Kalev, and H. Hofmann, "Control of high-speed solid-rotor synchronous reluctance motor/generator for flywheel-based uninterruptible power supplies," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 8, pp. 3038–3046, Feb. 2008.

[26] G. Pellegrino, R. I. Bojoi, and P. Guglielmi, "Unified direct-flux vector control for AC motor drives," *IEEE Transactions on Industry Applications*, vol. 47, no. 5, pp. 2093–2102, Sept.-Oct. 2011.

[27] I. D. De Martin, D. Pasqualotto, F. Tinazzi, and M. Zigliotto, "Model-Free predictive current control of synchronous reluctance motor drives for pump applications," *Machines*, vol. 9, no. 10, p. 217, Sep. 2021.

[28] W. Fei and P. C.-K. Luk, "Torque ripple reduction of a direct-drive permanent-magnet synchronous machine by material-efficient axial Pole pairing," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 6, pp. 2601–2611, Jun. 2012.

[29] G. Foo, S. Sayeef, and M. F. Rahman, "Low-speed and standstill operation of a sensorless direct torque and flux controlled IPM synchronous motor drive," *IEEE Transactions on Energy Conversion*, vol. 25, no. 1, pp. 25–33, 2010.

[30] H. Heidari, A. Rassõlkin, A. Kallaste et al., "A review of synchronous reluctance motor-drive advancements," *Sustainability*, vol. 13, no. 2, p. 729, Jan. 2021.

[31] H. Heidari, A. Rassõlkin, T. Vaimann et al., "A novel vector control strategy for a six-phase induction motor with low torque ripples and harmonic currents," *Energies*, vol. 12, no. 6, p. 1102, Mar. 2019.

[32] A. Senthilnathan and P. Palanivel, "A new approach for commutation torque ripple reduction of FPGA based brushless DC motor with outgoing phase current control," *Microprocessors and Microsystems*, vol. 75, Article ID 103043, Jun. 2020.

[33] P. Sivakumar, V. Rajasekaran, and K. Ramash Kumar, "Investigation of intelligent controllers for varibale speeed PFC buck-boost rectifier fed BLDC motor drive," *Journal of Electrical Engineering*, vol. 17, no. 4, pp. 459–471, 2017.

[34] J. Gayathri Monicka, D. Noguna Sekhar, and K. Ramash Kumar, "Performance evaluation of membership functions on fuzzy logic controlled AC voltage controller for speed control of induction motor drive," *International Journal of Computer Application*, vol. 13, no. 5, pp. 8–12, January 2011.

[35] A. T. De Almeida, J. J. Ferreira, and G. Baoming, "Beyond induction motors—technology trends to move up efficiency," in *Proceedings of the 49th IEEE/IAS Industrial and Commercial Power Systems Technical Conference*, Stone Mountain, GA, USA, May 2013.

[36] M. H. Holakooie, A. Taheri, and M. B. B. Sharifian, "MRAS based speed estimator for sensorless vector control of a linear induction motor with improved adaptation mechanisms," *Journal of Power Electronics*, vol. 15, no. 5, pp. 1274–1285, Sep. 2015.

[37] R. Kumar, S. Das, P. Syam, and A. K. Chattopadhyay, "Review on model reference adaptive system for sensorless vector control of induction motor drives," *IET Electric Power Applications*, vol. 9, no. 7, pp. 496–511, Aug. 2015.

[38] C. Lascu, S. Jafarzadeh, M. S. Fadali, and F. Blaabjerg, "Direct torque control with feedback linearization for induction motor drives," *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2072–2080, Mar. 2017.

[39] D. Herrera, J. E. Villegas, E. Galván, and J. M. C. Carrasco, "Powertrain EV synchronous reluctance motor design with redundant topology with novel control," *IET Electric Power Applications*, vol. 13, no. 11, pp. 1647–1659, 2019.

[40] H. Hofmann, S. R. Sanders, and A. El-Antably, "Stator-flux-oriented vector control of synchronous reluctance machines with maximized efficiency," *IEEE Transactions on Industrial Electronics*, vol. 51, no. 5, pp. 1066–1072, Oct. 2004.

[41] M. Ibrahim, P. Sergeant, and E. M. Rashad, "Simple design approach for low torque ripple and high output torque synchronous reluctance motors," *Energies*, vol. 9, no. 11, p. 942, Nov. 2016.

[42] M. Ibrahim, E. M. Rashad, and P. Sergeant, "Performance comparison of conventional synchronous reluctance machines and PM-assisted types with combined star–delta winding," *Energies*, vol. 10, no. 10, p. 1500, Sep. 2017.

[43] I. Jlassi and A. J. Marques Cardoso, "Model predictive current control of synchronous reluctance motors, including saturation and iron losses," in *Proceedings of the 2018 XIII International Conference on Electrical Machines (ICEM)*, pp. 1598–1603, Alexandroupoli, Greece, November 2018.

[44] G. V. Kumar, C.-H. Chuang, M.-Z. Lu, and C.-M. Liaw, "Development of an electric vehicle synchronous reluctance motor drive," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 5, pp. 5012–5024, 2020.

[45] R. E. Betz, R. Lagerquist, M. M. Jovanovic, T. F. Miller, and R. P. Middleton, "Control of synchronous reluctance machines," *IEEE Transactions on Industry Applications*, vol. 29, no. 6, pp. 1110–1122, 1993.

[46] ABB, "Time to make a difference be part of the energy efficiency movement," 2023, https://www.energyefficiencymovement.com.

[47] M. M. Bouiabady, A. D. Aliabad, and E. Amiri, "Switched reluctance motor topologies: a comprehensive review," *Switched Reluctance Motor-Concept, Control and Applications*, vol. 21, Jun. 2017.

[48] E. S. Obe, "Calculation of inductances and torque of an axially laminated synchronous reluctance motor," *IET Electric Power Applications*, vol. 4, no. 9, p. 783, Nov. 2010.

[49] T. Orosz, D. Panek, and P. Karban, "FEM based preliminary design optimization in case of large power transformers," *Applied Sciences*, vol. 10, no. 4, p. 1361, Feb. 2020.

[50] E. Obe, "Direct computation of ac machine inductances based on winding function theory," *Energy Conversion and Management*, vol. 50, no. 3, pp. 539–542, 2009.

[51] M. D. Nardo, G. L. Calzo, M. Galea, and C. Gerada, "Design optimization of a high-speed synchronous reluctance machine," *IEEE Transactions on Industry Applications*, vol. 54, no. 1, pp. 233–243, Jan. 2018.

[52] E. Armando, P. Guglielmi, G.-M. L. Pellegrino, M. A. Pastorelli, and A. Vagati, "Accurate modeling and performance analysis of IPM-PMASR motors," *IEEE Transactions on Industry Applications*, vol. 45, no. 1, pp. 123–130, 2009.

[53] L. Ortombina, F. Tinazzi, and M. Zigliotto, "Magnetic modeling of synchronous reluctance and internal permanent magnet motors using radial basis function networks," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1140–1148, Feb. 2018.

[54] S. Piriienko, U. Ammann, M. Neuburger, F. Bertele, T. Röser, and B. Alexander, "Influence of the control strategy on the efficiency of SynRM based small-scale wind generators," in *Proceedings of the 2019 IEEE International Conference on Industrial Technology (ICIT)*, pp. 280–285, Melbourne, VIC, Australia, April 2019.

[55] E. M. Rashad, T. S. Radwan, and M. A. Rahman, "A maximum torque per ampere vector control strategy for synchronous reluctance motors considering saturation and iron losses," in *Proceedings of the Conference Record of the 2004 IEEE Industry Applications Conference, 2004. 39th IAS Annual Meeting*, vol. 4, pp. 2411–2417, Seattle, WA, USA, January 2004.

[56] A. Rassõlkin, A. Belahcen, A. Kallaste et al., "Life cycle analysis of electrical motor-drive system based on electrical machine type," *Proceedings of the Estonian Academy of Sciences*, vol. 69, no. 2, p. 162, Jan. 2020.

[57] R. Strzelecki, G. L. Demidova, D. V. Lukichev, N. A. Polyakov, A. Abdullin, and S. Lovlin, "Survey on fuzzy logic methods in control systems of electromechanical plants," *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, vol. 19, no. 1, pp. 1–14, Feb. 2019.

[58] Z.-N. Fan, L. Han, Y. Liao et al., "Effect of damper winding and stator slot skewing structure on No-load voltage waveform distortion and damper bar heat in large tubular hydro generator," *IEEE Access*, vol. 6, pp. 22281–22291, Apr. 2018.

[59] H. Heidari, A. Rassõlkin, A. Kallaste, T. Vaimann, and A. Belahcen, "Harmonics distortion in inverter-fed motor-drive systems: case study," in *Proceedings of the 2019 Electric Power Quality and Supply Reliability Conference (PQ) and 2019 Symposium on Electrical Engineering and Mechatronics (SEEM)*, pp. 1–4, Kärdla, Estonia, September 2019.

[60] X. Zhang and G. Foo, "Overmodulation of constant-switching-frequency-based DTC for reluctance synchronous motors incorporating field-weakening operation," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 1, pp. 37–47, 2019.

[61] L. Tang, L. Zhong, M. Rahman, and Y. Hu, "A novel direct torque controlled interior permanent magnet synchronous machine drive with low ripple in flux and torque and fixed switching frequency," *IEEE Transactions on Power Electronics*, vol. 19, no. 2, pp. 346–354, 2004.

[62] A. Taheri, H.-P. Ren, and M. H. Holakooie, "Sensorless loss model control of the six-phase induction motor in all speed range by extended kalman filter," *IEEE Access*, vol. 8, pp. 118741–118750, Jan. 2020.

[63] M.-Y. Wei and T.-H. Liu, "A high-performance sensorless position control system of a synchronous reluctance motor using dual current-slope estimating technique," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 9, pp. 3411–3426, Sep. 2012.

[64] T. Sun, J. Wang, M. Koc, and X. Chen, "Self-learning MTPA control of interior permanent magnet synchronous machine drives based on virtual signal injection," in *Proceedings of the 2015 IEEE International Electric Machines and Drives Conference (IEMDC)*, pp. 1056–1062, Coeur d'Alene, ID, USA, June 2015.

[65] J. Pando-Aced, A. Rassõlkin, A. Lehikoinen, T. Vaimann, A. Kallaste, and E. Romero-Cadaval, "Hybrid FEA-simulink modelling of permanent magnet assisted synchronous reluctance motor with unbalanced magnet flux," in *Proceedings of the 2019 IEEE 12th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, pp. 174–180, Toulouse, France, December 2019.

[66] J. C. Ting and D.-F. Chen, "Nonlinear backstepping control of SynRM drive systems using reformed recurrent hermite polynomial neural networks with adaptive law and error estimated law," *Journal of Power Electronics*, vol. 18, no. 5, pp. 1380–1397, Sep. 2018.

[67] E. Trancho, E. Ibarra, A. Arias et al., "PM-assisted synchronous reluctance machine flux weakening control for EV and HEV applications," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 4, pp. 2986–2995, Apr. 2018.
[68] B. Wang, J. Wang, B. Sen, A. Griffo, Z. Sun, and E. Chong, "A fault-tolerant machine drive based on permanent magnet-assisted synchronous reluctance machine," *IEEE Transactions on Industry Applications*, vol. 54, no. 2, pp. 1349–1359, March-April, 2018.
[69] B. Wang, J.-B. Wang, A. Griffo, and B. Sen, "Experimental assessments of a triple redundant nine-phase fault-tolerant PMA SynRM drive," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 1, pp. 772–783, Oct. 2019.
[70] D. Wang, K. Lu, and P. Rasmussen, "Improved closed-loop flux observer based sensorless control against system oscillation for synchronous reluctance machine drives," *IEEE Transactions on Power Electronics*, vol. 34, no. 5, pp. 4593–4602, May 2019.
[71] Y. B. Zbede, S. Gadoue, and D. Atkinson, "Model predictive MRAS estimator for sensorless induction motor drives," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 6, pp. 3511–3521, Jan. 2016.
[72] J. Xu, B. Zhang, X. Kuang, H. Guo, and S. Guo, "Influence analysis of slot parameters and high torque density optimisation for dual redundant permanent magnet motor in aerospace application," *IET Electric Power Applications*, vol. 14, no. 7, pp. 1263–1273, Mar. 2020.
[73] A. Senthilnathan, P. Palanivel, and K. R. Kumar, "Mathematical modelling and torque ripple waning in BLDC motor using outgoing-phase current discharge hysteresis controlled ANFIS controller," *Mathematical Problems in Engineering*, vol. 2022, Article ID 3971695, 21 pages, 2022.
[74] F. Niu, B. Wang, A. S. Babel, K. Li, and E. G. Strangas, "Comparative evaluation of direct torque control strategies for permanent magnet synchronous machines," *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 1408–1424, Feb. 2016.
[75] K. Ramash Kumar, "FLC and PWM SMC for KY boost converter," *Journal of Circuits, Systems, and Computers*, vol. 28, no. 11, Article ID 1950184, 2019.
[76] D. Flieller, N. K. Nguyen, P. Wira, G. Sturtzer, D. O. Abdeslam, and J. Merckle, "A self-learning solution for torque ripple reduction for nonsinusoidal permanent-magnet motor drives based on artificial neural networks," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 2, pp. 655–666, Feb. 2014.
[77] J.-F. Stumper, V. Hagenmeyer, S. Kuehl, and R. Kennel, "Deadbeat control for electrical drives: a robust and performant design based on differential flatness," *IEEE Transactions on Power Electronics*, vol. 30, no. 8, pp. 4585–4596, Aug. 2015.
[78] G. Wu, S. Huang, Q. Wu, F. Rong, C. Zhang, and W. Liao, "Robust predictive torque control of N∗3-Phase PMSM for high-power traction application," *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10799–10809, Mar. 2020.